Baryon Momentum Transfer
in Hadronic and Nuclear Collisions
at the CERN NA49 Experiment

Ph.D. thesis

Gábor I. Veres

Graduate School of Physics
Head: Dr. Zalán Horváth

Particle Physics and Astronomy Program
Head: Dr. György Pócsik

Consultant: Dr. György Vesztergombi

Department of Atomic Physics
Eötvös Loránd University, Budapest

November, 2001
Contents

1. Introduction .................................................. 1
   1.1 Soft hadronic physics and QCD .......................... 1
   1.1.1 Theoretical aspects .................................. 1
   1.1.2 Experimental aspects ................................ 3
   1.2 Baryon number transfer .................................... 5
   1.3 Heavy Ion Physics ........................................ 6
   1.4 Outline of the thesis ..................................... 8

2. Phenomenology of soft hadronic physics ......................... 10
   2.1 Dual Parton Model ........................................ 10
   2.2 VENUS .................................................... 12
   2.3 UrQMD ................................................... 13
   2.4 HIJING/BB ................................................. 14
   2.5 ALCOR .................................................... 16
   2.6 Nova or Resonance models ................................ 18

3. The NA49 Experiment ........................................... 20
   3.1 Time Projection Chambers ................................ 22
   3.1.1 Basics ................................................ 22
   3.1.2 Magnets ................................................. 22
   3.1.3 Geometrical Arrangement .............................. 22
   3.1.4 Field Cages, Construction ............................. 23
   3.1.5 Gases in the TPCs ..................................... 24
   3.1.6 Readout Chambers ..................................... 25
   3.1.7 Electronics and Data Acquisition ..................... 26
   3.1.8 Alignment, Laser System, Coordinates ................. 28
   3.2 Tracking and momentum measurement ...................... 30
   3.3 Time of Flight Systems .................................. 33
   3.4 Trigger System, Calorimeters ............................ 34
   3.4.1 Beam Intensity and Position .......................... 34
   3.4.2 Trigger ............................................... 34
   3.4.3 Target ................................................ 34
   3.4.4 Centrality Selection .................................. 34
   3.4.5 Ring Calorimeter ..................................... 36
4. The Veto Proportional Chamber ........................................... 37
   4.1 Motivation ............................................................ 37
   4.2 Design and Construction ............................................. 38
      4.2.1 Layout, Assembly ............................................. 38
      4.2.2 Materials ....................................................... 39
      4.2.3 Signal readout ................................................ 40
   4.3 Operation test ....................................................... 41
   4.4 Electronics, software .............................................. 42
      4.4.1 Test plate ...................................................... 42
      4.4.2 On- and off-line software .................................. 44

5. Ionization (dE/dx) measurement ........................................... 46
   5.1 The general method of ionization measurements .................. 46
      5.1.1 Ionization in gases .......................................... 46
      5.1.2 The Bethe-Bloch function .................................. 48
      5.1.3 Truncated mean methods ..................................... 52
      5.1.4 Monte Carlo simulation of the ionization .................. 55
      5.1.5 On the energy distribution of the primary electrons ..... 57
   5.2 Corrections of the ionization measurement ....................... 58
      5.2.1 Kr calibration ................................................ 59
      5.2.2 Pressure and temperature .................................... 59
      5.2.3 Length of flight ............................................... 61
      5.2.4 Drift length and angle dependent losses .................. 61
   5.3 Sector Calibration ................................................... 67
      5.3.1 If the Bethe-Bloch function is known ....................... 67
      5.3.2 Earlier ionization measurements ............................. 70
      5.3.3 Determination of the Bethe-Bloch function ............... 70
      5.3.4 "Global" dE/dx ............................................... 72

6. Particle identification, spectra ......................................... 76
   6.1 dE/dx fits .......................................................... 76
      6.1.1 Histogram, fit function ..................................... 77
      6.1.2 Fit of the amplitudes ....................................... 78
      6.1.3 Fit of the peak positions ................................... 79
   6.2 Phase space factors for spectra ................................... 81
      6.2.1 Variables, quantities ....................................... 81
      6.2.2 Inclusive invariant cross sections .......................... 82
6.2.3 Number densities ............................................................ 84
6.3 Trigger cross section ............................................................ 85
6.4 Corrections ........................................................................ 86
  6.4.1 Acceptance and efficiency ............................................... 87
  6.4.2 Target correction ............................................................. 88
  6.4.3 Feed-down from weak decays .......................................... 90
6.5 Available data sets ............................................................... 93

7. Results ................................................................................. 95
  7.1 Baryons in p+p and n+p interactions ..................................... 95
    7.1.1 \( p \) and \( \bar{p} \) spectra in p+p collisions ...................... 95
    7.1.2 \( p \) and \( \bar{p} \) spectra in n+p collisions ......................... 96
    7.1.3 Baryon spectra in p+p collisions .................................... 99
    7.1.4 Comparison with earlier measurements .......................... 103
    7.1.5 Comparison with phenomenological models ..................... 109
    7.1.6 Energy dependence ....................................................... 112
  7.2 Leading and central baryons in p+p interactions .................... 114
  7.3 \( \pi^+p \) and p+p interactions .............................................. 117
  7.4 Baryon stopping in p+A interactions .................................... 119
  7.5 Comparison of baryon stopping in p+A and A+A reactions ........ 122
  7.6 Summary of the experimental results .................................... 123
List of Figures

1 Phase diagram of QCD ............................................. 7
2 Two-chain diagram in DPM for $p + p$ interaction ................. 11
3 Baryon string configurations ..................................... 15
4 NA49 setup ..................................................... 21
5 TPC assembly .................................................... 23
6 Readout chamber layout ........................................... 25
7 Laser pulse shape on pads ......................................... 27
8 TPC sector numbering ............................................. 29
9 VTPC-2 pad layout ............................................... 30
10 PID using dE/dx and ToF ......................................... 33
11 Centrality Detector ............................................... 35
12 CD hit distributions ............................................... 35
13 Position of VPC in NA49 ......................................... 37
14 Cathode strip layout of VPC ...................................... 38
15 VPC sandwich assembly ........................................... 39
16 Pickup pads of the VPC ........................................... 40
17 Strips and sandwich of the VPC ................................ 41
18 Working point of the VPC ......................................... 41
19 Test VPC electronics .............................................. 42
20 Pulsing the VPC strips ............................................ 42
21 Strip pair capacitance ............................................. 43
22 VPC ............................................................. 45
23 Particle-electron cross section ................................... 47
24 Bethe-Bloch function ............................................. 48
25 Bethe-Bloch function vs. momentum ............................. 51
26 Moyal function ................................................... 52
27 Truncated mean vs. $N$ ........................................... 54
28 Simulated Landau distribution ................................... 55
29 Optimization of truncation ........................................ 56
30 Truncated mean and dE/dx ....................................... 57
31 Effective exponent vs. $Z$ in noble gases ......................... 58
32 Kr ionization spectrum ........................................... 59
33 Pressure correction of the gas gain ................................ 60
34 Origin of threshold loss ........................................... 62
35 Cluster shape ..................................................... 63
<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>Simulated charge loss</td>
<td>63</td>
</tr>
<tr>
<td>37</td>
<td>Tilted pads</td>
<td>65</td>
</tr>
<tr>
<td>38</td>
<td>Cluster shape comparison</td>
<td>66</td>
</tr>
<tr>
<td>39</td>
<td>Simulated and measured charge loss</td>
<td>66</td>
</tr>
<tr>
<td>40</td>
<td>First look on dE/dx</td>
<td>68</td>
</tr>
<tr>
<td>41</td>
<td>Result of the sector calibration</td>
<td>69</td>
</tr>
<tr>
<td>42</td>
<td>Older ionization measurements</td>
<td>70</td>
</tr>
<tr>
<td>43</td>
<td>Determination of the Bethe-Bloch function</td>
<td>71</td>
</tr>
<tr>
<td>44</td>
<td>Final Bethe-Bloch functions</td>
<td>72</td>
</tr>
<tr>
<td>45</td>
<td>Calibrated dE/dx scatter plot</td>
<td>74</td>
</tr>
<tr>
<td>46</td>
<td>dE/dx distribution around 10 GeV/c</td>
<td>75</td>
</tr>
<tr>
<td>47</td>
<td>dE/dx fit - example</td>
<td>80</td>
</tr>
<tr>
<td>48</td>
<td>$x_F$ and $y$ variables</td>
<td>83</td>
</tr>
<tr>
<td>49</td>
<td>Geometrical acceptance</td>
<td>87</td>
</tr>
<tr>
<td>50</td>
<td>Origin of vertex correction</td>
<td>89</td>
</tr>
<tr>
<td>51</td>
<td>Vertex correction; example</td>
<td>90</td>
</tr>
<tr>
<td>52</td>
<td>Feed-down correction; example</td>
<td>91</td>
</tr>
<tr>
<td>53</td>
<td>Acceptance windows in azimuthal angle</td>
<td>96</td>
</tr>
<tr>
<td>54</td>
<td>$p$ and $\overline{p}$ in $p+p$ collision</td>
<td>97</td>
</tr>
<tr>
<td>55</td>
<td>$p$ and $\overline{p}$ in $n+p$ collision</td>
<td>99</td>
</tr>
<tr>
<td>56</td>
<td>Cartoon on the calculation of $p+p \rightarrow n+X$ spectrum</td>
<td>100</td>
</tr>
<tr>
<td>57</td>
<td>$n$ and $\overline{n}$ in $p+p$ collision</td>
<td>101</td>
</tr>
<tr>
<td>58</td>
<td>$\overline{p}$ and $\overline{n}$ in $p+p$ collision</td>
<td>101</td>
</tr>
<tr>
<td>59</td>
<td>Net baryons in $p+p$ collision</td>
<td>102</td>
</tr>
<tr>
<td>60</td>
<td>Examples of $p_F$ fits on earlier datasets</td>
<td>105</td>
</tr>
<tr>
<td>61</td>
<td>Energy dependence of the central baryon density. Other experiments</td>
<td>106</td>
</tr>
<tr>
<td>62</td>
<td>Proton $x_F$ spectra in earlier datasets</td>
<td>108</td>
</tr>
<tr>
<td>63</td>
<td>Comparison of baryon spectra with models</td>
<td>110</td>
</tr>
<tr>
<td>64</td>
<td>$p$, $\overline{p}$ spectra at 100 and 158 GeV/c</td>
<td>112</td>
</tr>
<tr>
<td>65</td>
<td>Energy dependence of the central baryon density</td>
<td>113</td>
</tr>
<tr>
<td>66</td>
<td>Illustration of difference between $y$ and $x_F$ variables</td>
<td>114</td>
</tr>
<tr>
<td>67</td>
<td>$p$ and $\overline{p}$ spectra with selected leading baryons</td>
<td>115</td>
</tr>
<tr>
<td>68</td>
<td>Illustration of the resonance picture</td>
<td>116</td>
</tr>
<tr>
<td>69</td>
<td>Cartoon of target and projectile components</td>
<td>117</td>
</tr>
<tr>
<td>70</td>
<td>$p$ and $\overline{p}$ spectra in $\pi^+p$ and $\pi^-p$ collisions</td>
<td>118</td>
</tr>
<tr>
<td>71</td>
<td>Projectile component of $p-\overline{p}$ in $p+p$ collisions</td>
<td>119</td>
</tr>
</tbody>
</table>
LIST OF TABLES

72  $p$ and $\bar{p}$ spectra in p+Pb collisions ................................. 121
73  Baryon stopping in p+Pb collisions ......................................... 121
74  Baryon stopping in Pb+Pb collisions ......................................... 122

List of Tables

1  TPC sizes ................................................................. 24
2  Pad and wire sizes ....................................................... 26
3  Number of pads, pad-rows ............................................... 29
4  Ionization parameters .................................................... 47
5  Cluster model parameters ............................................... 64
6  NA49 datasets on p+p, p+A reactions ................................... 94
7  ALCOR and p+p data compared ......................................... 111
Abstract

In the thesis I discuss experimental methods and results concerning baryon momentum transfer (or "stopping") and antibaryon production in hadronic and nuclear collisions, like p+p or p+Pb interactions, obtained at the CERN SPS NA49 fixed target experiment at 158 GeV/c beam momentum.

Motivation to study baryon momentum transfer, and introduction to several widely used phenomenological models is given, and their predictions are compared with experimental data. The NA49 detector system and its operation is briefly explained. Design considerations and construction of a multiwire proportional chamber is discussed, a detector necessary to carry out large part of the studies presented here.

A detailed description of the particle identification in NA49, based on the specific ionization measurement in Time Projection Chambers is given. Correction and calibration methods developed and applied to the ionization data represents a serious effort to produce the entire amount of calibrated data in NA49 concerning elementary hadronic beams.

These data, prepared in the framework of the thesis, were used to extract single particle momentum spectra, and perform correlation measurements. Particle identification and methods necessary to obtain final cross sections are discussed. The following results are presented:

- Inclusive longitudinal momentum distributions of protons and antiprotons in p+p and n+p collisions. Comparison with models and earlier measurements is presented.

- Inclusive longitudinal momentum spectra of neutrons and antineutrons in p+p collisions are derived from the above result. Higher multiplicity for π than for η, and marked difference between the n and p spectra is found, neither being reproduced by phenomenological models.

- Strong correlation between the isospin of the leading nucleon and the abundances of the other baryons is found in p+p interactions, not reproduced by the studied event generators. Possible physical origin of these observations is suggested.

- Approximate Feynman-scaling is verified for protons in p+p interactions, in the beam energy range of 100 to 158 GeV, corresponding to \(\sqrt{s}=13.8\) and 17.2 GeV center of mass energy.

- A new idea to separate projectile and target contributions to the net proton spectrum in p+p collisions using π beams is presented, using assumptions consistent with the data.

- The projectile component of the net proton spectrum (which represents the "stopping" of the incoming beam proton) in p+Pb collisions is estimated, using p and π beams on a Pb target, with controlled centrality of the collisions.

- Baryon stopping in p+Pb and Pb+Pb is compared, in various centrality regions. Larger amount of stopping is found in the p+Pb case, even in the case where the approximate average number of 'elementary' collisions per participant nucleon was the same.
Összefoglaló

A dolgozatban azokat a kísérleti módszereket és eredményeket tárgyalom, amelyeket a baryonok "megállásának", azaz impulzusuk jelentős megváltozásának és antibaryonok keltésének kapcsán kaptam hadronok illetve atommagok ütközésekor (pl. $p + p$ vagy $Pb + Pb$ kölcsönhatásban), az NA49 kísérletben a CERN SPS gyorsítójánál, 158 GeV/c nyalábenergiánál.

A dolgozat bevezetése közt a barion-"fékeződés" tanulmányozásának okait, valamint a szakmában széles körben használt fenomenológiai modeleket mutatom be, melyeket később összetevők a kísérleti eredményekkel. Kitérek az NA49 detektorrendszernek és működésének rövid leírására is. Egy új sokszálás proporcionalis kamra tervezési szempontjait és megépítésének fázisait is tárgyalom, melynek szerepe elengedhetetlen volt a bemutatott eredmények elérésében.

Ezután az NA49 részecske-azonosításának leírása következik, amely a TPC rendszerből kapott fajlagos ionizáció adatokon alapszik. Az itt kidolgozott korrekciók és calibrációs módszerek révén vált lehetővé az NA49 kísérlet hadronikus nyalábokkal gyűjtött összes adatának pontosítása, és ezzel a részecske-azonosítás lehetővé tétele.

Ezekből az adatokból - melyek előkészítése a dolgozat előfeltétele volt - inkluzív impulzuseloszlások, valamint korrelációs mérések készültek. A részecske-azonosítással és a hatáskeresztmetszetek előállításával külön fejezet foglalkozik. Végül a következő eredményeket ismertetem:

- Protonok és antiprotonok inkluzív longitudinalis impulzuseloszlását $p + p$ és $n + p$ ütközésekben, modelekkel és korábbi mérési eredményekkel összehasonlítva.


- Korrelációt a vezető nukleon izospínje és a többi barionfajtáj számára között $p + p$ ütközésekben, amely nincs jelen a bemutatott modelekben; valamint javaslatot a jelenség okára.

- A közeliőből Feynman-skálázás igazolását protonokra $p + p$ ütközésekben a 100 és 158 GeV közötti nyalábenergiákrá (ez $\sqrt{s}=13.8$ illetve 17.2 GeV tömegközépponti energiának felel meg).

- Új módszert a valencia proton spektrum szétválasztására a cél tárgy illetve a nyaláb proton járulékára $p + p$ ütközésekben, pion nyalábok és az adatokkal konzisztens feltévek segítségével.

- A $p + Pb$ ütközésekben kapott valencia proton spektrum nyaláb járuléknak (mely a nyaláb proton "lellassulását" jellemzi) kiszámítását a $p$ és $\pi$ nyalábokkal Pb cél tárgyon végzett mérések eredményeiből, az ütközések centralitásának kontrollált változtatásával.

- A barion "lellassulás" összehasonlítását különbsző centralitású $p + Pb$ és $Pb + Pb$ ütközésekben. A $p + Pb$ esetben adódik nagyobb mértékű impulzusveszteség, még akkor is amikor a nyaláb proton "elemi" ütközéseinek átlagos száma ugyanaz volt a két esetben.
1. Introduction

In this chapter we try to motivate the experimental work invested in the preparation of this thesis. General remarks are presented concerning the situation of soft hadronic physics both from theoretical and experimental point of view.

1.1 Soft hadronic physics and QCD

1.1.1 Theoretical aspects

The strong interaction is a basic force of Nature which plays a crucial role in the evolution of the Universe, and in the synthesis of elements. It is responsible for the stability of protons and neutrons of atomic nuclei and neutron stars. The theory of strong interactions (QCD) describes the dynamics of quarks, the elementary constituents of matter, and gluons, the mediators of the strong force.

Quantum Chromodynamics (QCD) has been available from the 1970’s to explain in principle all hadronic phenomena. QCD belongs to the family of gauge theories (together with the model describing two other basic interactions, the electromagnetic and the weak), and features interacting gauge fields called gluons, and fermion fields called quarks, which come in three different ”colors”. Color is a quantum number playing an essential role in the dynamics of the strong interactions through the color-SU(3) gauge symmetry.

However, it has been found difficult to deal with strong processes involving small momentum transfer - the soft hadronic physics - on the basis of QCD. The reason can be illustrated by discussing the general features of the theory. The QCD Lagrangian can be written in terms of the $A_\mu$ gluon and $q_k(x)$ quark fields (k stands for the flavor quantum number) as:

$$L_{QCD} = -\frac{1}{2} \text{Tr} G_{\mu\nu} G^{\mu\nu} + \sum_{j=1}^{n_f} \bar{q}_j(i\gamma^\mu D_\mu - m_j)q_j$$

where $G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_{\mu}, A_{\nu}]$ is the gauge field tensor, $D_\mu q_j = (\partial_\mu - igA_\mu)q_j$ is the covariant derivative of the quark field ensuring the local gauge invariance of the theory, $g$ is the coupling constant, and summation over color indices is included. $A_\mu$ is a short notation for $A_\mu = \sum_{a=1}^{8} A_\mu^a \lambda^a / 2$ where $\lambda^a$ are the normalized Gell-Mann matrices satisfying the SU(3) commutation relations.

When calculating certain physical quantities (like quark and gluon propagators), one faces infinities which are to be subtracted using renormalization methods. It appears that the effective $\bar{g}(g,t \equiv \ln \eta)$ coupling depends on the $\eta$ momentum scale ($p \rightarrow \eta p$) as $\bar{g}^2(g,t) = g^2 / (1 + 2bg^2t)$ where $g = \bar{g}(g,0)$ and $b = (11 - 2n_f)/16\pi^2$ and $n_f$ is the number of quark flavors. Thus, when $\eta \rightarrow \infty$ then $\bar{g} \rightarrow 0$, which is a remarkable property of QCD called asymptotic freedom.
1. INTRODUCTION

Therefore, at high momentum transfers (small distances) the structure of the theory allows the application of perturbative expansions in the coupling constant (Feynman diagrams). The most precise experimental tests of the model correspond to this region, where the theory is referred to as perturbative QCD.

At low momentum transfer \( (Q^2) \) the coupling constant formally diverges as will be shown below. Let us set the \( \eta \) scale as \( \eta^2 = Q^2/\mu^2 \) where \( \mu \) is the subtraction scale needed to eliminate the mentioned divergences, and define \( \alpha_s \) as \( \alpha_s(Q^2) = \frac{\tau^2(t)}{4\pi} \). Let us define the \( \Lambda \) fundamental QCD scale parameter as \( \ln \Lambda^2 = \ln \mu^2 - 1/4\pi b_0 \alpha_s(\mu^2) \). Thus, we obtain the familiar formula for the running strong coupling constant:

\[
\alpha_s(Q^2) = \frac{4\pi}{(11 - \frac{2}{3}n_f) \ln (Q^2/\Lambda^2)}.
\]

where \( \Lambda_{QCD} \approx 200 \text{ MeV} \) as extracted from experimental data. When \( Q^2 \to \Lambda^2 \), \( \alpha_s \) diverges, therefore \( \Lambda \) represents a relevant measure of energy scale for the strong coupling.

In view of the above, one can understand why the physics at low \( Q^2 \) remains poorly understood when starting from a QCD basis. The quarks and gluons stay confined in the hadrons and are not accessible for experiments separately. Remarkably, however, the overwhelming fraction of the reaction cross sections reside in this difficult soft hadronic domain.

After the recent technological and scientific revolution in computer science and numerical applications, one can solve exactly the QCD equations using numerical techniques. These efforts lead to an entirely separate field in high energy physics, called lattice gauge theory. The space-time is discretized on a lattice, and the grid size \( a \) serves as a natural cut-off which regularizes the theory. These methods involve path integral techniques and the operators can be calculated with the help of the partition function of the physical system. Several problems, like the mentioned quark confinement can be studied using lattice calculations. The existence of the linear confinement potential between color charges can be verified. This leads to the phenomenological picture of strings which is the basis of several particle production models (e.g. Schwinger-mechanism for quark-antiquark production during string breaking).

The hadrons (mesons or baryons) observed are composites of 2 or 3 valence quarks, gluon fields and sea quarks (consisting of equal numbers of quarks and antiquarks). Each of these components give a peculiar contribution to the momentum of a high energy composite particle. In the final state of a hadronic interaction, these particles can be produced in abundance, and they are coming in many flavors, quantum numbers, spins and masses. To understand these complicated final states in high energy soft hadronic physics, effective phenomenological models are widely used. Some of these, which were selected to be compared with the experimental data obtained in the framework of this thesis, will be discussed in the following section.

In the situation where obvious difficulties arise in the theoretical treatment of soft QCD
starting from first principles, precise experimental input is essential and valuable for any comparison between phenomenological models, hints provided by lattice theory and the reality provided by Nature. New experimental data is needed both in differentiating between various models which are mostly successful in describing the bulk properties of the existing measurements, and in further refining them. New theoretical scenarios also may become competitive after revealing eventual novel features of the data.

1.1.2 Experimental aspects

The role of new, detailed experimental studies is clearly essential in leading the phenomenological models towards dynamical scenarios most appropriate to describe the data. The experimental investigations concerning the bulk properties of elementary soft hadronic collisions practically disappeared two decades ago, and were mainly carried out in the 1970’s using bubble chambers, single arm spectrometers, thus having limited statistics and energy range, or limited momentum space coverage, respectively. After the birth of the fundamental theory, QCD, the interest shifted to its experimental tests, obviously restricted to the perturbative region of the strong processes, or studying other specific features, using polarized beams etc.

The remarkable experimental development in the last 20 years makes it possible to solve most of the weaknesses of the earlier data sets. The work of NA49 fixed target experiment and data taken in the last years fulfill several requirements which could not be done before, all of this carried out by the same experimental set-up:

- **Large acceptance and momentum-space coverage.** For studies going beyond the inclusive particle production, like correlation within events, spectroscopy of hadronic resonances, fluctuation studies of various observables, a small spectrometer arm is not any more sufficient. The NA-49 detector covers most of the relevant kinematical region with sensitive volumes, detecting $\approx 80\%$ of the final state charged particles in the event. This was originally the principal design goal of the detector, aiming to observe event-by-event fluctuations and complete event patterns in heavy ion collisions. Large acceptance would be desirable certainly also for neutral particles. The first steps in this direction were the development of single particle detection in the Ring Calorimeter of NA49, supplemented by a Veto proportional chamber to distinguish neutral/charged particles (both works only for studies of elementary collisions).

- **Particle identification.** At SPS energies, most of the produced particles are pions, but the most interesting observables (strangeness production, baryon momentum transfer) make the particle identification necessary. The particle identification (PID) in the NA49 experiment is solved by ionization measurement provided by Time Projection Chambers, and it is one of the main subjects of this thesis. PID is available (at 158 GeV/c beam energy) in the full forward hemisphere in the center of mass system of the collisions, and somewhat to the backward
1. INTRODUCTION

direction.

- **Energy dependence.** Specific processes built in phenomenological theories and models have a particular energy dependence. In addition, the beam energy is an essential parameter to adjust in heavy ion collisions in order to change the initial conditions for eventual phase transition from hadronic to quark matter. Therefore data have been taken at several different beam energies: in elementary hadronic collisions 40, 100, 158 and 250 GeV/c, in heavy ion collisions 40, 80 and 158 GeV/c/nucleon was used (and 20 and 30 GeV/c is planned for the future). Most of our statistics is taken with 158 GeV/c beam momentum, therefore in most cases we will restrict ourselves to the discussion at this energy.

- **Diversity of beams and targets.** The NA49 experiment has been able to cover a large variety of particles used as beam and target, including elementary hadronic and heavy ion collisions. In the present thesis, p+p, d+p, π+p, p+Pb, π+Pb and Pb+Pb reactions will be discussed, but we have taken data with Al, Si, C target as well. A more detailed list of data sets can be found in Table 6. We adopt the strategy which has two main points:

  → The dynamics of these non-perturbative processes should be understood starting from simpler elementary collisions to more difficult nuclear systems.

  → Heavy ion physics itself needs an elementary baseline, since most observables relevant for the new kind of physics in heavy ion collisions are generally compared to some extrapolations from hadronic processes. If this new physics has to rely on quantitative experimental data, it also needs quantitative hadronic reference to establish departures from it.

The recently rising interest on the above two aspects is clearly visible in the community working on heavy ion physics [1].

In this thesis, we deliver information on a subject suitable for the above comparisons: baryon and antibaryon spectra (also presented in [2], [3] and [4]).

- **Centrality control.** There is a great deal of interest in studying collisions with different impact parameter. From the heavy ion physics point of view, the central and peripheral events may not feature the same kind of dynamics, the onset of quark and gluon deconfinement can be looked for by scanning various impact parameter regions. In the more elementary, proton+nucleus collisions it was found that the final state dramatically depends on the impact parameter, or, the amount of nuclear matter the projectile traverses. Therefore information on centrality selected data is much more informative than the minimum bias measurements practiced so far. Information of the impact parameter was earlier available only in bubble chamber studies (like [5]) with relatively limited statistics. In Ref. [5], the number of slow (grey) protons knocked out of the nucleus during the intranuclear cascade after the p + A collision are related to the number of collisions undergone by the projectile, in the framework of the Glauber model. In the discussion of Ref. [94], an analogy between measurements with
smaller nuclear targets and the peripheral $p + Pb$ collisions were used as a possible indirect estimate of the centrality in $p + Pb$ collisions. Studies with centrality control on a basis of grey particle detection are feasible with the NA49 experiment, and are also included in the present thesis.

- **Large statistics.** The many parameters mentioned above span a sizeable space, thus the number of recorded events needed for quantitative work is huge, taken into account that around a million events are necessary for each type of data. With the complexity of the eventual analysis, like correlations and resonance spectroscopy, the desired statistics increases rapidly. As will be demonstrated, the modern experimental methods and electronics of NA49 make it a suitable detector system to realize this program.

## 1.2 Baryon number transfer

The aim of the studies presented in the following chapters is to collect experimental information on

- the momentum transfer of the baryons, as well as the
- antibaryon production in different reactions.

In the final state of proton+proton interactions, we find that the longitudinal (beam direction) momentum distribution of protons (in the center of mass system) is remarkably flat, leading to the conclusion that the protons have "lost" around half of their momentum on the average in the process.

Since baryon number is a conserved quantity, the total number of protons, neutrons, hyperons must be equal to two in a proton+proton collision. Certainly, one has to take into account (subtract) the antibaryon production: antiprotons, antineutrons and antihyperons.

One main subject of this thesis is to provide experimental data on neutron and antineutron production, together with proton, antiproton and hyperon production measured also in the NA49 detector system, thus establish the spectrum of *net baryons* in the proton-proton reaction.

There are two main points which can be mentioned in connection with the baryon spectrum in proton-proton reactions:

→ How are baryons transferred to the low center of mass momentum values, observed already in proton-proton reactions? In order to achieve large momentum (rapidity) shifts of baryons (baryon number), one has to invoke special scenarios, to be discussed in the next chapter. It is not straightforward to predict a baryon spectrum observed in experimental data of proton-proton interactions. When making predictions for baryon stopping in heavy ion collisions, it is important to adjust these models to the elementary processes as precisely as possible. Also, the understanding of elementary processes is interesting on their own right.

→ The proton and baryon spectra are much different in the final state of the proton-proton
interaction: the (net) proton spectra are not to be identified with net baryon spectra. In heavy ion collisions, however, if one has approximately equal number of isospin states (protons and neutrons) initially, the final state proton and neutron spectra have to be equal as well.

Consequently, (net) proton spectra are not directly comparable in p+p and A+A collisions, without taking into account neutrons and antineutrons in the elementary process.

Information on these spectra are provided in the present thesis.

In the next section a brief overview is presented concerning the role of baryon stopping in heavy ion physics.

1.3 Heavy Ion Physics

The interest in baryon stopping is mainly rooted in heavy ion physics. For this reason, we give a short introduction to the field of heavy ions and the role baryon transfer plays in it, especially because the NA49 experiment was designed for studying heavy ion collisions.

Two particularly interesting features of QCD and the strong interactions are confinement (quarks and gluons are not observed separately, only in composite particles, hadrons) and the origin of hadron masses (which are much larger than the constituent masses, thus most of the hadron masses are generated dynamically).

Chiral symmetry, a basic property of QCD for massless quarks, has a profound impact on the hadron masses. This symmetry is spontaneously broken, resulting in a light Goldstone boson, the $\pi$. Qualitative information on the connection of chiral symmetry breaking and generation of hadron masses is still lacking.

One way to investigate the confinement problem is to compress nuclear matter in heavy ion collisions. At high temperatures and densities, a new phase of matter (quark-gluon plasma) was predicted [6]. In the QGP phase the quarks and gluons are deconfined and weakly interacting. Below the transition, they are confined in hadrons, forming an interacting hadron gas. The main objective of heavy ion collision studies is to get new information on the confinement by observing this phase transition experimentally (see Fig. 1).

In the QGP phase the chiral symmetry is restored as well. Hadron masses are most likely modified in dense and hot hadronic matter. The in-medium properties of hadrons are valuable observables exposing the role of chiral symmetry in QCD and in the origin of hadron masses.

The phase transition can be predicted and studied also with lattice QCD. Lattice calculations suggest that for $N_f=2+1$ (2 massless + 1 massive quark flavour) the phase transition at $\mu_B=0$, $T>0$ is possibly second order [7], at $m_{u,d} > 0$ (in reality) more likely higher order one (crossover), while model investigations quoted by [8] suggest that it is first order at $\mu_B \neq 0$ and $T\approx0$. In case of crossover phase transition at $\mu_B = 0$, a critical point with second order phase transition (‘end-point’) must exist at a $T>0$ and $\mu_B > 0$ point on the phase diagram.
1. INTRODUCTION

Its position was estimated recently in [10] using numerical methods on a lattice to be $T \approx 160$ MeV and $\mu_B \approx 725$ MeV. For a review of the QCD phase diagram, we refer to [8].

In the laboratory, attempts to create the QGP phase involve high energy collisions of heavy nuclei, in case of the NA49 experiment the $^{208}$Pb. These experiments are running at the CERN SPS, BNL RHIC and planned at CERN LHC (with increasing order of energy). At ultra-high energies, newly produced quark-antiquark pairs dominate, similarly to the early Universe, a few microseconds after the Big Bang. The mentioned experiments study the region of QCD phase diagram at high temperatures but low baryon densities (Fig. 1).

A complementary approach is to explore the properties of matter at high baryon densities and low temperatures, similarly to the interior of neutron stars. Increasing the baryon density, baryons lose identity and dissolve into quarks and gluons. The critical density at which this transition happens is yet unknown. At very high baryon densities, a color superconductor phase is predicted. But this region of the phase diagram is largely unexplored both theoretically and experimentally, while it can be reached by heavy ion collisions at intermediate beam energies. Such experiments are proposed in the GSI (Darmstadt) facility, aiming to reach 10 times the normal nuclear density.

The mentioned critical endpoint is expected to be possible to observe, for example, via fluctuations in different observables like strange to non-strange quark ratio (flavor fluctuations), or transverse momentum fluctuations of produced pions. But how can one make the colliding system of heavy ions closely pass by the critical point? This is a place where baryon stopping plays a role. On the phase diagram, the collision starts from a $\mu_B > 0, T=0$ point corresponding to the nuclear matter. The collision creates high energy density (high temperature), thus the system moves upwards on the diagram (see Fig. 1). If the initial nucleons (baryons) do not lose major part of

Fig. 1: Phase diagram of QCD. The different phases of the strongly interacting matter are depicted in the baryon chemical potential – temperature plane. The amount of stopping is relevant for the study of phase transition between hadronic and quark-gluon phase, and experimentally it can be varied by changing the beam energy, the size - and the shape - of the colliding nuclei, and the centrality of the collision. The blue lines are only illustration (since there is probably no thermal and chemical equilibrium during the whole evolution of the system).
their momentum, do not 'stop' to a large extent, some energy density can still be created (in a color string picture, the energy of the strings fills the midrapidity region), but the baryon density remains small, thus the trajectory of the system in the T vs. $\mu_B$ plane proceeds leftwards (in Fig. 1 it could eventually miss the critical point).

If, in contrast, there is much baryon stopping, the trajectory will move up and rightwards, reaching high values of chemical potential (like in the proposed GSI SIS200 intermediate energy collisions possibly with deformed, cigar-shaped nuclei). If the boundary of phase transition is crossed, the system begins to cool down and both the chemical potential and temperature decreases, and another crossing of the boundary is expected. The phase transition can be observed if the freeze-out of the hadrons happens sufficiently close to the critical point in the phase diagram.

A certain degree of baryon stopping is necessary to create also sufficiently high temperature to reach the phase transition. By energy conservation, only the momentum degradation of the initial nucleons can lead to intense pion (entropy) production.

Therefore the extent of baryon stopping is essential in heavy ion experiments.

Let us note that the above discussion still does not shed much light on the origin and mechanism of the baryon stopping, neither delivers a better insight in the question, what is the carrier of baryon number etc. This thesis was motivated by a conservative strategy suggesting that the mechanism of baryon stopping is more natural to study in the simplest systems: proton-proton and pion-proton collisions\textsuperscript{1}.

The eventual discovery of the QGP phase can be based on powerful signals, which are characteristic to the phase transition but cannot be explained by any alternative way. The other, probably more promising strategy is to understand the dynamics of heavy ion collisions aiming at a quantitative description. The latter, however, should not leave the questions of dynamics in simpler systems ($p + p$, $p + A$) unanswered: this is an approach which I kept in mind when examining these simpler systems and baryon stopping occurring in them.

1.4 Outline of the thesis

The present thesis is an experimental work, and it closely reflects the activity of the author during the years of preparation. It puts therefore more weight on the experimental methods applied to obtain certain results. However, as much introduction and orientation is given towards interpretation and phenomenology as was possible without unreasonable extension of the text.

\textsuperscript{1}It is worthwhile to note, that also electron-proton collisions were studied at HERA recently in [9], providing interesting evidence for baryon momentum transfer across a rapidity interval of 8 units.
1. **INTRODUCTION**

Thus, in the 2nd chapter a brief and by far not exhaustive summary is given on a few possible phenomenological models or ideas connected to the soft hadronic interactions and mainly to proton-proton interactions.

Chapter 3 is dealing with the introduction of the NA49 experimental apparatus, and its design goals, with some explanation of the operational features of the detectors, mostly those relevant for the following chapters.

This is followed by a summary on the construction and operation of a multiwire proportional chamber, which plays an essential role in neutral particle detection necessary for the following analysis. It represents the part of my efforts being connected to experimental hardware.

Chapter 5 includes the major part of the software effort of the project, the ionization measurement in the Time Projection Chambers and its corrections and calibrations. All data presented in the thesis (as well as the data files analyzed by other NA49 members on hadronic collisions) are a result of my calibration methods developed here, and used for particle identification.

The methods connected to the physical analysis of inclusive and semi-inclusive spectra, which concerns partially the particle identification and certain physical corrections, are discussed in Chapter 6. The steps necessary to arrive to a physical result are presented.

Finally, the results concerning baryon and antibaryon spectra, baryon stopping in p+p, p+Pb and Pb+Pb reactions are presented, and compared to widely used phenomenological models introduced in Chapter 2.

At certain points of my analysis I used contributions of other members of the NA49 collaboration: feed-down corrections, vertex corrections and neutron spectra.
2. Phenomenology of soft hadronic physics

Since the aim of the present thesis is an experimental study of baryon momentum transfer in elementary hadronic collisions, it was necessary to devote a chapter to a brief discussion of phenomenological models and their description of baryon stopping. Most of these models will be confronted with the measurements in the last chapter. We could not aim to give an exhaustive account of these models, and the selection made here is not meant to be discriminative for the ones eventually omitted.

At the CERN SPS, a large degree of stopping is observed together with an enhanced strange hyperon production in p+A and A+A collisions. The stopping is significantly underpredicted by models which assume that the dominant mechanism of baryon momentum transport involves only diquark-quark hadronic strings.

In the HIJING [11], the Lund Fritiof [12] and the dual parton model (DPM) [13], the colliding baryons cannot slow down more than about 2 units of rapidity because of the assumed diquark fragmentation dynamics of the $qq - q$ strings. Several models have included additional mechanisms to overcome this problem. In the VENUS model [14] stopping is reproduced by an extra double string mechanism with parameters adjustable to fit the data. The RQMD [15] and UrQMD [16] event generators include an incoherent multiple inelastic scattering of the valence (di)quarks to account for the baryon stopping in nuclear matter, however, time dilatation of inelastic processes lead to coherence rather than incoherence. The new version of HIJING model, the HIJING/BE introduces a new mechanism related to the gluon field of the nucleons, which increases baryon stopping both in elementary and heavy ion interactions.

In the following we briefly introduce these models.

2.1 Dual Parton Model

The first example of string fragmentation models we consider is the Dual Parton Model [13]. The ideas and considerations used in color string models, like simple string models for mesons and baryons, the particle production mechanism from the string fragmentation as described by the Schwinger mechanism, the LUND model for particle production in $e^+e^-$ interactions, the topological expansion and the large $N$ limit of QCD, the basics of Regge theory, duality and applications to N+N interactions is overviewed and summarized for example in [20]. DPM is one of the models applying the methods connected to the topological expansion, Regge theory and the parton structure of hadrons. The large $N$ limit of QCD is a non-perturbative approach where $N$ can be either the number of colors $N_c$ or flavors $N_f$, giving rise to a topological expansion where topologically complicated diagrams are suppressed. Constraints of unitarity and duality provides the dual topological unitarization (DTU) scheme, which is the basic ingredient
of DPM.

Diagrams in the DTU expansion involve multiple exchanges of Pomerons in the $t$-channel, and are in close relation with Regge field theory. Single Pomeron exchange gives two chains of hadrons stretched between valence quarks of the initial hadrons to form color singlets, while multi-Pomeron exchanges give multiple number of chains, and a single string corresponds to a Reggeon exchange. With increasing energy, diagrams with more and more difficult structure become important. A dominant two-chain diagram describing particle production in $p + p$ collisions is illustrated by Fig. 2. The $x$ momentum fractions taken by constituents are determined from momentum distribution functions, and particle production in any chain is given by fragmentation functions. Particle spectra are computed by convolution of the above two functions. Diagrams essentially refer to two-step processes: separation of color in the collision and fragmentation of colored objects (chains).

The most probable process related to Fig. 2 is a separation of the proton to a slow (held-back) valence quark and a fast diquark. The eventual separation is determined by the $x^{-1/2}$ form of the valence quark momentum distribution, which results in a rapidity separation probability of the form $\exp[-(y - y_{\text{max}})/2]$ where $y$ is the valence quark rapidity. Held-back quarks will give an influence on the central ($x_F \approx 0$) particle production up to relatively high $\sqrt{s}$.

The DPM model was found to describe important features of soft hadronic processes like single particle inclusive spectra, multiplicity distributions, correlations between $\langle p_T \rangle$ and multiplicity, and many others. For further details, we refer to [13].

The measured large amount of baryon stopping in central $Pb + Pb$ collisions was not possible to describe with the DPM model in its original form. In an improved version of the DPM [17, 18] the enhanced baryon stopping is achieved by a diquark breaking mechanism: a gluon exchange can mediate the diquark breakup by changing its color state from 3 to 6, or other scenarios are possible as well. The baryon number follows one of these valence quarks instead of the diquark, resulting a slower baryon in the CM system. The cross section for this mechanism reads (similarly to the one invoked by the modified HIJING model):

$$\frac{d\sigma}{dy}(p + p \rightarrow p + X) = (7 \text{ mb}) \sqrt{\frac{1 \text{ GeV}}{\sqrt{s}}} \cosh \frac{y}{2}.$$  

In nuclear collisions, these diquarks are assumed to stay broken afterwards. In a heavy nucleus, where the number of collisions of the projectile is large, very few diquarks can survive. This scenario is able to describe the A+A data at the CERN SPS [17]. In $p + p$ collisions, the effect
of the diquark breaking mechanism is small, and the amount of baryon stopping in the data is not large enough to require its presence. The mechanism is designed in a way that in the $p + p$ case we recover the original diquark preserving component: diquark breaking is only effective if the projectile undergoes multiple collisions (only possible in $p + A$ and $A + A$ interactions). Strangeness enhancement comparable to the measured data in heavy ion collisions could be achieved by including final state interaction effects, not originally part of independent string models.

### 2.2 VENUS

One of the most widely used event generators in the field of hadronic physics is the VENUS (Very Energetic NUclear Scattering) model [14], which is (similarly to DPM) based on the Gribov-Regge theory of hadronic interactions. Such models agree concerning elastic scattering and the weights for certain inelastic processes, but those processes are defined differently. VENUS was designed to study high energy $N + N$, $N + A$, $A + A$ reactions. It considers Pomeron exchange as a basic hadron-hadron scattering process, although the precise nature of Pomeron in terms of gluons and quarks is not completely understood. Sum of multiple Pomeron exchange amplitudes give the elastic scattering amplitude, while discontinuities of elastic amplitudes are related to the inelastic scattering via unitarity. The total cross section is $\sigma = \sum \sigma_m$, where $\sigma_m$ is related to the contribution of $m$ cut Pomerons. This is associated in VENUS with a certain string configuration. Particle distributions from string fragmentation are related to such configurations.

VENUS does not restrict that the strings should break into a hadron and a string (as the Lund model does), but into two substrings which can be hadrons or high mass strings. Finally, after a mass of the string decreases below a certain limit, it is identified with a resonance, being not necessarily on-shell.

The two exchange particles relevant in hadron-hadron collisions, the Reggeon and the Pomeron is identified with a planar and cylindrical QCD diagram, respectively, whose surfaces contain networks of gluons and closed quark loops. Regge theory gives a total cross section for these exchanges $\sigma_{tot} \propto s^{\alpha(0)-1}$ where $\alpha(t) = \alpha(0) + \alpha'(0)t$ is the Regge trajectory with $\alpha(0)$ intercept. Pomerons are characterized by $\alpha(0) = 1 + \epsilon$, Reggeons by $\alpha(0) < 1$, thus Pomerons dominate at high energies. VENUS is based on Gribov-Regge theory, which deals with multiple Pomeron exchanges in a way not to violate unitarity. This way elastic cross sections are obtained, and using the optical theorem, inelastic ones as well.

The two steps of the process are the string generation and the above discussed string decay. First $m$, the number of color exchanges is generated consistently with Regge considerations (the case of $m$ cut Pomerons) and the actual strings are generated for the given $m$. Color
exchange means that a quark from the target nucleon is removed and attached to the projectile "remnant" and vice versa, stretching two strings. This is common for many string models, but VENUS is unique in a sense that it involves antiquarks as well in the color exchange process, and that the first color exchange is treated identically with the following ones. Thus diquark breakup is naturally allowed.

Further details, inclusion of semihard processes, parameters, aspects of collisions with nuclei, as well as a discussion of the basic string dynamics can be found in the complete review of VENUS [14].

2.3 UrQMD

The Ultrarelativistic Quantum Molecular Dynamics model [16] is a microscopic model used to simulate (ultra)relativistic heavy ion collisions in the wide energy range from about 1 GeV/nucleon to \( \sqrt{s} \approx 200 A \cdot GeV \). Its main goals are to gain understanding about the following physical phenomena within a single transport model: creation of dense hadronic matter at high temperatures, properties of nuclear matter, creation of mesonic matter and of anti-matter, creation and transport of rare particles in hadronic matter, creation, modification and destruction of strangeness in matter, emission of electromagnetic probes.

It deals with various reaction mechanisms: low energy compound nucleus formation and DIS, particle and resonance production at intermediate energies, string excitation and fragmentation and parton scattering at the highest energies, where quark and gluon degrees of freedom become relevant besides hadrons (resonances).

UrQMD is a microscopic model based on a phase space description of the reaction, containing many unknown parameters. The goal is to pin down physical ingredients that are relevant for predicting the observed quantities. Transport theories are well suited for the rapid time-dependence and non-equilibrium nature, finite size effects, inhomogeneity, particle/resonance production and collective dynamics of the heavy ion collisions, as opposed to simplified thermal equilibrium models. At high energies, the excited hadron states (resonances) reach high masses and a width/mass ratio increases to \( \approx 1 \), therefore UrQMD considers quark degrees of freedom and string excitations in this limit.

A sequence of particle propagations is simulated numerically, involving baryons and mesons eventually interacting with a potential, scattering and decaying. The main ingredients needed are cross sections, decay widths and two-body potentials: 55 different baryon and 32 meson species are included, as well as their antiparticles and isospin family. For higher masses than 2 GeV/c\(^2\) a string picture is used. Elementary cross sections are adjusted to available \( p + p \) and \( \pi + p \) data. Cross sections are interpreted geometrically as an area of a disk: two particles interact if they get closer than the respective disk radius. At lower energies, isospin effects like
differences in $p + p$ and $n + p$ cross sections are taken into account.

The properties of particles may change significantly in a dense and high temperature medium. Correct assessment of these features presents a major difficulty, and approximations are generally used. Quasi-particle (on-shell propagation) limit is not a valid approximation because of the short time between subsequent scatterings. The Markovian approximation (independent scatterings with memory lost between them) also fails at high energies. Correlations are obtained by letting the particles interact by individual 2-body forces, as opposed to the statistical coalescence models using 1-body phase space distributions.

Practical applications of transport models as UrQMD cannot retain coordinate frame independence, because of the actual realization of scatterings, decays etc.: Lorentz boosts can change the time sequence of these interactions at the practical simulation in space-time.

In UrQMD, a string excitation and fragmentation scheme is combined with the transport theoretical approach (while the other discussed models are based mainly on the dynamics of strings and partons).

Further details, like an exhaustive review of assumptions and parametrizations for elementary cross sections, and comparisons with experimental data applied by the UrQMD model can be found in Chapter 3 of [16].

2.4 HIJING/BBB

The HIJING model describes nucleon-nucleon interactions in terms of classical strings. Only two strings are formed, consistently with the lowest order cylindrical diagram of the topological expansion. The excited masses of the strings are obtained from a momentum exchange probability distribution defined for the N+N interactions. In multiple collisions, nucleons which have suffered a collision (wounded nucleons) are assumed to still interact as nucleons in subsequent collisions. Fragmentation of these $qq - q$ strings are similar to that of the $q\bar{q}$ strings in the $e^+e^-$ interaction. HIJING also studies the effects of perturbative QCD: minijets in $pp$ and $AB$ collisions. In the following we mention the ideas leading to the extensions of this model, which are relevant for baryon stopping.

The HIJING model was recently modified ([20]) to explain the amount of baryon stopping by a new mechanism, related also to the question on how the notion of baryon number is connected to the constituents of the baryons. As it was suggested in [21], the baryon number could be carried by a nonperturbative configuration of the gluon field inside the baryons, since the usual assumption that quarks carry 1/3 baryon number is not strictly dictated by QCD. As proposed in [21], the baryon production in the central rapidity region of ultrarelativistic $p+p$ and $A+A$ collisions provide a crucial possibility to test the baryon structure.

For example, in a proton-proton collision the valence quarks carry a substantial $x_V$ part
of the momentum $P$ of the nucleon, and at high energies, the valence quark distributions get strongly Lorentz-contracted to pancakes with a thickness of $z_V \approx (x_V P)^{-1}$ where $x_V \approx 1/3$. The typical time needed for valence quarks from different protons to interact is given by the average interquark distance in the impact parameter plane, around 1 fm/c. However, the time available to interact is only $z_V/c \approx (x_V P c)^{-1}$. At sufficiently high energies, the quarks (and in the conventional picture, the baryon number also) do not have time to interact and will populate the fragmentation, not the central (midrapidity) region.

However, the large number of gluons located at very low $x$ are less affected by the Lorentz-contraction, thus extend more in space.

In a proton-proton reaction the gluon fields have more time available to interact with each other, and the importance of this effect grows with increasing energy ($\sqrt{s}$).

The earlier string models of particle production in soft processes considered a configuration where a color string is pulled between a quark and a diquark (in a $\bar{3}$ color state), and particle production originated from the fragmentation of the string. If we imagine the baryon as valence quarks connected with flux tubes of the chromoelectric field (Wilson-lines), this would correspond to a linear $q - \bar{q}q$ configuration. Similarly, one can imagine a $\Delta$-configuration where the three quarks are connected by a triangle of gluon lines (see Fig. 3).

![Fig. 3: Four baryon string configurations: A) the linear, B) diquark-quark, C) triangle, D) junction configurations. All the others are special cases of the junction configuration.](image)

The only gauge invariant state vector representing a baryon is however the $Y$-shaped one, where the crossing point $x_\mu$ of the Wilson-lines is called the gluon junction\(^2\):

$$B = e^{ijk} \left[ P \exp \left( ig \int_{x_1}^{x} A_\mu dx^\mu \right) q(x_1) \right]_i \left[ P \exp \left( ig \int_{x_2}^{x} A_\mu dx^\mu \right) q(x_2) \right]_j \times \left[ P \exp \left( ig \int_{x_3}^{x} A_\mu dx^\mu \right) q(x_3) \right]_k$$

Since this is a unique feature of the baryons, one can postulate that the baryon number itself is connected to this junction rather than the valence quarks in the end of the three legs. There are

\(^2\)Note that if the junction is close to one of the quarks, one gets a $V$-shaped configuration, which is isomorphic with the linear one. Superposition of $V$ configurations can be the $\Delta$-configuration. Thus all of them are special cases of the $Y$-shaped one.
other consequences, like the object composed from a junction and antijunction, thus containing no quarks, can be exchanged in proton-proton interaction like a Regge trajectory. Dynamics based on the above idea is implemented into HIJING, now called HIJING/B$\overline{B}$. The new mechanism increases the amount of possible baryon stopping, since in an event where all three valence quarks are ripped off the junction, the ”new” valence quarks and the gluon field can have a relatively small total momentum resulting in a ”stopped” final state baryon. Therefore the agreement with the experimental data becomes more precise in p+p collisions. There is an other effect of the novel phenomena, the increased amount of strange and multistrange baryon production, which is a similarly important observable especially in heavy ion collisions. There, predicted observables include enhanced strangeness production, therefore it is important to estimate the expected amount of strange baryons while invoking only such dynamical features which are common with elementary collisions.

In Regge phenomenology, new $M^j$ Regge trajectories are introduced in [19]. The intercept of the leading term $M^j_0$ can be estimated from the energy dependence of the $\Delta \sigma = \sigma(p\bar{p}) - \sigma(pp)$ cross section difference (given by the $\omega$, $\rho$ and $M^j_0$ Regge exchanges). This way the $\Delta \sigma \propto s^{-1/2} \approx s^{\alpha_M^j(0)-1}$ relation gives $\alpha_M^j(0) \approx 1/2$. It was proposed in [21] to use $M^j_0$ Reggeon exchange in baryon production to yield a new baryon stopping mechanism. This phenomena was included in the HIJING/B event generator [20]. The energy and rapidity dependence of the inclusive baryon production was calculated using Mueller’s generalized optical theorem in the double Regge limit [21], giving the $\sqrt{\frac{1}{2\pi}} \cosh \frac{y}{2}$ dependence mentioned above. For the effective cross section of junction exchange, 18 mbarn is taken at 400 GeV/c, and 9 mbarn at 160 GeV/c beam momentum. HIJING/B is able to reproduce baryon stopping and hyperon enhancement in p+A collisions, but it does not fully account for the hyperon enhancement in heavy nuclear systems.

To summarize, the original HIJING model was modified to include the junction motivated baryon stopping mechanism, and the result is called HIJING/B. It was further modified to include junction-antijunction loop baryon pair production mechanism, now called HIJING/B$\overline{B}$. These are modeled by adding new string configuration to the usual $qq - q$ background. We will use for comparisons the latest version.

2.5 ALCOR

The Algebraic Coalescence Rehadronization model (ALCOR, [22, 23]) has been designed to calculate hadron multiplicities, by redistribution of quarks into hadrons in relativistic heavy ion collisions. The model incorporates a dynamical in-medium suppression of the light to heavy quark coalescence factors, and the influence of Bjorken-flow on the final hadronic composition.
Rehadronization after a prehadronic state in heavy ion collisions cannot be treated by perturbative methods because of the low-energy phenomenon leading to the valence quark confinement. Rate equations in hadro- or quark chemistry cannot be easily applied because the constraint that all the final state hadrons have to be color singlet states is difficult to fulfill. The idea of the model is to redistribute all the quarks and antiquarks into hadrons in a sudden process of rehadronization.

As input, one has to specify the initial number of later valence quarks and antiquarks with different flavors, to be hadronized. These numbers refer to the original quark content of the colliding nuclei, plus the yield from the newly produced \( q\bar{q} \) pairs. The number of newly produced particles are usually taken from the analysis of the experimental data (or other phenomenological models as string, color rope or thermodynamical models). Thus, the starting point of the ALCOR model is a state in local thermal equilibrium with all the quarks present which will form the final hadrons.

For each hadron type, a coalescence factor is introduced, \( C_M(i, j) \) and \( C_B(i, j, k) \) for mesons and baryons, respectively, where \( i, j, k \) refer to quark flavors \( (u,d,s) \). There are \( b(i) \) normalization factors, which get fixed by the requirement that all initial quarks must hadronize. Particles including the spin 0 and spin 1 meson octets and spin 1/2 and 3/2 baryon octet and decouplet is considered, the spin degeneracy is taken into account.

The important dynamical nature of the model is included into the rate equation, which describes that the probability of the \( q_1 + q_2 \rightarrow h \) one-way process is proportional to the density of quarks \( q_1 \) and \( q_2 \), and to the thermally averaged reaction rate, depending on the relative velocity of the partners. These coalescence factors are given by theoretical considerations, and their value will influence the relative distribution of s quarks between strange mesons and baryons.

The hadronization of a baryon is a two step process; first a diquark forms (in color 3 or \( \overline{3} \) state), and has some chance to decay before picking up a third quark.

The effect of the (hydrodynamical) flow on the reaction rate is essential. ALCOR uses a calculation of the reaction rate taking a local thermal momentum distribution in a flow background [22], in a finite space and momentum interval. Only those quarks may interact whose momenta in their center of mass frame points towards each other. Thus, the effect of the space-time evolution of the system on the reaction rate is treated and discussed.

The hadronization cross section (a priori unknown) is calculated based on an analogy with the \( p + A \rightarrow d + (A - 1) \) deuteron coalescence phenomenology.

Finally, the parameters of the model are: the number of newly produced \( u\bar{u} \) and \( d\bar{d} \) pairs \( (N_{u\pi} = N_{d\pi}) \), the number of produced (heavier thus suppressed) \( s\bar{s} \) pairs expressed by the \( f_s \) parameter: \( f_s = N_{s\pi}/(N_{u\pi} + N_{d\pi}) \), and the stopping parameter, \( P_{\text{stop}} \) (this factor determines
the portion of the quarks from the projectile and the target to melt into the central rapidity region generating baryon asymmetry).

The outputs of the model are the particle yields at midrapidity For example, in Pb+Pb collision at CERN SPS energy the parameters $N_{u}= N_{d}=121$, $f_s=0.22$ and $P_{stop} = 0.17$ reproduce quite well the experimental data in the central rapidity region [24]. Good agreement was obtained at RHIC energy in Au+Au collisions [24].

We will use the model to give predictions in 158 GeV/c $p+p$ interactions, where - given the small number of valence quarks - the model can be used formally, although it was not meant to describe such small colliding systems.

2.6 Nova or Resonance models

There are phenomenological models which emphasize the role of resonance excitation and subsequent decay through a cascade, as a dominant mechanism of particle production in soft hadronic interactions.

The Nova Model three decades ago [25] discussed excitation of ”nova” states, which are resonance-like objects, decaying mainly via a cascade emission of pions. The production cross section of these objects does not depend on energy ($\sqrt{s}$), and as a function of the nova mass, it rises to maximum and falls off in a way controlled by Regge behavior and duality. This picture can account for the observed rapid approach of Feynman-scaling for high momentum secondaries, and certain correlations between the average multiplicity, the longitudinal and transverse momentum distributions of produced particles, and the remarkable difference between meson and baryon distributions.

It is suggested that the dominant inelastic process (2/3 of the inelastic cross section) at $\sqrt{s} = 5...8$ GeV energies is the diffractive excitation of either the beam or the target particle, followed by a decay through pion emission to a hadronic ground state. These novas behave as resonances and the quantum numbers (like baryon number) of the excited beam or target particle is kept by the nova. This has consequences for the branching ratios, as long as there are not too many secondary particles. The number of resonance states may compensate the low individual yields, to build up a dominant contribution of the cross section. The nova mass spectrum is rising to a maximum at around 2 GeV, then decreases as $M^{-2}$, a feature connected to the behavior of the triple Pomeron coupling. The excitation is associated with low momentum transfer squared, and at the above energies the single excitation should dominate, to reproduce the observed relatively low multiplicities and the strong leading particle effect. At higher energies double excitation is not any more unfavored, while at lower energies quantum

---

3The machine energies were at that time between 10 and 30 GeV, which corresponds to $\sqrt{s} = 4.5$ to 7.6 GeV $p+p$ collisions. Our experiment operates at $\sqrt{s} = 17.3$ GeV
number exchange can play a role. The pion inclusive spectra are determined by relatively low mass novas, since the nova production cross section falls strongly with the nova mass \( M \). Experimental data on pion distributions are well reproduced (\([25]\)).

Once the \( \rho(M) \) nova excitation function is fixed (in \([25]\) the form
\[
\rho(M) \propto \exp[-\beta/(M - M_a)]/(M - M_a)^2
\]
was used, where \( M_a \) is the mass of the excited beam/target particle), the model gives a connection between the total inelastic cross section, the pion multiplicity and the average Q value of the pions in nova decay. Reasonable Q values are around 300...400 MeV. As for the nova decay, a chain of isotropic decays through resonant states is assumed, during which the nova performs a random walk in momentum space. (High mass novas include high-spin states, which can be produced polarized normal to their production plane, but in case of many secondaries these asymmetries average themselves out.)

Many features of inclusive distributions can be calculated using simple assumptions. High mass novas will dominate the low \( |x_F| \), low mass ones the higher \( |x_F| \) regions of the pion spectrum. The parameters of the model are fixed by data on average multiplicities, total and inelastic cross sections, measured \( x_F \) and \( p_T \) distributions.

The model predicts correctly that lighter particles (\( \pi, K \)) approach Feynman-scaling \([63]\) faster than protons, with increasing \( \sqrt{s} \). At intermediate \( |x_F| \) values, scaling is reached faster, while the energy dependence is most prominent at \( x_F \approx 0 \) and \( |x_F| \approx 1 \). This is in good agreement with data and other models.

Another type of resonance excitation and decay scenario is discussed in \([92]\) with the aim to reconsider these mechanisms in soft hadronic processes and the study of basic kinematical features in comparison with data. There, excitation of both the beam and target particle takes place, without quantum number exchange, simulated by multiple exchanges of massless on-shell \( p_T = 0 \) gluons. In a \( \sqrt{s} = 17.3 \text{ GeV} \) \( p + p \) interaction (measured at the experiment NA49), the two initial baryons acquire not necessarily equal, high masses (able to reach almost the kinematical limit of around 8 GeV), then decay through a resonance cascade, allowing high mass decay daughters, not only gradual pion emission. The motivation for this study is the observed inclusive spectra, the correlation between mean \( p_T \) and \( x_F \) of different particles, the correlation between the number of pions in the \( p + p \) event and the \( x_F \) of the fastest proton, and the observed features of resonance production in \( p + p \) collisions; all are present in the data as well as in the above simple simulation.

Before going into further discussion and presentation of data, we proceed with the introduction of the experimental apparatus and methods leading to quantitative measurements in the NA49 experiment.
3. The NA49 Experiment

The NA49 experiment is located in the North Area of the SPS\textsuperscript{4} accelerator at CERN\textsuperscript{5}. It was conceived to cope with the difficult task of operation under extreme conditions, like the 1500-1800 produced charged particles in a central Pb+Pb collision, with precise tracking and momentum determination and good two-track resolution. At the same time, the detector system is able to handle events with charged multiplicity as low as 7-10, in elementary hadronic (p+p, π+p) as well as proton-nucleus collisions. It covers the whole spectrum of studies in hadronic and nuclear physics, with variable beam energy (from 20 to 250 GeV/nucleon), possibility of on-line and off-line centrality selection of p+A and A+A collisions and changeable size of beam and target nuclei (from protons through C and Si to Pb ions).

The tracking system was designed to provide momentum measurement and identification in a wide acceptance range, making the event-by-event analysis of different kind of fluctuations and correlations feasible. The first one is important in a search for critical fluctuations near the energy density related to the much expected hadron-parton phase transition, the second allows us to perform hadron spectroscopy, HBT correlation analysis and to explore the semi-inclusive nature of the elementary hadronic interactions, only to mention a few subjects.

The above ambitious requirements, the fixed target configuration and the angle distribution of final state particles, together with the large (max. 9 Tm) bending power of the magnets (necessary for good separation of the particles) constrained the design and general features of the NA49 setup, which is seen in Fig. 4. It comprises four large volume Time Projection Chambers (TPCs), taking care of the momentum and ionization measurement, four Time of Flight (ToF) scintillator walls facilitating particle identification around midrapidity (angle of 90 degrees with respect to the beam in the c.m. frame). Trigger system with Veto Calorimeter (VCAL in the figure) measuring the centrality of the Pb+Pb collision, and a CentralMultiplicity Detector (CD in the figure) looking at the p+A collision centrality is featured. Multiwire chamber beam position detectors (BPDs) and scintillators are used in positioning and timing the incoming beam particles. In low multiplicity reactions the Ring Calorimeter (RCAL) is used to detect and separate neutral particles, with a reasonable energy measurement, supplemented by a Veto Proportional Chamber (VPC) to distinguish between charged and neutral particles arriving to the Ring Calorimeter and passing by the TPCs.

The detailed description of the detector system can be found in [26]. Only details of importance concerning this thesis will be discussed below.

\textsuperscript{4}Super Proton Synchrotron
\textsuperscript{5}European Organization for Nuclear Research, Geneva
Fig. 4: The setup of NA49 experiment with different beam definitions and target arrangements for a) A+A; b) p+p; c) p+A collisions. The target is placed at the front face of the VXT-1 magnet.
3. THE NA49 EXPERIMENT

3.1 Time Projection Chambers

3.1.1 Basics

There is already extended literature available, discussing the operational principles of Time Projection Chambers ([27, 28, 29]), and experience is gathered in several experiments, like NA35 (CERN), EOS\(^6\) TPC (LBL\(^7\)). As the NA49 TPCs are discussed also in [30] and [31], we only give a brief introduction here.

The high energy charged particles flying through the gas-filled TPC volume interact with the electrons of the gas, and ionize some of the gas atoms. The free electrons are initially located along the trajectory of the charged particle (called track), but they drift to the top of the chamber under the influence of the vertical electric field of 175-200 V/cm. There, arriving to the attractive sense wires, they induce an electron avalanche (multiplication by a factor of 10\(^4\)) which induces a voltage pulse on the segmented horizontal cathode plane. This way information is obtained on the three space coordinates (location on the horizontal plane and duration of drift) and the specific ionization of the particle (pulse heights). The latter is used for particle identification (mass measurement). That is the reason why we can think of a TPC as a "four dimensional camera".

3.1.2 Magnets

Of the four NA49 TPCs two (named Vertex-1 and Vertex-2) are placed inside the aperture of two superconducting dipole magnets, operating at 1.5 and 1.1 Tesla magnetic field (corresponding to 5000 and 3500 Amper current in the coils) providing 7.8 Tm total bending power which means in turn a maximum of 2.3\(GeV/c\) transverse momentum kick for singly charged particles. The other two large TPCs (Main Left and Right) are located outside the magnetic field in a temperature controlled hut (Fig. 4). Precise magnetic field maps are calculated numerically [32] (based on the geometry of the material, yokes and coils), and agree with the Hall-probe measurements to better than 0.5\%, and are monitored continuously.

3.1.3 Geometrical Arrangement

There is a gap between the TPCs symmetrically around the (neutral) beam line to exclude the highly ionizing Pb-ions (and very high density region of secondary particles in Pb+Pb collisions) from the active volume. It would be possible to let the proton beam pass through inside the chambers, but the necessary movements, taking into account the beam schedule alternating between protons and heavy ions, are not feasible to do; all TPCs are fixed and held precisely.

\(^6\)Equation of State

\(^7\)Lawrence Berkeley Laboratory
in place since several years, and also the readout chambers are optimized geometrically to the gap configuration. The above fact implies serious constraints and difficulties in measurement of weakly decaying neutral particles, since most of them decay in the gap and the charged daughters are visible only much further when arriving to the TPC volume. It causes the inability of measuring very forward particles, thus completing an exclusive experiment (in the forward hemisphere) in p+p, p+A reactions for the moment is not possible. Effort has been devoted to supplement the detector system by a Veto Proportional Chamber placed downstream (Fig. 4, VPC) of the Main TPCs (and covering the gap between them) within the framework of this thesis, which will be discussed later.

3.1.4 Field Cages, Construction

The mechanical design was required to achieve possibly small amount of material to be crossed by the particles, mechanical and electrostatic stability (up to 100 µm) and homogeneous electric field, high voltage safety etc.

![Diagram of field cages in vertex TPCs](image)

Fig. 5: Assembly of field cages in case of Vertex TPCs.

Aluminized mylar strips are suspended on ceramic tubes standing vertically in the corners of the rectangular field cages, and are connected to the high voltage supply through a resistor chain, this way creating the closely homogeneous electric drift field in the TPC volume. On the bottom of the cages, high voltage planes are constructed from the same Al-mylar strips, supported by wires.
The whole volume is enclosed in gas envelopes of double layer mylar foil. The spacing between the foils is flushed with $N_2$ barring the way of $O_2$ and $H_2O$ diffusion into the chamber (necessary to avoid attachment of drifting electrons).

The cages and gas envelopes are attached to massive Al support plates from below. Special care is taken of gas tightness and planarity at a level of 100-150 $\mu$m. The assembly is shown in Fig. 5. The geometrical dimensions of the chambers are summarized in Table 1.

<table>
<thead>
<tr>
<th>dimensions (mm)</th>
<th>VTPC-1</th>
<th>VTPC-2</th>
<th>MTPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>width</td>
<td>2000</td>
<td>2000</td>
<td>3900</td>
</tr>
<tr>
<td>length</td>
<td>2500</td>
<td>2500</td>
<td>3900</td>
</tr>
<tr>
<td>height</td>
<td>980</td>
<td>980</td>
<td>1800</td>
</tr>
<tr>
<td>drift length</td>
<td>666</td>
<td>666</td>
<td>1117</td>
</tr>
</tbody>
</table>

Table 1: Geometrical dimensions of the TPCs

3.1.5 Gases in the TPCs

Given the high track density in Pb+Pb collisions, it is desirable to choose gases with low diffusion constants, because during the drift time of the ionized electrons, diffusion widens the electron clouds arriving to the top of the chambers and giving a recognizable hit, cluster at the plane of the readout segments (pads). If the diffusion or the drift time is high, the wide and close-by clusters cannot be separated any more (additionally, they will suffer from the "zero suppression loss", to be discussed later). In the Main TPCs, where there is no magnetic field to decrease the effective diffusion constant in directions perpendicular to the magnetic field, the caution is even more necessary.

However, at a constant pulse shaping time of the electronics, the high drift velocities are widening the clusters in drift direction measured in millimeters. Therefore a compromise is needed. For the Vertex TPCs (and the Main TPCs) the final choice of gas was 91% Ne and 9% CO$_2$ (91% Ar, 4.5% CH$_4$ and 4.5% CO$_2$), and diffusion constants of 220 (270) $\mu$m/$\sqrt{cm}$ were measured in both directions. The applied drift fields were 200 (175) V/cm, which resulted in a 1.4 (2.4) cm/$\mu$s drift velocity in the two gases. These details will become important in the discussion of a detailed cluster model simulation, which was developed for the part of this thesis dealing with particle identification.

One space coordinate of the measured trajectories depends linearly on the drift velocity which is proportional to the drift field, therefore the latter should be monitored and recorded at all times.
While the inclusion of $CO_2$ in the gas mixture greatly reduces the diffusion coefficients, there is a price to pay for it. The amount of drifting electrons is decreased by the electron attachment, a feature of gases containing $CO_2$ in the presence of $O_2$ and $H_2O$ vapor. This introduces a drift length dependence into the ionization measurement, thus the water is filtered out and fresh gas mixture is circulated in the chambers. Charge losses due to attachment is measured to be 1.2% (0.6%) per ppm $O_2$ in the total 50 $\mu$s drift time, and the $O_2$ content monitors yield no more than a few ppm $O_2$. Sensitivity on $H_2O$ was found to be much smaller.

### 3.1.6 Readout Chambers

The readout of the TPCs is based on the segmented pad plane, since sense wire readout would make pattern recognition of hits arriving to the same wire in this high track density environment impossible. Negative potential of 13 (20) kV is connected to the HV planes on the bottom of the chambers.

On the top, a cathode plane on ground potential attracts the drifting electrons. Below, a gating wire grid cuts the drift if the chamber is closed (no trigger signal arrived). Above the cathode plane, 20 $\mu$m sense wires on +1200 V potential collect the electrons and create avalanches, and are interspaced with thicker "field" (ground potential) wires (Fig. 6). The sense wires are connected to the high voltage in groups of 6 wires. The avalanches induce a voltage signal on the pads through their capacitive couplings, which are in turn picked up by the electronics. Relatively small distance between sense wires and pads ensure pad response functions sufficiently narrow to allow for the necessary two-hit separation. Typical dimensions in the readout chambers and sizes of pads are collected in Table 2. Sometimes we quote two numbers: pad length in VTPC-1 is 16 mm in the sectors 1 and 4 only$^8$, the pad width in MTPC is smaller in the two sector-rows close to the beam (High Resolution sectors). Pad angles will be discussed later.

---

$^8$see numbering conventions in the next chapter
<table>
<thead>
<tr>
<th>dimensions (mm)</th>
<th>VTPC-1</th>
<th>VTPC-2</th>
<th>MTPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>pad length</td>
<td>16.28</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>pad width</td>
<td>3.5</td>
<td>3.5</td>
<td>3.655</td>
</tr>
<tr>
<td>pad angles</td>
<td>12-55°</td>
<td>3-20°</td>
<td>0°,15°</td>
</tr>
<tr>
<td>pad-sense wire dist.</td>
<td>3</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>sense wire diameter</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>sense wire spacing</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>field wire diameter</td>
<td>0.125</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td>field wire spacing</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>cathode wire diameter</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
</tr>
<tr>
<td>cathode wire spacing</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>gating wire diameter</td>
<td>0.075</td>
<td>0.075</td>
<td>0.075</td>
</tr>
<tr>
<td>gating wire spacing</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2: Pad and wire dimensions in the readout chambers.

3.1.7 Electronics and Data Acquisition

Some features of the NA49 electronics are relevant for the precision of the ionization measurement. The readout of the 182000 pads (segments) of the TPCs is a significant challenge handled by VLSI (Very Large Scale Integration) technology.

A 12-bit dynamic range pulse preamplification is followed by shaping the signal into a 240 ns FWHM Gaussian wave form. This analog signal is sampled by a Switched Capacitor Array with a frequency of 10 MHz, thus dividing the 50 µs maximal drift length into 512 time bins. The signal is then digitized by ADCs with 8 bit precision.

The electronics delivering digitized output is placed directly on the TPC readout chambers, followed by a digital data transfer via optical links (768 electronic channels/fibre). The digital signal processing of VME based system is applied for pedestal (baseline, 0-level) calculation, zero-suppression and noise-rejection of the data, buffering the events (there are no higher level triggers) and transfer to the event builder (structure also followed by EOS and STAR collaborations). The NA49 event recording rate is 10-30 event per SPS spill (beam extraction of 2.4 s in 15 s periods), with a raw data volume of 100 MByte/event reduced to around 8 MByte/event (central Pb+Pb collision) until recorded with a SONY 19 mm tape recorder (transfer rate up to 16 MByte/s). Sizeable reduction of the data is achieved by keeping time bins with a signal above a fixed threshold (5 ADC) and patterns with at least two consecutive time bins above this threshold only, hence greatly reducing the noise. The price one pays for the fixed threshold cut is a difficulty to reconstruct the total integral of the signal precisely: due to the drift and
widening of the electron cloud, we exclude (and lose) higher and higher fraction in the tail of the signal by this cut, which appears as a drift length dependent charge loss\textsuperscript{9}.

![Diagram a)](image)

![Diagram b)](image)

Fig. 7: Time response of the NA49 TPC readout electronics, on different scales. One time bin corresponds to 0.1 $\mu$s

A typical pulse shape from a laser-induced track is presented in Fig. 7. The signal shows a short-term (1 $\mu$s) undershoot, and at larger times it is followed by a complicated structure. As no positive ions arrive in the pad plane, the time integral over the signal has to be zero, hence a negative undershoot appears starting around 5 $\mu$s and continues far in time (such long term shaping is not possible with VLSI technology). The importance of this effect lies in the ionization measurement for which the undershoot decreases the baseline, therefore the measured pulse integrals as well. In Pb+Pb collisions (due to the high track density) this becomes a charge loss having an apparent drift length dependence. Off-line corrections for the Pb+Pb case in the Main TPCs are described in [33]. In p+p and p+A collisions the 100 times less track density allows us to neglect these effects.

Another difficulty is, which renders the electronics calibration via field wire pulsing not feasible, the changes in gain and base line responding to the charge load on each chip: the channel gain varies up to 10% depending on the load pattern on the chip. As a consequence,\textsuperscript{9} additionally, in case of Pb+Pb interactions a significant baseline shift pattern calls for a detailed follow-up of the load history of the channels. Another problem is that the sense wires are coupled in groups of 6 as connected together to the High Voltage supply, and the charge load on one sense wire generates small, short term changes in the other 5 wires with opposite polarity, which affects entire pad-rows facing the wire group, thus contributing to the baseline movement affecting many other clusters if the track density is high. Both effects and corrections for them are introduced in [33].
alternative gain calibration had to be applied creating similar patterns as the real data. This is done by injecting radioactive $^{3}$K$_{r}$ gas into the chambers (similar procedure is used in ALEPH and DELPHI experiments). Following nuclear and atomic (Auger) transitions, finally three (9.4, 12.6, 14.3 keV) photons are produced and a characteristic charge (ionization) distribution is created. Comparing simulated and measured patterns the channel gains become possible to measure (for each chip - groups of 16 pads - with sufficient statistics). The calibration is repeated each year, and the time-dependence of the intermediate periods (arising from the atmospheric pressure changes and the chamber HV and electronics IV uncertainties) can be corrected for, using the measured data itself.

A sizeable water cooling capacity (300 W/readout chamber) is needed to compensate for the thermal load of the electronics. All the TPCs are operated in separate huts climatized to 20 ± 0.1°C and monitored by thermal resistors mounted on the readout chambers.$^{10}$

More detailed description of the NA49 electronics can be found in [34].

### 3.1.8 Alignment, Laser System, Coordinates

The position of the TPC system and its relation to the exterior SPS beam coordinates is determined to better than 0.2 mm absolute accuracy by optical methods. The consistency of these is checked with multiple targets and muon tracks from the beam halo with magnets switched off. Vertical (drift direction) coordinates are obtained with precisely (around 10$^{-3}$) measured drift velocities and fine-tuned using consistency requirements of the measured particle tracks. Two important distortions of the space coordinates arise: one from the transition region between the drift volume and readout chambers having complex electric field geometry, and the $E \times B$ effect in the magnetic field. The correction for these is handled by distortion tables, obtained both from calculations using the known field configuration of the chambers and from experimental assessment of the effects applying the TPC laser system. The latter is mounted on the TPCs and can be moved in small steps, sweeping through the TPC volume with its ionizing straight line tracks in the magnetic field switched on. These measurements make the (up to several cm large) $E \times B$ corrections possible to complete with better than 1% precision.

In this thesis we will refer to the NA49 coordinate system which is a rectangular system with horizontal $z$ axis corresponding to the nominal beam line$^{11}$ with downstream direction, $z = 0$ being the center of Vertex TPC-2, the target is approximately at $z = -580$ cm (see Fig.

$^{10}$ Some small day-and-night temperature variation of the TPC gases still could be extracted from the ionization measurements (see later), caused by the daily thermal cycle of the environment (gas mixing stations) and the large mass and heat capacity of the readout chambers the thermometers are mounted on, reluctant to follow fast temperature changes.

$^{11}$ We mean here the beam line without magnetic field or for neutral particles, since the beam bends to a large extent in the field-on configuration.
4 which is in the \( x - z \) plane).

The \( y \) axis is defined by the drift direction (vertically upwards) and the horizontal \( x \) axis completes the system to be right-handed, and it is also the bending direction of positive particles in the usual field polarity (called standard \(+\)). Each pad in the TPC readout corresponds to a \( x - z \) coordinate pair, and has a sector number, pad-row number and pad number. Pad-rows are \( z \approx const. \) lines.

The \( y \) (drift) direction is divided into 512 time bins as already mentioned. The VTPCs are assembled from 6, the main TPCs 25 sectors each, 62 sectors\(^{12}\) in total as shown in Fig. 8. A line of 5 sectors in the MTPC along the \( z \) direction is called sector row. The sector rows closest to the beam (21...25 in MTPC-L and 1...5 in MTPC-R) are the High Resolution sectors - the pads being narrower there. The other MTPC sectors are called Standard Resolution. Table 3 summarizes the number of pads, pad-rows and sectors in the TPCs.

<table>
<thead>
<tr>
<th></th>
<th>VTPC-1</th>
<th>VTPC-2</th>
<th>MTPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of sectors</td>
<td>6</td>
<td>6</td>
<td>25</td>
</tr>
<tr>
<td>number of pad-rows</td>
<td>72</td>
<td>72</td>
<td>90</td>
</tr>
<tr>
<td>pad-rows per sector</td>
<td>24</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>pads per pad-row</td>
<td>192</td>
<td>192</td>
<td>192 (HR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>128 (SR)</td>
</tr>
</tbody>
</table>

Table 3: Number of pads and pad-rows in the TPC readout chambers.

Each pad is tilted with respect to the nominal beam to agree with the average track angles at the given \( x - z \) position, to optimize the response to the ionization and the final \( dE/dx \) and

\(^{12}\) We will use an alternative numbering where sector number runs from 1 to 62, where 1.6 refers to VTPC-1, 7..12 to VTPC-2, 13..37 to MTPC-L and 38..62 to MTPC-R.
tracking performance ([35]). However, all pad-rows are straight and parallel to the chamber
edges. The Main TPCs are rotated by 0.98 degrees away from the beam as Fig. 8 shows, but
the pads are parallel to the chamber edge. Exceptions are the three outer sector rows (1...15
in MTPC-L and 11...25 in MTPC-R) where pads are tilted away from the beam by +(-)15
degrees with respect to the chamber edge, to follow the actual track angles better.

In the second inner sector rows (16...20 in
MTPC-L and 6...10 in MTPC-R) pads are not
 tilted but are as wide as in the other Standard
Resolution sectors, thus often called SR’.

In the VTPC-2, the projection of the pad
length on the z direction is 2.8 mm, the real length
is $2.8\text{mm}/\cos(\text{tilt})$ (see Fig. 9). The x coordinate
of the first pad is 128 mm. The pad pitch (distance
between centers of consecutive pads) changes con-
tinuously between 3.5 and 3.7 mm, while the row
pitch is alternating between 28 and 32 mm. The
shape of the pads is an elongated parallelogram.
The pad tilt can be given as $\tan^{-1}(0.0045 \times x)$
where x is the distance from the beam axis in cm.

In the VTPC-1 the pad pitch is changing between 3.55 and 3.95 mm and the pad tilt can
be approximated by $\tan^{-1}(x \times \exp(-6.082 - 0.004257 \times z))$ where x and z is given in cm.

More details can be found about the pad layout design in [36] and [37].

3.2 Tracking and momentum measurement

The NA49 off-line analysis software is organized in several consecutive steps, and aims at the
momentum measurement of the final state particles by a fit using the NA49 magnetic field
tables.

In the first step, two-dimensional charge clusters are formed by collecting information from
neighbouring pads and time bins in a given pad-row. The x and y coordinates are calculated
by a center of gravity method for each cluster (and the z coordinate is given by the position of
pad-row in the coordinate system). In the next phase segments of tracks (particle trajectories)
are searched for, using the set of space points generated by the cluster finding. The applied
method is called the Global Tracking Scheme, since it combines effectively the information given
by the track pieces in the different TPCs; a method which is nontrivial to optimize especially
for the high track density case of Pb+Pb collisions.

In general, first the tracks apparently originating from (geometrically pointing to) the target
position (interaction point, called main vertex) are treated, then eliminated from the space point set and the rest of the points are further searched for tracks. In the MTPCs (out of the magnetic field) a straight line is used as a track model, and tracks having clusters only in the MTPCs can be given a momentum only with the assumption that they originate from the main vertex.

In the VTPCs a precise momentum measurement is possible since there a track curvature is accessible; a helix is used as a track model to obtain the initial parameters of the fit, later the proper (not precisely homogeneous) magnetic field is taken to fit the momentum components. Compatibility with the above vertex constraint is studied by extrapolation to the target position.

The algorithm of tracking is the following: after clustering of hits in all detectors, first straight line tracks are reconstructed in the MTPCs, and momentum is assigned to those compatible with the main vertex assumption. Then all MTPC tracks are extrapolated back to the VTPC-2 and clusters are collected there along these trajectories. Clusters from MTPC tracks are set free, if the trajectory predicted clusters in the VTPC-2 but none were found, and after that all remaining tracks are reconstructed in the VTPC-2. The new ones are extrapolated to the MTPC and clusters are collected there along the predicted straight lines.

This is repeated for the VTPC-1: first the tracks already reconstructed are extrapolated to VTPC-1 and clusters are collected there. Again, clusters of MTPC track pieces having a predicted by not found VTPC-1 piece are set free, and all remaining tracks are reconstructed in VTPC-1. The new ones are extrapolated to the MTPC. Finally all remaining tracks are searched in the MTPCs, including "kink" tracks and "V0"-s (daughters of a weakly decaying particle).

In the end tracks matched between the detectors are obtained, and the fits give the momentum and the charge of the particles (+1 or -1 charge is assumed in all cases). Much effort has been devoted to the quality assurance of tracking, matching of track pieces and main vertex assumption test.

It is important to note here that tracks having \( q \times p_x > 0 \) or \( q \times p_x < 0 \) are called good side or wrong side tracks, respectively, where \( q \) is the charge and \( p_x \) is the \( x \) component of the momentum at the target (immediately after the collision). Looking at the experiment from above, good side tracks start out to the direction to which the magnetic field will bend them anyway, thus gaining a desirable space-separation from the crowded regions close to the beam line, and their angles matching with the pad tilts better. Furthermore, the tracks originating from weak decays are easier to filter out for good side tracks, and the matching between detectors and the dE/dx (ionization) measurement is of much higher quality. Therefore, wherever possible, only good side tracks are used in the analysis.

As a result, a space resolution of 0.12 to 0.27 mm is achieved depending on the drift distance of the clusters in the MTPC. The momentum resolution is a function of the number
of measured clusters along the track (between 10 and 234), the local space resolution, the total track length, the integral of the magnetic field along the track, and the amount of Coulomb scattering in the traversed material. Estimates of total momentum resolution give \( \Delta p/p^2 = 7 \times 10^{-4} \, \text{c/GeV} \) for VTPC-1 tracks \((0.5 < p < 8 \, \text{GeV/c})\) and \( \Delta p/p^2 = 3 \times 10^{-5} \, \text{c/GeV} \) for tracks detected both in VTPCs and MTPC \((4 < p < 100 \, \text{GeV/c})\).

The separation of close-by track pairs is limited by the width of charge distributions, and can be measured by comparing the spatial distance of track pairs in real events with an artificial (mixed) event sample where the tracks are taken from different events. The result shows that the separation probability is practically 100% at 2 cm, and drops to 50% at 1 cm average track distance, according to the expectations.

The main vertex is reconstructed using only the trajectories of the produced particles in Pb+Pb collisions with a precision of about 0.15 mm in \(x\) and 2.1 mm in \(z\) direction, while in \(p+p\) and \(p+\text{Pb}\) events, due to the low multiplicity one has to use the measured coordinates of the beam particle as well. Here the precision is around 6.5 mm (depends on the number of tracks) in \(z\) direction. Vertex position is measured this way to eliminate secondary decay vertices and gamma conversions, and to eliminate events originating from collisions with the walls of the target or other material. This has to be done in \(p+p\) and \(p+\text{Pb}\) reactions with a great care; as a consequence one has to apply multiplicity (vertex-resolution-) dependent corrections to the data.

Tracking efficiencies are found in \(p+p\) and \(p+\text{Pb}\) interactions close to 100% by eye-scans. In the \(\text{Pb+Pb}\) case tracks embedded and reconstructed in real events can be used to estimate the efficiency which is generally around 95% but can fall to around 30% in certain high track density areas where the electronics occupation density can reach as high fraction as 30%. Extra tracks found in excess of the secondaries of the beam-target collisions can originate from neutral particle decays, collisions of neutral fragments (neutrons) or charged particles with the detector material, pile-up of two events in the open time of the TPCs, gamma conversions, delta-rays from the ionization of the gas, often spiraling in the magnetic field, muon tracks from the beam halo, eventually cosmic ray tracks. The elimination of them can be done by requiring that tracks can be extrapolated to the main vertex, and by not using areas in coordinate and momentum space, where these tracks are accumulated.

The ionization (\(d\text{E}/d\text{x}\)) measurement which is used for the particle identification represents a large part of the preparation of this thesis, therefore it will be discussed in more detail later.
3.3 Time of Flight Systems

Particle identification based only on dE/dx measurements is not feasible at the region of minimum ionization, and certainly not possible track-by-track for kaons. With a flight path of 14 m and better than 0.1 ns time resolution, particles with momentum 6-10 GeV/c can be identified with the NA49 Time of Flight scintillation detector systems.

The momentum $p$ of the particles is known from the track reconstruction in the TPCs, and by measuring the total track length $s$ and time of flight $t$, the particle mass squared can be calculated as

$$m^2 = p^2 / s^2 (t^2 - t_0^2)$$

where $t_0$ is a time of flight for a photon for the same $s$ path length. Finally the quantity $m^2$ is given instead of $m$, since the experimental error on $m^2$ can make it negative.

The two detectors installed are: a 1800 pixel scintillator behind the MTPCs, operating in a momentum range between 3 and 12 GeV, and a 200 element grid scintillation system detecting 2-6 GeV/c particles; providing a time resolution of 60 and 85 ps, respectively. The identification capabilities are excellent when combined with the dE/dx measurement; an example is shown in Fig. 10. A disadvantage of the ToF systems is however that they cover only a small fraction of momentum space compared to the dE/dx measurements, and because different kind of corrections had to be used in the analysis of ToF and dE/dx data, the integration of ToF results into the dE/dx (wider acceptance) results is not straightforward.

Detailed information about the latter, which was built by the Budapest group of the NA49 Collaboration, can be found in [39] and [38].

Fig. 10: An example of combining dE/dx and ToF.
3.4 Trigger System, Calorimeters

3.4.1 Beam Intensity and Position

The NA49 experiment is located in the North experimental hall of the SPS accelerator. The H2 beam line transports the heavy ions, protons, or other secondary beams (π, K, d, C, Si) produced from primary protons/heavy ions to the detector system. Upstream, a set of Čerenkov and scintillation counters and beam position detectors (small, 3×3 cm proportional wire chambers) provide precise time reference and charge and position measurements of the incoming beam particles. Downstream of the target, several interaction counters (scintillators) and calorimeters can be organized to a trigger system sensitive to the type of beam particle and event centrality (spectator nucleons giving an energy deposit in the Veto Calorimeter).

The measurement precision of the beam position extrapolated to the target is 0.04 (0.17) mm for Pb (p) beams, to be compared to the width of the beam profile which is 0.5 (1.3) mm.

3.4.2 Trigger

For hadron beams, interactions in the target are selected by anti-coincidence of the beam particle with the S4 scintillation counter (2 cm diameter) placed on the beam line between the two vertex magnets. The counter defines a 29 mbarn trigger cross section for 158 GeV/c proton beam on proton target, eliminating 80% of elastic and 60% of diffractive cross section (both processes are anyway outside the TPC acceptance due to the gap between the detectors).

For the Pb ion beam, a He Čerenkov counter is used (S3) to select impact parameters below about 10 fm.

3.4.3 Target

Different types of nuclear targets are used, made of Pb foil (0.224 g/cm²), graphite (C), aluminium. To study proton, pion, deuteron beams colliding with proton target, a liquid hydrogen target was installed. The hydrogen is filled to a cigar shaped 20 cm long (3 cm diameter) and 60 μm thick mylar container. It is insulated by an inner vacuum vessel inside a Helium tank cooled by a cryogenics system. It can be emptied and filled with a remote control in order to be able to take empty target data periodically.

3.4.4 Centrality Selection

For Pb+Pb interactions, a Veto Calorimeter (20 m downstream of the target) is applied to select a given collision centrality/impact parameter. Beam particles, projectile fragments and spectator nucleons can reach the calorimeter which consists of lead/scintillator and iron/scin-
tillator parts (16 radiation and 7.5 interaction lengths, respectively). The energy resolution is estimated by the formula \( \sigma(E)/E = 1.0/\sqrt{E(\text{GeV})} \). Central collisions can be selected by discriminating the total energy deposited. The veto energy distributions are compared to simulations and a good agreement is verified, thus a number of participant nucleons or the impact parameter if the collision can be inferred.

The impact parameter of a **hadron-nucleus** collision is correlated to the number of gray protons in the laboratory momentum range between 0.15 and 1.0 GeV/c, as studied earlier in [40]. A Centrality Detector was developed in NA49, which surrounds the target (Fig. 4/c) and measures the number of these gray protons. It can be incorporated into the on-line trigger to select events with a given centrality.

It has a shape of vertical cylinder with 20 cm height and 16 cm diameter and a target placed inside in the center. It contains 32 proportional tubes being read out on 256 cathode elements, covering a range of polar angles 45° to 315°, leaving the tracking acceptance wedge of the NA49 TPCs free (Fig. 11).

![Centrality Detector used in p+Pb reactions.](image)

Protons slower than 0.15 GeV/c are cut off by absorption in a copper foil between the target and proportional tubes, thus filtering out the evaporation ("black") protons and nuclear fragments. Detection of protons above 0.6 GeV/c and pions is progressively suppressed by imposing a threshold on the electronics about three times the most probable energy loss of a minimum ionizing particle.

On-line trigger on the number of hits is available, as well as the off-line correction for particles generating multiple hits. Detector simulation based on events generated by the VENUS model was used to estimate the acceptance for grey protons, which was

![Fig. 12: CD hit distributions in p+Pb collision.](image)
found to be about 40%. These comparisons allowed us - including Glauber Model calculations as well - to estimate the number of collisions undergone by the beam particle, in a Glauber picture where the projectile collides a few times as an entity with the nucleons in the target. This quantity serves as a measure for the centrality of the hadron-nucleus collision.

As an example, Fig. 12 shows the distribution of gray protons detected in the TPCs and the Centrality Detector a) for the p+Pb data taking where we did not impose a threshold in the number of hits (*minimum bias data*) and b) for the actually recorded total amount of data. On-line triggering helped extend the centrality range accessible with high statistics towards the very central collisions.

### 3.4.5 Ring Calorimeter

The last element of the secondary particle detection is the Ring Calorimeter placed 18 m downstream of the interaction target. It was originally used to measure transverse energy production and event anisotropy in Pb+Pb collisions, but in the last few years a new application has been carefully developed: the single particle detection in p+p and p+Pb collisions (the segmentation of the calorimeter as well as the particle shower sizes do not allow us to separate tracks close to each other, this application is excluded in heavy ion collisions).

The calorimeter is cylinder shaped, with an inner bore of 56 cm diameter and an outer radius of 151 cm, divided into 240 cells (10 radial rings and 24 azimuthal sectors). The "electromagnetic" (front) part is made of a lead/scintillator sandwich (16 radiation length), and a 6 interaction length iron/scintillator "hadronic" part. Its energy resolution is $\sigma(E)/E = 1.0/\sqrt{E(\text{GeV})}$, and wavelength shifter bars and photomultipliers are used to read it out. Detailed recalibration and optimization was done in 1998.

The Calorimeter can be placed so as to cover the gap between the MTPC sensitive volumes, and the very fast (forward) and neutral particles which cannot be seen by the TPCs, can be detected, their energy (with a limited precision) measured. Discriminating the ratio of energy deposited in the first and the second segment, the electrons, gammas ($\pi^0\text{-s}$) can be filtered out, but there is no experimental way to separate $K^0_L\text{-s}$ and neutrons (high-momentum neutrals can only be neutrons, though). There is also no way to measure the charge of the particles; the magnetic field cannot separate the different charges - and neutrals in the middle - enough to distinguish between (for example) protons and neutrons - which is partially blamed on the rough spatial segmentation of the detector.

To resolve the problem and obtain a charge tag for the particles, a new detector, a Veto Proportional Chamber was constructed. As it is the only detector a construction of which was done partially in the framework of this thesis, and plays an important role in the studies of baryon transfer as well, more detail will be given in the next chapter.
4. The Veto Proportional Chamber

There are several reasons to discuss the construction and operation of the Veto Chamber in a separate chapter:

- It plays an important role of the data analysis of the proton+proton and proton+nucleus interactions as well as the deuteron+proton collisions, including also the studies presented in this thesis.

- It has been constructed, tested, operated and its data analyzed by a handful of students with the help of a senior physicist and a technician, from low-cost materials. The intention of the chamber construction was not only its role in the physical analysis but to give a precious working experience to the participating young people.

- It is the newest part (built in the summer of 1999) of the NA49 detector system already used in data taking and analysis, and it could not be described in Ref. [26], which appeared earlier.

---

**Fig. 13:** Position of the Veto Proportional Chamber in the NA49 detector system.

4.1 Motivation

The chambers sensitive volume covers a relevant, ”blind” region, namely the gap between the TPCs (Fig. 13). It is designed to detect reliably the charged particles crossing its planes, making the separation of neutrons and protons arriving to the Ring Calorimeter possible, as an off-line veto for charged particles. It is indispensable when attempting correlation studies
with fast forward protons in proton+proton reactions. Momentum spectra measurements of
neutrons in different reactions rely on the veto function of the detector.

In the studies of deuteron beam impinging on the liquid hydrogen target, one is interested
whether the neutron or the proton (or both) have interacted with the target proton, thus sepa-
rating the data sample to proton+proton and neutron(beam)+proton reactions. Information
on the charge of the spectator (not interacting) nucleon therefore is required. For our largest
data sample at 158 GeV/c beam momentum, this can only be attempted with the help of the
Veto Chamber combined with the Ring Calorimeter, since the projectile proton is too energetic
to be steered into the TPCs by the magnetic field.

4.2 Design and Construction

To achieve a relatively large sensitive area without an excessive number of electronics channels, we have cho-
sen a strip cathode readout for the proportional cham-
ber, the number of cathode strips being a compromise between available amount of electronics and required
space resolution (Fig. 14).

Simple and cost-effective construction was possible
by building only a very few types of commercially avail-
able materials in, re-using existing electronics, and ma-
chining, gluing etc. the different parts on our own in
CERN workshops, using the experience of the NA49 collab-
orators.

Students participated in the preliminary and oper-
tional tests, construction, installation, day-to-day op-
eration, on-line, off-line and physical analysis of the
Chamber and the data.

4.2.1 Layout, Assembly

Each of the two chambers contain a wire plane in the middle of a gap between the two readout
planes. These planes are sandwiches of hard Vetronite and Rohacell layers. The inner side of
the sandwiches (facing the wire plane) is equipped with silver spray strips tilted to opposite
directions in the two sides of the gap. The whole detector is placed perpendicularly to the
beam, between the TPCs and the Ring Calorimeter.

The 160×80 cm rectangular, 3 mm thick Vetronite plates were machined on both sides to
a precisely uniform 2.5 mm thickness. The Vetronite-Rohacell sandwiches were then glued and placed on a flat iron table, placing an aluminium frame around and polyethylene foil on the top as shown in Fig. 15.

We depressurized the enclosed air to about 80 mbar underpressure creating a uniform load to press the parts together, and covered the assembly with copper shielding as a heat conductor to assure uniform temperature during the 24 hours hardening time of the glue (this is to avoid later deformation since the large heat capacitance of the iron table creates a temperature difference between the table and the air with daily temperature cycle).

The finished sandwiches were tested for planarity by placing them horizontally and supporting them on the four corners. Sagging of typically 100 \( \mu \text{m} \) and below 20 \( \mu \text{m} \) was measured on the long and short side of the rectangles, respectively. Planarity is important to obtain finally a uniform wire plane - cathode strip plane distance, which in turn relates to the final gain of the strips. The detector was mounted in its final place vertically not horizontally which reduces the above mentioned sagging anyway.

In the end, a 30 \( \mu \text{m} \) thick copper foil was glued on one side of the sandwich for electronic shielding.

\[\text{Fig. 15: Assembly of a cathode plane sandwich.}\]

### 4.2.2 Materials

The cathode planes and plane separators are machined from Vetronite, a strong but easily handled material. Cathode plane sandwiches were completed by inserting Rohacell (a rigid acrylic foam) between the Vetronite planes. All parts were glued with air-tight two component Araldite epoxy resin. A copper foil was extensively used for electronics shielding. Cathode plane strips were separated by simple scotch tapes. "Solamet" silver paint spray (designed for solar cell current collection) compose the material of the cathodes. Aluminium clamps, a few printed circuit boards and an RTV sealant completes the list. Finally, the cathode wire planes are soldered of 21 \( \mu \text{m} \) diameter gold plated tungsten wire.
4.2.3 Signal readout

Copper pickup pads had to be inserted in the sandwiches to transport the signals arriving to the strips to the other (outer) side of the planes. 74 (16) pickups were air-tightly glued into 6 mm diameter holes drilled along the long (short) side of the rectangle. Metal studs soldered into the pads traversed the sandwich and were connected to a printed circuit on the other side, to be plugged into the amplifiers later.

A wire frame and wire support printed circuit was placed on the other side of the planes (see Fig. 16).

The inclusion of pads was followed by the spraying of cathode strips (Fig. 17, left panel). Solamet (DuPont) silver paint was chosen, diluted with butyl acetate ($C_6H_{12}O_2$) in a mixture of masses 1:1, and sprayed to the cathode plate. Separation of the 2 cm wide strips was solved by previously glued 1.6 mm wide "letraline" self-adhesive tape mask, removed after the strips dried. 80 strips were created on each plane, each strip covering a readout pad in the strip end. The inclination of the strips was $60^\circ$ and typical resistance measured to be 8 $\Omega$ for the longest ones.

The cathode wire planes were made of 80 cm long, 21 $\mu$m diameter gold plated tungsten wires, with 4 mm spacing and running parallel to the smaller chamber edges, soldered to printed circuit support plates. They are connected in parallel to the High Voltage.

A small wire stretch machine was applied for spacing and tensioning the wires, equipped with pivoting cylinders to make the movement and tension equilibration possible. The cylinders were tensioned by pistons filled with slightly pressurized Argon, and a force equivalent of 52±2 g of weight was exerted on the wires (total of 400 per chamber). The wire tension was checked with a detector using a permanent magnet and measuring the oscillation period of the tensioned wire.

The chamber was finally closed by an identical cathode plane with opposite strip inclination, and held together with small aluminium clamps. Gas tightness was ensured by epoxy and RTV sealings (Fig. 17, right panel). No gas leakage could be detected.
4.3 Operation test

The two chambers were flushed with Ar/CH$_4$ gas mixture (in 80% and 20% fraction). Initially one started with a gas flux of 30 liters/hour and dark currents were measured (kept) around 20 nA with slowly increasing high voltage from 1350 to 1600 Volts. Two months later, after properly 'burning in' the chambers, the operational flux of 10 l/h was sufficient, and dark currents as weak as 1 nA were measured at a potential of 1900 V between the electrodes. There was no spark, wires breaking or getting loose.

The working point of the chamber was set by a test with a small collimated $^{55}$Fe radioactive source, placed into a hole previously drilled into each chamber. The signals came from only one strip per plane due to the sizeable width of the strips. After discriminating the output signal, a counter measured the rate of the avalanches. A working point was set to 1900 V since this already saturated the rate, hence all avalanches were large enough to be detected (Fig. 18). The next strip gave a
rate of about 5% of the strip irradiated due to a crosstalk between neighbour strips.

Later measurements with particle beams verified the choice of the working point. Gas amplification was set thereby to approx. $10^4$.

4.4 Electronics, software

4.4.1 Test plate

Prior to the construction of the full size chamber, a simple test plate was constructed to test the silver strip technique and the electronics. It was a $84 \times 35$ cm vetronite rectangle with readout pads and 80 cm long, sprayed silver strips similar to the final chamber.

![Test plate electronics diagram](image)

Fig. 19: Test plate electronics for preliminary studies.

To test the influence by the separation between the strips on the cross-talk between them, both a 1.6 mm and a 3.2 mm separation was prepared using masks made of tapes having different widths. Resistance of 3.5-4.2 $\Omega$ was measured on the strips including the pickup pads.

Amplifiers and shapers were connected to the strips followed by an oscilloscope, and a waveform generator was applied to generate an input signal to one of the strips. The layout of the test electronics can be seen in Fig. 19. In the RC circuit, $R=50\,\Omega$ and $C=15$ and 27 pF were chosen.

Various noise tests were completed studying the effect of the presence of the amplifier, shaper and attenuator, with or without signal pulse, and optimizing the electronics shielding. Noise/signal ratios about 1:100 were reached. Linearity of the preamplifier was checked and found to be good up to 5 V of output signal, with an amplification factor of $K=100$.

The RC circuit roughly simulates the time-development of a pulse seen on the strips as the real ionization followed by an avalanche would cause it. Using the assumption that this pulse is
close to reality, the sensitivity of the final system can be measured as follows. In Fig. 20 the RC
circuit is shown which transforms the step function (arriving from the waveform generator) into
a pulse with and exponential shape and \( \tau = RC \) time constant. The amount of charge passing
through the strips and the preamplifier, is \( Q = U_0 C \), where \( U_0 \) is the input step pulse height.
This charge simulates the amount of electrons arriving at the wire in the real detector. Ratio
between the final output pulse height and the input voltage step was measured above, yielding
\( K = 100 \), therefore our sensitivity estimate is

\[
S = \frac{KU_0}{CU_0} = \frac{K}{C} = \frac{3.7 \text{mV}}{fC}.
\]

In the Ar gas, around 120 electrons (with large fluctuations) get freed by the ionizing particle
which has a 1.2 cm path length (this is the thickness of the gas layer in the chamber). Assuming
that 120 ionization electrons arrive at the wires, with gas amplification of \( 10^4 \), an expected final
pulse height of \( 50 \times 10^4 \times 1.6 \times 10^{-19} C \times 3.7 \frac{\text{mV}}{fC} = 700 \text{mV} \) can be estimated when a charged
particle traverses the chamber. This is only a rough calculation, and merely an upper limit,
but could be verified with the measurements using the final chamber.

The cross-talk between strips was also studied. Pulsing a strip, about 10% of the signal ap-
peared on the neighbour strip (placed with 3.2 mm separation) and 2% appeared on the second
neighbour, independently of the input pulse height (in the linear regime of the preamplifier).

Comparing the cross-talk between strip pairs having 3.2 mm and 1.6 mm separation,
\( 10 \pm 0.2\% \) and \( 12.7 \pm 0.3\% \) was found for the bigger and the smaller gap, respectively.

This is consistent with the difference between capacities of the two capacitors formed by the two 2
\( \text{cm} \) wide, long strips with the above two types of gaps between, lying in one plane. These capacitances can
in fact be calculated analytically if the gap is much smaller than the width of the strips, using a conform
transformation technique applicable in two-dimensional problems of electrostatics.

The right transformation is here the logarithm (on the complex plane), which transforms our arrangement
to an ordinary parallel-plane capacitor (see Fig. 21),
whose capacitance is proportional to its width (assuming homogeneous electric field in the latter case, which
is only an approximation). Thus the ratio between the
two capacitance:

\[
\frac{\ln(w + d_1/2) - \ln(d_1/2)}{\ln(w + d_2/2) - \ln(d_2/2)} = 1.25
\]
where we substituted the \( w = 20 \) mm width of the strips and the \( d_1 = 1.6 \) mm and \( d_2 = 3.2 \) mm gap widths. The ratio 1.25 agrees with the measured ratio of cross-talks in the two configurations. Finally the wider gap was chosen to realize the full-size chamber, where somewhat smaller cross-talks, below 10% have been observed.

### 4.4.2 On- and off-line software

The readout electronics of the Veto Chamber is identical of the one used in the Beam Position Detectors. It consists of preamplifiers mounted directly on the chambers and equipped with extensive copper foil shielding, signal shapers and Analog-Digital Converters in the Counting Hut of the experiment. The low voltage supply for the preamplifiers delivering 6 and 12 V, the low voltage and signal cables and gas lines are placed close to the detector and/or mounted on a large steel frame together with the chambers. A total of 320 electronics channels were incorporated to the NA49 readout scheme, and given the similarity to the BPD chambers, the on-line software for monitoring was also available. Charges, pedestals, gains, RMS of noise can be conveniently checked and these studies have lead to successful noise reduction by isolating and shielding the preamplifiers and cathode strips.

Fig. 22 is an example of a signal pattern arriving from the Veto chambers. The hit structure shows that a single, charged particle crossed both chambers, leaving a smaller amount of ionization in the first than in the second one (this is consistent with the large Landau fluctuations expected in such a thin gas layer traverse). The electrons freed at the ionization process travel to the sense wires, creating an avalanche. Once the size of this avalanche is given, the signal heights in both planes of the chamber must be close to each other, since the distance from the wire plane is the same from both planes. Therefore the pulse heights of the two planes in each chamber should closely correlate, which they indeed do. Is it also visible in Fig. 22 that the signal pulls down the baseline of the other strips. Therefore pattern recognition, baseline correction and in case of multiple hits, a correlation study between the signals is necessary to derive the number and position of charged particles traversing the chamber pair. Particle showers created by an interaction of an incoming particle and the material of the chambers are also observed, they result in cleaner situations in the upstream than in the downstream chamber. The probability of crossing the chambers for a charged particle without leaving a recognizable signal was found to be negligible.

Calibration of the channel gains can be done by pulsing the HV wire plane. Relative gain factor could be calculated within each plane for the individual strips, and these factors were corrected for the differences between the geometrical surface of the strips.

Credit should be given to D. Varga for the development and tedious completion of the off-line analysis software for the Chamber and the Ring Calorimeter apart from his contribution
Fig. 22: Signals from the Veto chambers. The pattern shows that a single particle crossed both chambers, leaving a smaller amount of ionization in the first than in the second one. The charges measured on the two planes of the same chamber closely correlate.

to the construction. Various studies had to be done, like the baseline variations due to the charge load on the strips, and corrections for them, hit (cluster) finding on the two wire planes, and correlating them, measuring experimentally the efficiency, the space resolution, and the cross-talk between consecutive strips.

The space resolution of the chambers can be measured by the RMS of the difference between the coordinates of a hit in the two chambers, shooting the proton beam through the detectors. The positions are given not simply by a center of gravity of a cluster, but a correction applied which takes into account the ratio between the pulse heights from the consecutive strips. With this method, a better space resolution could be achieved than expected from the 2 cm geometrical strip width, namely an RMS of 3.8 mm and 2.1 mm in the horizontal and vertical coordinates, respectively (the difference is expected, since the opposite strips in one chamber are not perpendicular but enclosing an angle of 60°).

The experimental observations revealed a 9-10% crosstalk between neighbour strips caused by the capacitive coupling between them.

Finally, total working time of 50 days was sufficient to complete the entire construction.
5. Ionization (dE/dx) measurement

This chapter deals with the principal technical challenge and its solution in the NA49 particle identification, it also comprises a major technical project in the preparation of the present thesis.

In the majority of its geometrical acceptance, the NA49 experiment relies on the measurement of the specific energy loss (dE/dx) for its particle identification. As we shall see, the particle identification following this method is not capable - with some exceptions of very highly ionizing particles - of evaluating the particle's mass uniquely on a track-by-track basis (as opposed to the Time of Flight measurements), only statistically. This does not inhibit carrying out studies on inclusive and semi-inclusive particle spectra on longitudinal and transverse momentum, studies of weakly or strongly decaying particles, resonances, and many kinds of correlation measurements.

Time of Flight detectors deliver precious additional information necessary to identify particles track-by-track, but they cover only a fraction of the momentum space available for the dE/dx measurement. Below we will discuss only those identification methods, which are based on the dE/dx measurement.

5.1 The general method of ionization measurements

5.1.1 Ionization in gases

The Time Projection Chambers measure the number of freed electrons (the number of ionized atoms), while dE/dx is the energy lost by the particle over a flight path of a unit length. These are not the same quantities (since some energy is lost for excitations as well), but proportional to each other, therefore one uses the notion of dE/dx widely, instead of ionization.

Several processes contribute to the energy loss of a relativistic particle in gases filling the TPCs ([29]). For example, the particle excites an atomic state by depositing a certain, given amount of energy, no free electron arises but the excited atoms may undergo further reactions with each other leading to the ionization of some of them (like the Penning-effect where two metastable excited atom collides and one of them de-excites while the other gets ionized). Besides, there may be reactions of already ionized atoms with entire ones like He⁺+He→He₂⁺⁺+e⁻.

For the ionization in one step, the transmitted amount of energy is not quantized but bounded from below by the ionization potential. Excitation processes are more abundant, since the probability density of the collision is a decreasing function of the transferred energy.

Electrons set free by the above mentioned primary ionization, if energetic enough, can ionize themselves as well, leading to the secondary ionization.
Table 4: Ionization parameters of noble gases

<table>
<thead>
<tr>
<th>gas</th>
<th>primary ionization (cm⁻¹)</th>
<th>total ionization (cm⁻¹)</th>
<th>average energy needed to create an ion-electron pair (eV)</th>
<th>dE/dx (keV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>4.6</td>
<td>8.11</td>
<td>41</td>
<td>0.32</td>
</tr>
<tr>
<td>Ne</td>
<td>12</td>
<td>39</td>
<td>36</td>
<td>1.41</td>
</tr>
<tr>
<td>Ar</td>
<td>29</td>
<td>94.110</td>
<td>26</td>
<td>2.44</td>
</tr>
<tr>
<td>Kr</td>
<td>22</td>
<td>192</td>
<td>24</td>
<td>4.0</td>
</tr>
<tr>
<td>Xe</td>
<td>44</td>
<td>307</td>
<td>22</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Table 4 summarizes the basic ionization properties of the noble gases used in gaseous chambers, for a particle which is \textit{minimum ionizing}\textsuperscript{13} and for 1 atm gas pressure. The amount of ionization and the specific energy loss increases, while the average ionization energy decreases with growing atomic number [42].

It can be already seen, what level of difficulty it reaches to calculate the cross section of the ionization processes ([41]) in a given (high mass number) noble gas mixture, and the amount ionization for a given detector, gas pressure, read-out configuration etc. An example of the total cross section for the ionization process is shown in Fig. 23, compared to the Rutherford cross section for free electrons $\sigma_R \sim 1/E^2$.

On the other hand, even experimentally the determination of the amount of ionization is nontrivial; the compilation of former attempts shows a significant variation as well.

We shall aim at a self-consistent calibration method of the TPCs based on real data, providing both the relative gain factors (conversion factors between the number of free electrons

\textsuperscript{13}At a certain velocity, the amount of specific ionization generated by a charged particle reaches a global minimum. Particles moving at this velocity are minimum ionizing particles. More details on this Bethe-Bloch function will be given later.
5. **IONIZATION (DE/DX) MEASUREMENT**

and the integral of the final electronic signal) in the detectors and an estimate of the Bethe-Bloch functions (connecting the velocity of the particles and the ionization) characteristic to our setup. This method is necessary for reliable particle identification, and was used for all existing NA49 data (for Pb+Pb data, in a further developed and somewhat different form, [33]).

### 5.1.2 The Bethe-Bloch function

In the TPCs of the NA49 experiment one measures the number of ionized electrons along the tracks of the particles (or rather an electronic signal being proportional to this number), over 4 cm long (or even shorter in the VTPCs, see Table 2) pads. The identification of the particle becomes possible - as we already know the momentum from a fit in the magnetic field - since the rate of the ionization per unit length (or the energy loss, dE/dx) depends on the velocity of the (singly charged) particle only. This rate decreases as the velocity increases, then, passing through a wide minimum, it starts to increase (relativistic rise), until a slow approach of a saturation value. An illustration is shown in Fig. 24, where the dE/dx axis is normalized to the value corresponding to the minimum ionizing particle (MIP).

The precise parameters of this function (called *Bethe-Bloch function*) depend on the composition, pressure and temperature of the detector gas, and the form of this function itself is known only as an approximate analytic expression. In the following sections we will use this form, and its parameters will be obtained using the experimental data. The normalization of the function will be - by convention - such that the minimum value is always unity.

The ionization rate of the ultrarelativistic (very high energy-) particles (the *plateau*) in our TPC reaches approximately 160 percent of the minimum ionization.

The usual variable of this function is not the velocity of the particle, but the \( \log_{10}(\beta\gamma) \) quantity, where \( \beta = v/c, \quad \gamma = 1/\sqrt{1-\beta^2} \), and \( c \) is the speed of the light in vacuum. Note that \( \beta\gamma = p/mc \) where \( p \) is the momentum of the particle with mass \( m \) in the rest frame of the

![Bethe-Bloch function (example)](image-url)

Fig. 24: An example for the Bethe-Bloch function. Only the general behaviour of the function is to be illustrated here.
medium (gas).

The basic method of particle identification (mass measurement) relies on the fitted momentum \( p \) and the velocity \( v \) of the particle, and the mass is given by

\[
m^2 = p^2 \left( \frac{1}{v^2} - \frac{1}{c^2} \right).
\]

Time of Flight measurements obtain \( v \) from the flight length and duration, while ionization measurements use the Bethe-Bloch function to infer the \( v \) velocity.

Many attempts have been made so far to describe this function using basic principles and the knowledge of the interaction properties of the particles and atomic electron shells, for example studies by Landau [43], Bethe and Bloch, Allison and Cobb [44], Sternheimer [45], Blum [28], H. Bichsel [41] and many others.

Taking the interaction between the electric field of the incident charged particle and the electrons of the gas (assuming a uniform density), the momentum transfer (depending on how distant the electron is) can be calculated, while the particle passes through a \( dx \) distance in the medium. After integration over all possible \( b \) impact parameters, one finds a logarithmically divergent integral (in SI):

\[
\left\langle -\frac{dE}{dx} \right\rangle = \rho \kappa \frac{Z}{A} \frac{1}{\beta^2} \int_0^\infty \frac{db}{b}
\]

where \( \rho \) is the density of the medium, \( \kappa \) is a universal constant \( (\kappa = 4\pi N_A r^2 mc^2 = 4.9 \times 10^{-18} \text{ Jm}^2/\text{mol}=0.307 \text{ MeVcm}^2/\text{mol} \) where \( N_A \) is the Avogadro number, \( m \) and \( e \) is the electron mass and charge, and \( r \) is the classical electron radius \( r = e^2/4\pi \varepsilon_0 mc^2 = 2.82 \times 10^{-15} \text{ m} \), \( Z \) and \( A \) denotes the atomic number and weight of the medium and \( z \) is the projectile charge in units of \( e \). Here, the only velocity-dependence is the \( 1/\beta^2 \) term which originates from the time duration (squared) which is needed for the projectile to propagate \( dx \) distance.

The integration limits are set taking into account, that the de Broglie wavelength of the electrons seen from the projectile frame is finite (lower limit) and that the classical revolution time of an electron around its nucleus should be bigger than the time the projectile can interact with it\(^{14} \) (upper limit). Both regularization have the same effect, giving a term known as the relativistic rise, the domain which is most important for the NA49 particle identification.

The energy loss of the particle now reads

\[
\left\langle -\frac{dE}{dx} \right\rangle = \rho \kappa \frac{Z}{A} \frac{1}{\beta^2} \left( \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \delta(\beta) \right)
\]

where \( I \) is the mean excitation energy of the medium. The last two terms (\( \beta^2 \) and \( \delta \)) are introduced to describe yet a new phenomenon, the screening of the Coulomb interaction by the

\(^{14}\)At this point one takes into account that the electric field of the projectile is Lorentz-contracted therefore stronger in the direction perpendicular to the propagation. This increases the maximal \( b \) by a factor of \( \gamma \).
polarization of the material, which affects long-distance interactions. As a result, the Bethe-Bloch function approaches a plateau value, at asymptotically large $\beta \gamma$.

A more exact treatment gives an expression for the energy loss

\[
\langle -\frac{dE}{dx} \rangle_{\text{ionization}} = \rho \frac{Z}{A} \frac{1}{\beta^2} \left( \frac{1}{2} \ln \frac{2mc^2 \beta^2 \gamma^2 E_{\text{max}}}{I^2} - \beta^2 - \delta(\beta) \right)
\]

where $E_{\text{max}}$ is the maximum energy which can be transferred to a free electron in a single collision and not yet considered as a separate $\delta$ ray (very energetic knock-on electrons form a separate track and their ionization is not to be attributed to the projectile.) This restricted energy loss is more appropriate to use in ionization measurements.

In the end, the constant factors and the detailed functional form is less important for particle identification in measurements, than the good description of the measured data by an easily treatable functional form, the parameters of which can be fitted to the measurements. This is the strategy we will follow as well (similarly to [30], [46] and [33]), using the functional shape:

\[
(-\frac{dE}{dx})_{\text{mean}} = E_0 \beta^a (b + 2\ln(\gamma) - \beta^2 - \delta).
\]

with the $\delta$ term parametrized as:

\[
\delta = \begin{cases} 
0 & \text{if } X < X_0 \\
2\ln(10)(X - X_A) + a(X_1 - X)^M & \text{if } X_0 < X < X_1 \\
2\ln(10)(X - X_A) & \text{if } X_1 < X
\end{cases}
\]

where $X = \log_{10}(\beta \gamma)$. The variables $X_0$, $X_1$, $X_A$, $E_0$, $\alpha$, $a$, $b$ and $M$ are parameters to be adjusted. More precisely, the $\alpha$ exponent is given by the above theoretical considerations ($\alpha = -2$), and this is compatible with the data as well. Furthermore, by requiring the continuity of the function and its first derivative, we can get two more constraints on them, while the third constraint comes from the requirement that the minimum of the function has to be unity (we shall follow this normalization convention). In the end, we are left with 4 parameters: the $X_0$ and $X_1$ interval limits, where the saturation effect takes place, and the two other parameters can be expressed as the function of the $s$ saturation (plateau) value, and the $\beta \gamma$ value where the Bethe-Bloch function takes its minimum, called $\mu$. This reparametrization helps attribute a simple meaning to the free parameters.

Taking any set of the $X_0$, $X_1$, $s$, $\mu$ parameters, one gets for the old parameter set:

\[
E_0 = -\frac{\alpha}{2} \left. \frac{1 - B^2}{B^{\alpha+1}} \right|_{\alpha=-2} = \frac{1}{\mu^2}
\]

where $B = \mu/\sqrt{1 + \mu^2}$, the $\beta$ value where the function is minimal.

\[
b = \mu^2 \left( 1 - B^2 \left( 1 + \frac{2}{\alpha} \right) \right) + \ln \left. (1 - B^2) \right|_{\alpha=-2} = \mu^2 + \ln \left( 1 - B^2 \right)
\]
\[ M = (X_1 - X_0) \left( \frac{s/E_0 - b + 1}{2 \ln(10)} - X_0 \right)^{-1} \]

\[ X_A = X_0 - \frac{(X_0 - X_1)}{M} \] and finally \( a = 2 \ln(10) \mu^{-1} (X_1 - X_0)^{1-M} \). By inserting these parameters to the original Bethe-Bloch function, we retain the intuitive \( X_0, X_1, s \) and \( \mu \) parameters only.

Fig. 25: The above discussed Bethe-Bloch formula, as a function of momentum, for the long-lived charged particles detected in the TPC system.

We will constrain these parameters to describe the measured ionization in a self-consistent way, and at the same time obtain the - a priori unknown - amplification (gain) factors of the individual TPC sectors, by a method called inter-sector calibration which is based on the measured data itself.

While Fig. 24 showed the Bethe-Bloch function against the variable \( \beta \gamma = p/mc \), in Fig. 25 we plot it as a function of momentum \( p \) for a few different kinds of particle (mass).

In general, the most important objective of the study is to assign an ionization rate (dE/dx) to each track, which depends on the total momentum and mass only, not being hampered by detector effects. This way the mass and the dE/dx of a particle will be correlated at each fixed momentum value, thus making the particle identification possible.

This can be achieved by applying precise corrections to the measured charge. If we plot these dE/dx values against the total momentum, the particles carrying different masses should concentrate near the lines of Fig. 25, corresponding to their mass.

One cannot separate the different particles in the region where the above curves cross each other, or, if we do not have sufficiently precise ionization measurement. Therefore, the challenge
and demand is a high quality dE/dx measurement.

5.1.3 Truncated mean methods

In our fixed target experiment the ionizing particle loses only a small fraction of its energy while crossing the TPCs. The length of flight in the gas volume can be several meters, and the number of clusters along the track has an order of magnitude $N \approx 100$ (precisely between 10 and 234). One could simply sum up these $N$ charges; this way measuring the amount of ionized electrons along the entire path in the chambers. Division by the total length of the track in the gas would give the ionization over a unit length, which are interested in.

However, this is not the optimal procedure, for a purely mathematical reason. As we measure the ionization over 4 cm long track segments, getting this way $N$ charge values, there is a possibility to extract more information from them. The only measure of the precision is the separation power, for example between protons and pions: not only the resolution of dE/dx should be good, but we must not diminish the difference of the mean dE/dx between pions and protons artificially. This has to be kept in mind while considering a method for obtaining a single value from these $N$ numbers (as well as when comparing dE/dx resolution between experiments or data chunks).

The specific energy loss is a variate corresponding to a probability density called Landau-distribution, not being available in closed analytical form. An approximate formula has been written by Moyal [47] based on the original calculations by L. D. Landau [43]:

$$M(\lambda) = \frac{1}{2\pi} e^{-\frac{1}{2} (\lambda + e^{-\lambda})}$$

where $\lambda(\epsilon) = \frac{\epsilon - \epsilon_p}{R}$

and $\epsilon_p$ is the most probable amount of the energy loss and $R$ is a medium-dependent constant. An example of the Moyal function can be seen in Fig. 26.

The distribution of measured cluster charges will be similar, having a long upper tail (depending on the actual $dx$ length). The clusters of high ionization introduce a large fluctuation in the average (sum) of the cluster charges, and this propagates into a poor dE/dx resolution.
A possible solution could be to take a logarithmic average:

$$\langle \frac{dE}{dx} \rangle = \exp \left[ \frac{1}{N} \sum_{i=1}^{N} \ln(Q_i) \right]$$

where $Q_i$ (i=1..N) are the cluster-charges. This method has an advantage that it uses all $N$ charges available, and the logarithm reduces the effect of the above fluctuations.

The so called **truncated mean** method has been proven to be even more useful. Here a subset of the charges is selected, and the average is calculated over this subset only. Each application has different optimum concerning the subset of charges, which has to be determined.

The simplest way is if we sort the charges belonging to the track into increasing order (below, the $Q_i$ charges are regarded to be ordered), eliminate the first $x$ and last $y$ fraction ($0 \leq x, y \leq 1$) of these numbers, and average over the rest. This is actually a weighted average, where - if there are $N$ clusters - the weights should take care that $N$ is a finite integer\footnote{$[x]$ denotes the integer part, \{x\} = x - [x] the fractional part of any $x$ real number.}, like:

$$w_i = \begin{cases} 
0 & \text{if } 1 \leq i \leq \lfloor Nx \rfloor \\
1 - \{Nx\} & \text{if } i = \lfloor Nx \rfloor + 1 \\
1 & \text{if } \lfloor Nx \rfloor + 2 \leq i \leq N - 1 - \lfloor Ny \rfloor \\
1 - \{yN\} & \text{if } i = N - \lfloor Ny \rfloor \\
0 & \text{if } N + 1 - \lfloor Ny \rfloor \leq i \leq N
\end{cases}$$

and the **truncated mean** is defined as

$$\langle Q_i \rangle_{\text{truncated}} = \frac{\sum_{i=1}^{N} w_i Q_i}{\sum_{i=1}^{N} w_i} = \frac{\sum_{i=1}^{N} w_i Q_i}{N(1 - x - y)}.$$  

The above precise weighting is needed, because if we work with 0 and 1 weights only, the truncated mean will (in a statistical sense) oscillate as a function of $N$ (this problem was mentioned also in [30] and [31], and corrected for it in an alternative way in [31]).

For example, if we used $x = 0$ and $y = 0.5$, and weights were defined (carelessly) as

$$w_i = \begin{cases} 
1 & \text{if } 1 \leq i \leq \lfloor N/2 \rfloor \\
0 & \text{if } \lfloor N/2 \rfloor + 1 \leq i \leq N
\end{cases},$$

the weighted mean would be systematically higher for tracks having even $N$, and lower for tracks with odd $N$ (since in the latter case we disregard the cluster in the middle of the $Q_i$ sequence). The effect can be as much as a couple of percent change of the truncated mean (see Fig. 27). By our weighting method we get rid of the oscillation without loss of information, however there is a residual effect: taking the Landau-distribution and sampling it $N$ times (that is what our experiment does) the truncated mean of the $N$ numbers (on average) increases as $N$ decreases...
to low integer numbers. The relative size of this variation is around a percent, and is corrected for, using a pre-calculated table delivered by a high statistics Monte-Carlo simulation. The method described above is called \((x; y)\) truncation, \(x\) and \(y\) expressed in percents, e.g. \((0; 50)\).

The **weighting** can be carried out in more sophisticated ways as well. The measure of the quality of such an algorithm is the achieved precision of the result (in our case \(dE/dx\)), or rather the separation power. We can apply a weighting function \(w(i)\) \((i=1..N)\), for example, which — in the \(N \to \infty\) limit — leads to a *Gaussian* weighted charge distribution \(w(i)Q(i)\) \((i=1..N)\), as opposed to the simple \((x; y)\) truncation (which gives back the original Landau distribution, with tails cut off). This Gaussian can have an integral equal to the half of the integral of the Landau distribution, and the same most probable value (provided that \(N \to \infty\)). This only means a different arrangement of the weights compared to the latter method, and it keeps similarly the "half" of the points, in a sense. However, more detailed studies did not reveal significant room for improving the simple \((x; y)\) truncation, therefore the latter was kept for all following applications, due to its simplicity. Finally, it is important to note that all the above methods based on the weighted average have a great advantage that they are *linear* in the input \(Q_i\) charges:

\[
\langle \alpha Q_i + \beta \rangle \equiv \frac{\sum_{i=1}^{N} w_i(\alpha Q_i + \beta)}{\sum_{i=1}^{N} w_i} = \alpha \frac{\sum_{i=1}^{N} w_i Q_i}{\sum_{i=1}^{N} w_i} + \beta \equiv \alpha \langle Q_i \rangle + \beta
\]

since the \(Q_i \mapsto \alpha Q_i + \beta\) operation does not affect the ordering of the \(Q_i\) charges.

With the help of simulations or the analysis of the experimental data one can study, which \(x\) and \(y\) values provide the maximum precision of the truncated mean. For better controllability, the optimization was based on a simulation.

![Fig. 27: The systematic effect caused by the truncation on the tr. mean. Simple rounding leads to the even-odd two branch function as opposed to our method](image-url)
5.1.4 Monte Carlo simulation of the ionization

For simulating the number of ionized electrons one has to apply the relevant physical constants valid for our conditions (gas composition, pressure). If the high-energy particle undergoes on average $N$ collisions with atomic electrons over a certain distance ($N$ is known for our gases, see Table 4), the probability of exactly $n$ collisions follows a Poissonian distribution. One can choose random integer numbers following the above distribution: we regard these as the number of primary interactions in each collision.

The kicked electrons have an energy spectrum approximated by $1/E^2$, thus we can assign an energy $E$ to each kicked electron. If this energy is less than the first ionization energy, the electron does not get free, and we do not count it. One has to define an upper energy limit of $E$ as well, e.g. the energy of our ionizing particle. We approximate the number of secondary electrons by the ratio of the energy of the primary electron and the (known) average energy necessary to create an ion-electron pair. This way the total ionization can be counted, for a given $dx$ path of a projectile. Fig. 28 gives an example of such a simulated ionization distribution. It is clear that the above method oversimplifies the processes occurring at the ionization of a particle, but it was sufficient to study some already mentioned sampling effects and as an interesting by-product concerning the energy distribution of primary electrons in different noble gases.

Using the high-statistics simulation, it was straightforward to optimize the $x$ and $y$ truncation limits: at each $x$, $y$ pair a large number of ”tracks” (e.g. with $N=90$ clusters) were generated and the truncated mean was calculated for them. Finally the standard mean deviation of the truncated means (resolution) was calculated for each $x$, $y$ pair. The result is plotted in Fig. 29. In the upper panel the $y$-dependence can be seen, at different $x$ values, on the lower panel vice versa. The $x=0$, $y=50\%$ parameters minimized the resolution, therefore the (0:50) truncation was used in all following studies. Naturally, the resolution depends on the $N$ number of clusters on a track, and follows approximately the $\sigma_{dE/dx} \sim 1/\sqrt{N}$ rule.
Fig. 29: The simulated dE/dx resolution as a function of the x,y truncation parameters.
Finally, as a last effect of a mathematical type, it is important to discuss the difference between the notions "dE/dx" and "truncated mean". The latter was devised to describe the amount of ionization with a single real number, in a very specific way, while dE/dx is the mean energy loss (or mean ionization). The difference arises from the fact that the mean and the truncated mean of the Landau-distribution (or a measured charge distribution) is not only different, but they are not even proportional.

The reason is simply that if the dE/dx is high, that is, if the number of primarily ionized electrons is large, the relative spread of their Poissonian distribution is smaller than for low-dE/dx tracks. Even after taking into account the secondary electrons, the relative width of the final Landau-distribution decreases with increasing dE/dx. Consequently, the mean and the truncated mean approaches each other; the (truncated mean)/(dE/dx) ratio increases. Fig. 30 shows this ratio, normalized to unity at dE/dx=1.

The functional forms of them are:

\[ 1.0 + 0.1800 \ln(dE/dx) - 0.0155 \ln^2(dE/dx) \]

for the Vertex, and

\[ 1.0 + 0.1544 \ln(dE/dx) - 0.0140 \ln^2(dE/dx) \]

for the Main TPCs. In our analysis, we will always use the truncated mean instead of dE/dx, therefore we modify the Bethe-Bloch formula to become a 'truncated mean formula' applying the above conversion, though keeping the term 'Bethe-Bloch formula'.

5.1.5 On the energy distribution of the primary electrons

One has no doubt that the $1/E^2$ distribution cannot describe the energy distribution of the primary electrons (see also Fig. 23) very precisely. After applying the necessary corrections (to be discussed in the next chapter) the measured charge distribution appears to be narrower than the simulated one (and this is difficult to interpret as a hidden detector effect). One can try to change the energy distribution to $1/E^\alpha$ ($\alpha > 2$), as this evidently shrinks the simulated Landau-distribution. $\alpha$ is regarded as an effective exponent, and we cannot claim to connect it to any physical theory but only want to investigate how the $\alpha$ exponent depends on the atomic number of the gas, for practical purposes.
It is helpful to define a "full-width at 0.2×maximum" of the \( \mathcal{L}(x) \) Landau-distribution: let us define the \( x_1 \) and \( x_2 > x_1 \) charge values as \( \mathcal{L}(x_1) = \mathcal{L}(x_2) = 0.2 \max(\mathcal{L}) \), and the \( w \) width as \( w = (x_2 - x_1)/(x_1 + x_2) \) since this is invariant under the rescaling of the \( x \) axis. Now it is simple to adjust \( \alpha \) in a way that the simulated and the measured \( w \) widths become equal. This exercise can be done for Argon (Main TPC) and Neon (Vertex TPC) in NA49. To complement this comparison, other experiments had to be used. In Ref. [48] one can find
- full-width-at-half-maximum of Landau distributions
- full-width-at-half-maximum of truncated mean distributions, using (0:60)
  truncation and 64 clusters per track
measured in different noble gases at 1 atm pressure. For Helium, Ref. [49] contains the number distribution of secondary electrons, related to the energy distribution of primaries. Thus, a reanalysis of this data to extract the effective exponent was possible.

Fig. 31 shows the result, where we can conclude that the \( \alpha = 2 \) assumption becomes more and more reasonable for heavier noble gases — at least within this simple-minded framework.

This effect could account for the somewhat surprising observation, that experiments applying different kinds of noble gases exhibit approximately equal resolution of ionization measurements (under similar conditions): the increasing number of primary electrons per collision (Table 4) is roughly compensated by the decreasing \( \alpha \) exponent, leading to Landau-distributions of a comparable width.

### 5.2 Corrections of the ionization measurement

In this section we summarize the correction procedures to be applied to the dE/dx data off-line. Their aim is to compensate detector effects, some of which are known and controlled and some are not.
5. IONIZATION (DE/DX) MEASUREMENT

5.2.1 Kr calibration

As it was already mentioned, the first step of electronic channel gain calibrations is the krypton-calibration [50]. Small amount of radioactive $^{83m}\text{Kr}$ mixed into the TPC detector gases generates characteristic ionization pattern caused by the successive decays of the non-stable Kr states. By comparing a reference histogram to the measured ones, the relative channel gains can be obtained. An illustration of this ionization spectrum can be seen in Fig 32.

As this test needs decreased high voltages on the sense wires with respect to the real data taking (to avoid overflows), the result is precise only inside the individual sectors, but different sectors (having their separate low- and high voltage supplies, different geometrical readout constructions etc.) should be compared in an alternative way, as well as the time dependences of these amplification factors should be followed - based on the data itself.

Krypton calibration is able to spot dead or aging channels and chips, this detailed information is used further in the reconstruction chain.

5.2.2 Pressure and temperature

In general, the gas gain of the Time Projection Chambers depends on the density of the gas mixture. While it is possible to thermalize the TPC environment at a $\approx 0.1^\circ \text{C}$ precision (by applying air-conditioners), the atmospheric pressure variations cannot be easily kept constant. Therefore the atm. pressure is monitored during measurements, and the measured gain is corrected for its effect during the off-line analysis. Fig. 33 (left panel) shows the gas pressure and gain variations in the Vertex Chambers during a selected week in September, 2000. The
anticorrelation between the two is clearly observed. The formula

\[ Q_{\text{corr}} = Q / [1 - \alpha (p' - \beta p^2)] \]

was used for correcting the pressure effect, where \( p' = p - 970 \text{ mbar}, Q \) is the measured charge on the readout pads, \( Q_{\text{corr}} \) is the corrected charge. The \( \alpha \) and \( \beta = 0.0033 \) factors were measured separately in previous tests, but \( \alpha \) finally extracted from the data to be 0.0039 in the Main TPCs, 0.0020 in the Vertex-2, 0.0032 in the Vertex-1, sectors 2,3,5,6 and 0.0040 in sectors 1,4.

![Graph](image)

**Fig. 33:** Pressure and gain variations during a selected week in the Vertex TPCs (left), and the gain corrected for the pressure changes (right).

The right panel of Fig. 33 proves that the corrected gain is constant within \( \pm 0.5\% \). Still, there are three effects which are responsible for residual time-dependent gain variations:

- **day/night variations** (indicated on the plot), in size corresponding to \( \pm 1^\circ C \) temperature variations. Those could be eventually present if the massive readout plates (equipped with the thermometers) cannot follow the daily thermal cycle of the circulating gas mixture;

- **sudden jumps** in the gain (not seen on this plot), at a size of a few percent, different in size for separate sectors, but often the same time. Those can be due to the power cycling of chambers for test reasons, which activity was avoided after the discovery of instabilities connected to them;

- **Slow drift** of the gain in time, not related to the pressure variations, smaller in size than the jumps.

As the separation of the pions, kaons and protons is typically 20% in the ionization measurement at a given momentum, and the resolution of the well corrected ionization measurement is better than 4%, one cannot tolerate the above remaining effects. Therefore a simple method was developed to follow up the development of the sector gains in time (separately for each of the 62
sectors): all measured ionization values were collected from a given sector as a function of time, and after appropriate averaging over small time intervals, the gain history for the sector was put into correction tables. (Actually, the truncated mean of the collected charges is calculated, to maintain a similar procedure to what will be used for single tracks.) This contains relative changes, but a comparison between gains of different sectors is not possible because the particle composition and momentum distribution differs between sectors. Note, that for each different beam or target type, trigger condition etc. one has to complete a separate time-dependence study, since the particle composition in the sectors will not stay the same.

In low multiplicity (p+p, p+A) reactions the procedure is more difficult to automatize reliably, than for A+A reactions, since sectors on the edge get much fewer tracks than sectors close to the beam. Besides, temporary operational instabilities and failures were also discovered by inspection of these tables, and the concerned data chunks later discarded.

To summarize, all remaining gain variation is taken out from the data, based on the measured data itself (using only valid particle tracks, and excluding noise, delta rays and spirals, muon tracks from the beam halo etc.), to a precision better than $\approx 0.2\%$, at the same time providing an important off-line monitoring and quality control of the TPC performance.

5.2.3 Length of flight

The measured ionization of a track adds up from the cluster charges found in the pad-rows. Each pad-row contributes to the track with a two dimensional cluster extending in $y$ (time, drift) and $x$ (pad-row) directions. We are interested in a specific ionization of the particle over unit length of flight. Therefore, we multiply each cluster charge by a factor of

$$\frac{t \cdot p}{|t||p|}$$

where $p = (\pm \tan(\alpha), 0, 1)$ is the direction of the chamber edges (always perpendicular to the pad-rows), and $t = (x, y, z)$ is the direction of the particle’s path. Here, $\alpha=0$ except in MTPCs which are slightly rotated. $t$ is calculated from the cluster positions, by fitting a line (MTPC) or a circle (VTPC) depending on the magnetic field, locally around the position of a given cluster. As we discussed, the Landau-distribution gets relatively narrower as we increase its mean. This is true in this case as well, where we vary the length of flight over a pad-row, but we neglect this second order effect and apply only the simple formula above.

5.2.4 Drift length and angle dependent losses

As drift length dependent charge losses can in some cases degrade our measured ionization by 10-20 percent, their treatment is the most important, and by far the most difficult of all.\cite{51}.
5. IONIZATION (DE/DX) MEASUREMENT

The ionization electrons along the particle's trajectory are drifting a long, up to 110 cm distance until they reach the readout plane. In the meantime they can be lost for our purposes, by attachment to $O_2$ (and $H_2O$) molecules. Even if the gas mixture is always circulated and filtered, a few ppm (part in a million) oxygen remains inside the TPC volumes due to the continuous diffusion from outside. In the Main TPCs, $\approx 3$ ppm $O_2$ results in a 2% charge loss over a meter of drift, in the Vertex chambers, a $\approx 5.5$ ppm $O_2$ causes around 10%/m loss. These are exponential functions of the drift distance but can be approximated well with a linear formula in our case.

The second reason of charge loss is the one which is much more difficult to assess and correct for, namely the threshold losses. The origin of this loss is simple: for the sake of noise and zero suppression, only those signals are recorded from the electronics channels which are at least 5 ADC$^{16}$ units large in amplitude. Clusters are combined collecting consecutive hits in x and y direction, in a given pad-row, which reach this threshold (in y direction, two such consecutive hits are required). Consequently, when the total cluster charge is calculated by adding up these ADC values, the smaller hits are left out - that is, the tail of the cluster is cut off (Fig. 34). Though the typical size of the cluster maximum is at least 50 ADCs, this loss in the tail is still sizeable because the charge cluster is not one, but two dimensional.

Let us first estimate this loss in a simplified model where the cluster shape is a two-dimensional Gaussian with A amplitude, T=5 ADC threshold and $\sigma$ width:

$$q(x, y) = A \exp(- (x^2 + y^2)/2\sigma^2).$$

In radial coordinates, one can easily obtain the amount of lost charge:

$$2\pi \int _R ^\infty Ar \exp(-r^2/2\sigma^2) dr = 2\pi \sigma^2 A \exp(-R^2/2\sigma^2) = 2\pi \sigma^2 T$$

$^{16}$Analog-digital converter units: for each time bin and for each pad, a digital number proportional to the pulse height is available - if being above threshold.
where \( R \) is the distance from the center where the Gaussian reaches \( T \). The total charge is 
\[ 2\pi \sigma^2 A \]
therefore the fraction of loss is \( T/A \), 10\% in our example above.

We have pads of finite size, and the cluster shape is much more complicated, thus the best solution was to study the effects in a Monte-Carlo simulation of the cluster shapes\(^{17}\).

The charge loss depends (through the cluster shape) on the drift length, the original amplitude and the direction of the particle’s path as well. Our aim was to create a table where the loss could be looked up for all possible combinations of these parameters, for all clusters in the data.

For example, at a given \( y_0 \) coordinate, the drift distance is the same for clusters on tracks having different directions, still, the threshold loss can be different due to the varying cluster shape. The simple old methods, which used only the drift distance as a relevant parameter, could not account for this track angle effect.

Tilt angles of the pads, the width of the pads and time slices (drift velocity), diffusion constants, the gap between pad plane and sense wires, pad lengths are all important input parameters of the simulation. In \( x \) direction, a few pad wide pad response function describes the signal shape caused by a single charge arriving to the sense wire. The time response function is determined by the time constants of the electronics, the shaper unit and there is a characteristic undershoot (below zero) after the signal peak. By diffusion (longer drift distances) this dip can be “filled” as the electron cloud gets wider; finally changing the amount of charge loss. Using the known diffusion constants, a cluster starting from a given \( y \) position takes a Gaussian distribution in \( x \) and \( y \) with a calculable

\(^{17}\) A much more detailed simulation has been written before for other reasons [52], however neither the achieved computing speed nor the specific questions we raise here have been addressed.
5. IONIZATION (DE/DX) MEASUREMENT

width. Reaching the sense wires, the electron cloud produces a certain signal distribution on the pad plane. In the end, the cluster shape will be a convolution\(^{18}\) of a Gaussian and the known (previously measured) time-response function. An example of the cluster shape is shown in Fig. 35, where the drift length was 50 cm in the Main TPC. The undershoot after the signal is well visible.

If the track is not parallel to the beam direction, the above result has to be integrated along the path of the ionizing particle above the given pad-row, giving the proper, elongated shapes ("cigar"-shape).

Now it is easy to bin our 2-dimensional cluster to a pad/timeslice grid, pick up the hits above threshold, and calculate the charge loss in ADC units, provided the amplitude of the cluster is known.

We certainly cannot take into account the precise position of the cluster centers in the data, but we apply an average correction (that is, we do not want the cluster center position to be yet new parameters to handle). Therefore one has to average the loss over all possible initial center positions, to avoid fake binning effects.

<table>
<thead>
<tr>
<th>parameters</th>
<th>M.HR</th>
<th>M.SR(^{1})</th>
<th>M.SR</th>
<th>V2</th>
<th>V1,ex.S.1,4</th>
<th>V1,S.1,4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resp. width scale</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>1.02</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td>pad resp. width scale</td>
<td>0.837</td>
<td>0.65</td>
<td>0.65</td>
<td>0.93</td>
<td>0.63</td>
<td>0.60</td>
</tr>
<tr>
<td>pad width [mm]</td>
<td>3.6</td>
<td>5.5</td>
<td>5.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>time slice width [mm]</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>pad length [mm]</td>
<td>39.5</td>
<td>39.5</td>
<td>39.5</td>
<td>28.5</td>
<td>28.5</td>
<td>16.</td>
</tr>
<tr>
<td>diff. const. x [mm/√cm]</td>
<td>0.29</td>
<td>0.31</td>
<td>0.31</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>diff. const. y [mm/√cm]</td>
<td>0.36</td>
<td>0.35</td>
<td>0.35</td>
<td>0.24</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>electr. attachment [%/m]</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>12</td>
<td>7.5</td>
</tr>
<tr>
<td>threshold [ADC]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>average horiz. angle [deg.]</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>average vert. angle [deg.]</td>
<td>0.5</td>
<td>2</td>
<td>1.2</td>
<td>2</td>
<td>0.3y</td>
<td>0.57y</td>
</tr>
<tr>
<td>ref. plane [cm]</td>
<td>+50</td>
<td>+50</td>
<td>+50</td>
<td>+25</td>
<td>+25</td>
<td>+25</td>
</tr>
<tr>
<td>sense w. - pad gap [mm]</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>sense w. position [cm]</td>
<td>+56.4</td>
<td>+56.4</td>
<td>+56.4</td>
<td>+29</td>
<td>+29</td>
<td>+29</td>
</tr>
</tbody>
</table>

Table 5: Parameters used in the simulation of the cluster shapes.

Finally, we obtain the estimated loss for any given track angle (2 parameters), total ADC

\(^{18}\)These convolutions are possible to make even analytically, if one approximates the pad response and time response functions by sum of Gaussians. A few appropriate Gaussians provide already an excellent description of the measured curves.
and drift distance, in any type of sector construction. An example of the simulated charge loss can be seen in Fig. 36 in a Main TPC High Resolution sector, for a cluster having originally 500 ADC total charge, and the track was in the $y = 0$ mid-plane. The horizontal and vertical angles of the track modify the charge loss; it is more sensitive to the vertical angle since the time slice width is smaller than the pad width. The model parameters for different sector types are summarized in Table 5.

A further complication is that most of the pads in the NA49 TPCs are tilted (by up to 55 degrees) in the horizontal plane to match the typical track angles at the given pad position (Table 2).

The above simulation with the simple rectangular binning in the end holds for non-tilted pads only, but one can generalize this to any tilt angle in a simple geometrical way. Let us imagine a single pad to be composed of tiny segments (which are parallel to the pad-row direction).

The signal developing on such a small segment depends only on the distance of the segment and the track, therefore we can transform the pad into a tilted one by shifting each segment, and the track piece by the appropriate amount (Fig. 37). The construction of the chambers are fortunate: the pad widths are constant in a row if measured along the pad-row direction, not if measured perpendicular to the edge of the pad; so there will be no $x$-dependence necessary in our look-up correction tables.

This way (as one can derive from the above concept) one should use, as a parameter, not the difference between tilt angle ($\Theta$) and horizontal track angle ($\alpha$), but the $\gamma$ angle, where

$$\tan(\gamma) = \text{abs}(\tan(\Theta) - \tan(\alpha)).$$

This way one can still use the tables derived for non-tilted pads.

Finally, the output of the simulation is a look-up table, where one has to specify the sector type and the two angles describing the track direction. The table then contains the parameters of a linear function of the total measured ADC charge and the $y$ (drift distance), which gives the corrected charge. The approximation with linear correction functions was necessary to decrease the number of parameters by two, otherwise a look-up table would be unreasonably large.
And, since the detailed "on-line" calculation of the cluster shape for each case in the data is not feasible with the present computing speed, a mentioned correction table has been preferred.

One could think that the wire \textbf{E}x\textbf{B} effect still has to be taken into account. This makes clusters wider or narrower, depending on the magnetic field polarity and horizontal track angle: the electrons arriving to a sense wire travel in a horizontal direction as well, and the magnetic field deviates them sideways. A simple calculation showed that the increase of the cluster width is a few percent only, if the track is perpendicular to the sense wires (parallel to the beam). If it makes even a small angle, the effect nearly vanishes, since the pads are much longer than the 4 mm spacing between sense wires, and the deviation of the electrons is proportional to this spacing. In the end, the wire \textbf{E}x\textbf{B} effect was not included in the cluster shape model.

To compare the cluster shape results with the real data, a \textbf{fine tuning} of the known physical constants and parameters was necessary. By allowing only a few percent deviation from the known values, the new parameters described very precisely the clusters in the real data. Three measures were used to describe the cluster shape: the number of time slices and pads in a cluster, and the maximal ADC value. An example of such a comparison is shown in Fig. 38.

Now, as a real test, one could verify whether the losses observed in the real data are described well with the model, besides the cluster shapes. The agreement between simulation and measurement is quite good, providing a better general understanding of the ionization data and TPC operation (Fig 36). We stress again the importance of
the model: some quantities can be measured experimentally, like the charge loss over one meter (with averaging over track angles), but some others can only be calculated with the model, like absolute losses in ADCs, angle dependence of the loss etc. We adjust the model to the measurable quantities, than extract from it those necessary details which cannot be directly observed.

As the $O_2$ content of the chambers shows slight changes in time, and to avoid uncontrolled variation of the threshold losses in the data, for all data set the amount of measured charge loss was compared to the values given by the correction tables. At this point, a final adjustment of the charge loss correction was carried out in each sector type, sized no more than a couple of percent loss over a meter of drift. This ensures precise drift dependent correction even under slightly changing conditions.

One should note here that the above (large) threshold loss correction is indispensable to have a reliable particle identification via ionization measurement, and the amount of necessary corrections is not possible to extract from the data itself, only from a simulation well compared with the measured data.

5.3 Sector Calibration

The last major step to obtain the correct ionization data is the sector calibration. It was already mentioned that the 62 TPC sectors (50 of them in the Main TPCs) can fairly independently change their gain factors, as they are individual units, and their differences in design and construction leads to difficulties to conclude about their gains from other methods (krypton, pulser) of calibration.

The time dependence of the sectors is already discussed; but for each dataset, the starting values of these amplification (gain) factors need to be extracted from the data itself, using a small reference data chunk. The resulting iterative process, a kind of self-consistent calibration became a basis of all particle ionization measurements in the NA49 experiment [53].

A first look on the dE/dx data (Fig. 40) shows that there is nothing like the expected smooth relativistic rise yet seen - without sector calibration. Fig. 40 shows the truncated mean of cluster charges for each track in the MTPC, as a function of the track momentum.

5.3.1 If the Bethe-Bloch function is known

First let us assume, that the precise Bethe-Bloch parametrization is known from somewhere else. We can take this function, and change the sector gains in a way that the data follows this function in the end. This can be carried out since the individual sectors each have a characteristic momentum region in which they detect tracks. Since tracks cross several sectors,
Fig. 40: First look on ionization data in the MTPC. Crosses represent tracks. A major intervention is clearly needed to correct the data - sector gains are not yet calibrated. See also Fig. 25.

the gains of various sectors can be normalized to each other, using an iterative algorithm. At our energy, pions are the most abundant secondary particles, therefore we know that most of the entries in Fig. 40 correspond to pions. Now we can follow the steps below:

- Let us take the Bethe-Bloch function for pions (Fig. 25), and define a window around it (with a few percent width in dE/dx). This band should contain most of the pions ideally.
- Take all the tracks inside this band ("pions"). Collect all the clusters on a given track, in each sector separately. Divide the cluster charge by the Bethe-Bloch value for that given track momentum. (For example, if there is a sector in which we collected numbers much larger than unity, the gain of this sector is too large.)
- After collecting a large number of cluster charges in a given sector, calculate the truncated mean of them, to maintain the similarity to the procedure applied on the tracks.
- This way we get the relative gain of each sector. Saving it into a table, next time we can correct for these numbers (divide by them) before calculating the truncated means for the tracks. These numbers differ by up to $\approx 10\%$. We call them sector constants.
- We can now recalculate truncated mean values for all the tracks, taking first into account the sector constants.
- Going back to the first point, pions are selected again, and the iteration continues.

This procedure converges sufficiently after $\approx 20$ iterations. The convergence is insured by
the large pion abundance. If we keep the pion selection window fixed, the pion distribution tends to move in a way, that inside the window the mean value of the truncated means be equal to the Bethe-Bloch value in the end.

![Graph showing truncated mean vs log10(p)](image)

Fig. 41: The result of the sector calibration in the Main TPC. A clean relativistic rise is seen. Pions compose the band above, protons the one below. Dominance of high momentum protons in proton-proton collisions is already observed here.

The precision of the sector constants depends on the size of the data chunk we process in the above loop, but can be kept better than 0.3% easily.

One should modify the above procedure in many cases, for example, in proton-proton collisions. There, a fast proton is produced with high probability, but fast pions are rare. Therefore, above a certain momentum protons dominate over pions. There, one should use a "proton window" to select tracks for the iterative calibration, in addition to the slow pions. One should take care that the whole TPC volume is covered by the momentum space in which these selection criteria and the iterative procedure make sense.

The result of the iterative sector calibration in the Main TPC is shown in Fig. 41. This quality makes already possible to compare data with the Bethe-Bloch function in detail, to be discussed later.

One should note that the position of the Main TPC sectors are very much correlated with the momenta of the tracks crossing them. This implies that almost arbitrary Bethe-Bloch functions can be taken, and still one can tune the sector constants to move the pions onto the
Bethe-Bloch function. This makes almost hopeless to measure the real Bethe-Bloch function under our conditions, but we can still require a consistency between different particle types (often referred to as $\beta\gamma$ scaling).

### 5.3.2 Earlier ionization measurements

Cannot we get a precise idea for our experiment about the Bethe-Bloch function, to avoid the mentioned complications? NA49 uses argon and neon gases in the TPCs. It is possible to find in the literature measurements with $0.95\text{Ar}+0.05\text{CH}_4$ ([54], [55], [56] and [57]); $0.90\text{Ar}+0.1\text{CH}_4$ ([58]); Ar ([59], [60] and [61]); finally with $0.90\text{Ne}+0.10\text{C}_2\text{H}_4$ ([57]).

We use the following two measures to compare the various publications. The Bethe-Bloch function has a nearly linear part, the "relativistic rise", where the specific energy loss is a linearly increasing function of $\beta\gamma$. One can extrapolate this linear function to the $\beta\gamma$=10 and 100 values, and by dividing the difference of the functions in these two points by the smaller one, a scale-independent "steepness" of this function can be obtained.

The other measure we present is the approximate extent of the linear region. The result is summarized in Fig. 42, and a clear need to proceed with a self consistent method is seen, preferred over the acceptance of certain results from the existing literature. The results of this method is also indicated on the plot by black rectangles (corresponding to the truncated mean functions).

### 5.3.3 Determination of the Bethe-Bloch function

In order to get a constraint on the Bethe-Bloch parameters, we naturally invoke the $\beta\gamma$ scaling: the Bethe-Bloch function for pions, kaons and for protons is the same, except that they are shifted by $\log(m)$ — if plotted as a function of $\log(p)$. Therefore, all particle types should be concentrated around their respective

![Fig. 42: Older results on the relativistic rise of the Bethe-Bloch function. Because of the large variation, an own determination of the function was developed and applied.](image-url)
Bethe-Bloch function, if the parametrisation we used was correct. Detectorwise, the gain (sector constants) can change the result of the ionization measurement, but by varying a sector gain, one can change the result only in a certain momentum range.

It is easy to see, that if the relativistic rise of the parametrisation is too steep, and we "force" the pions to lie on the pion Bethe-Bloch curve, the protons will be above their respective curve, since we cannot change the ratio of pion and proton ionization in a certain sector (momentum range) by tuning the multiplicative sector gains. Fig. 43 helps illustrate this method: let us denote by \( b^\alpha_\pi (p_0) \) the mean ionization by a pion with \( p_0 \) momentum, and by \( b^\alpha_p (p_0) \) the same for protons, as given by the Bethe-Bloch parametrization having four adjustable parameters called here \( \alpha \). Let us call the measured mean ionizations (after sector calibration with a given Bethe-Bloch function with parameters \( \beta \)): \( m^\beta_\pi (p_0) \) for pions and \( m^\beta_p (p_0) \) for protons. Now, as we argued, \( m^\beta_\pi (p_0)/m^\beta_p (p_0) \approx \text{const.} \), more precisely, does not depend on the sector constants, in other words, on the \( \beta \) parameters of the Bethe-Bloch function: \( m^\beta_\pi (p_0)/m^\beta_p (p_0) \equiv m_\pi (p_0)/m_p (p_0) \). We can now follow the procedure below:

- Take a reasonable \( \alpha \) parameter set for the Bethe-Bloch function.
- Complete the sector calibration taking this function as a basis.
- Take the scatter plot of \( dE/dx \) vs. \( \log(p) \) for all tracks. The particles should concentrate around the Bethe-Bloch curves for pions and protons now (and kaons in between). Work out a procedure on how to fit these particle distributions (see the next chapter on particle identification) and obtain positions of the density peaks. These \( dE/dx \) positions (\( m^\alpha_\pi (p_0) \) and \( m^\alpha_p (p_0) \)) now should lie close to the Bethe-Bloch curves.

- Evaluate the ratio \( m^\alpha_\pi (p)/m^\alpha_p (p) \equiv m_\pi (p)/m_p (p) \) as a function of the \( p \) momentum.

- Calculate the same ratio for the Bethe-Bloch function: \( b^\alpha_\pi (p)/b^\alpha_p (p) \). Should it be different from \( m_\pi (p)/m_p (p) \), the Bethe-Bloch curve must be modified; adjust the \( \alpha \) parameter: fit \( m_\pi (p)/m_p (p) \) by \( b^\alpha_\pi (p)/b^\alpha_p (p) \). The new parameter set will be \( \alpha' \).
Take the Bethe-Bloch function with the new $\alpha'$ parameters and start from the first point. In the end, one gets a self-consistent description of all particle types by their respective Bethe-Bloch curve (which are essentially the same, only shifted along the $\log(p)$ axis since $\beta\gamma \equiv p/mc$).

The NA49 experiment uses two different gas mixtures, with noble gases Ne in the Vertex TPCs and Ar in the Main chambers. Therefore two, slightly different parameter set is obtained ($\alpha_V$ and $\alpha_M$) in the two gases. The Bethe-Bloch functions obtained by this method are plotted in Fig. 44.

According to the expectations, the relativistic rise is steeper in Ne than in Ar (Fig. 42). The optimized parameters of these functions, which were used in the analysis are the following (for definitions, see section 4.1.2):

$\alpha = -2.0, \mu = 3.77$, $X_0 = 1.44$,
$X_1 = 4.00$ and $s = 1.53$ for the Vertex TPCs and $\alpha = -2.0, \mu = 3.85$,
$X_0 = 1.21$, $X_1 = 4.00$ and $s = 1.48$ for the Main TPCs.

5.3.4 "Global" dE/dx

An essential part of the momentum space covered by the NA49 detector system is the low momentum region (below $\approx 5$ GeV/c), where the particles are detected mostly by the Vertex TPCs. Concerning the ionization measurement (and tracking as well), these are much more complicated to treat than the Main TPCs, because the magnetic field causes various distortions in the cluster positions, the tracks are closing a large angle with the beam and are not perpendicular to the pad-rows, the pads are arranged in a difficult pattern of tilts, and in heavy ion collisions, the large track density makes even the clustering less effective. Still, the main goal of developing the possibly most precise correction methods for the ionization measurement was to be able to make use of this valuable momentum space region, and unify the data treatment of Vertex- and Main TPCs.

In case of tracking this comprises creating "global" tracks from the cluster positions, extending eventually into both Vertex and Main TPCs, but being a trajectory of a single particle.
The challenge of the ionization measurement is to make use of the measured cluster charges in all TPCs, allowing us to use low momentum tracks in the analysis, and making use of the additional information of Vertex chambers in case of long tracks having clusters in both Main and Vertex units. Due to the various technical complications (which we overviewed in the last chapters) this task could be completed so far only for the collisions producing low multiplicity, i.e. proton-proton, proton-nucleus, pion-nucleus, carbon-carbon, silicon-silicon, and the most peripheral lead-lead collisions in the framework of the present thesis.

To calculate the ”global” dE/dx, one should first obtain the truncated mean values from the two TPC systems separately. These are added up with the proper weights to deliver the global dE/dx. However, as the two Bethe-Bloch functions are different, first a transformation is applied to the Main TPC truncated mean, to make it compatible with the Vertex TPC data. Furthermore, the experimental errors should be known, to derive the appropriate weights for the sum.

We apply a linear VTPC→MTPC transformation which moves (at any momentum value) the MTPC proton position to the VTPC proton position, and the same for pions. To formulate, we apply the

\[
dE/dx_M \mapsto [dE/dx_M(b^V - b^V_p) + b^M \cdot b^V - b^V_p/(b^M - b^V_p)]
\]

transformation where indices V and M refer to the Vertex and Main TPCs. The reason why we do not transform the Vertex TPC values instead is, that the denominator can be (closely) zero there, since the proton and pion Bethe-Bloch functions cross each other. They do as well for the Main TPC parametrization, but fortunately Main TPCs do not have acceptance around this crossing point, thus we will not find tracks which make the denominator vanish.

According to the analysis performed on the dE/dx distributions in momentum bins, the experimental error can be given as:

\[
\sigma_V = 0.425 \times (dE/dx_V)^{0.625}/\sqrt{N_V - 0.343 N_{V11}}
\]

\[
\sigma_M = 0.375 \frac{b^V_p - b^V}{b^M_p - b^M} (dE/dx_M)^{0.625}/\sqrt{N_M}
\]

where \(N_{V11}\) is the number of clusters found in the sector 1 or 4 of the Vertex-1 TPC (having shorter pads). The global dE/dx and its error will be:

\[
dE/dx_G = \frac{dE/dx_V \sigma^2_M + dE/dx_M \sigma^2_V}{\sigma^2_V + \sigma^2_M}
\]

and \(\sigma_G = \frac{\sigma_1 \sigma_2}{\sqrt{\sigma^2_1 + \sigma^2_2}}\).

Finally, in Fig. 45 we present a scatter plot of the calibrated proton+proton data, the dE/dx values of the tracks as a function of the momentum (positives and negatives together), together with the Bethe-Bloch functions for protons and pions. Kaons can be seen between these two species.
If we select a narrow momentum bin and collect the dE/dx values into a histogram (Fig. 46), a more qualitative picture emerges. By an appropriate fit method, the histogram can be compared to a function representing all our knowledge about the TPCs, and the abundance of different particles can be measured - at least statistically, not track by track. The achieved 3.04% resolution is even better than the design expectation (around 4%).

Fig. 45: Ionization vs. momentum of the tracks produced in proton-proton collisions, together with the Bethe-Bloch functions.
Fig. 46: dE/dx distribution in a selected momentum bin around 10 GeV/c.
6. Particle identification, spectra

There are different applications of the measured ionization, and the procedures applied on these data strongly depend on the physics goals. For example, when studying weak decays of strange particles, like the \( \Lambda \) and \( \Xi \) baryons, one should look for decay vertices far from the target, i.e. two particles pointing geometrically to the same vertex point (not at the target position). Afterwards, one is interested in what kind of particles are the decay daughters, and identifies them with the help of the dE/dx vs. \( \log(p) \) scatter plot (see Fig. 45): a narrow band around the pion Bethe-Bloch function include mostly pions, and depending on the definition of this window, a chance for a pion to fall inside it can be calculated, and selective cuts can be applied keeping only daughters which are pion candidates etc.

There are other applications where the above simple selection is sufficient, and it is also ideal for fast checks on some results obtained in a more complicated and more precise way.

In the following, we will concentrate on particle spectra, where one needs to develop a more adequate, quantitative way of particle identification.

We will summarize the steps which lead to the particle spectra. First, one should discuss the fit method used to extract the ratios of particle types in a momentum space bin, than the definitions of phase space factors and their derivation from the data, which lead to physical quantities. Certain corrections need to be applied afterwards, both connected to the detector operation, and to the physical meaning of the results. One should mention the calculation of the trigger cross section, which completes the procedure for the analysis of particle spectra. Finally, the available data sets of the NA49 experiment on hadronic collisions will be overviewed.

6.1 dE/dx fits

The first important step towards spectra is to obtain particle ratios in a certain (momentum) bin, that is, a percentage contribution of different species to the entries in a histogram like Fig. 46.

The ionization depends on the ratio of the mass and the total momentum \( p \) only \( (\beta \gamma = p/mc) \), thus the natural variables to bin the data are total momentum (magnitude of the three-momentum vector) and – because of the cylindrical symmetry of the collision – the transverse momentum \( (p_T) \). Apart from \( (p, p_T) \) bins, one can use other variables to subdivide the data, depending on the detailed goal and practical considerations of the analysis. Here we assume we have already a selected momentum space bin, and an ionization histogram.

Let the mean momentum of the tracks in our bin be \( p_0 \). The Bethe-Bloch values corresponding to \( p_0 \) are known, these are the expected peak positions in the dE/dx histogram. The actual peaks can deviate by a small amount \( (\approx 1\%) \) with respect to them. The aim is twofold:
• For a given peak position set, obtain the best fit of the amplitudes. This can be done without fit (in a usual sense), and errors are easily derived.
• Optimize the positions of the peaks for the four particles, and a common width parameter of the histogram. These are 5 parameters, and they can be fit by an automatic minimizing software package (like MINUIT), but we will prefer an alternative way to be discussed.

6.1.1 Histogram, fit function

Let us first fix the peak positions \((x_j, j=1..4)\) and concentrate on the amplitude fit. To the four particle species \((e, \pi, K, p)\), four amplitudes \(A_k\) \((k=1..4)\) should be assigned, where \(A_k\) denotes the (estimated) number of particles in our \(dE/dx\) histogram.

At first, we build the measured histogram \((M^i, i=1..N\) where \(N\) is the number of bins) by collecting \(dE/dx\) values of our tracks. The Bethe-Bloch functions (at the relativistic rise) increase with momentum, and our momentum bin is not infinitely small. We can avoid smearing our histogram artificially, by applying a small correction before the binning:

\[
dE/dx_{\text{part.}} \rightarrow dE/dx_{\text{part.}} + b_n(p_0) - b_n(p_{\text{part.}}).
\]

In addition to the measured histogram, one should build a reference "lineshape" in the following way. We have seen that the error on the \(dE/dx\) measurement can be estimated, and for each track we know its \(dE/dx\) and its error \(\sigma_{dE/dx}\) (in a Gaussian approximation). We know as well that \(\sigma_{dE/dx}\) increases with \(dE/dx\) as a power law. We can therefore construct the reference lineshape for imaginary particles having the \(dE/dx\) equal to our peak positions \(x_j\), by generating a Gaussian distribution \(G_{\sigma_j}^x = \exp[-(x - x_j)^2/2\sigma_j^2]/2\pi\sigma_j\) with mean \(x_j\) and the corrected width

\[
\sigma_j = (x_j/[dE/dx])^{0.625}\sigma_{dE/dx}.
\]

By adding up these Gaussians (one for each particle) with different widths, we get a non-Gaussian, though symmetric line shape function for the 4 particle species\(^{19}\), with the means \(x_j, j=1..4\). These \(p_j^x\) functions are histogrammed similarly to the measured histogram and normalized: \(\sum_{i=1}^N p_j^x = 1\ \forall j\) (lower indices run over the particle species, upper ones over the \(dE/dx\) bins).

\(^{19}\)A non-Gaussian treatment was also developed and used: for a given \(N\) number of clusters on a track, the probability density function of the truncated mean of the cluster charges will not be Gaussian, only in the \(N \rightarrow \infty\) limit, but a skew function with longer upper than lower tail. However this is only relevant for tracks shorter than \(N \approx 30\) and for the sake of simplicity we do not discuss any further details about this method, which involves some simulation work and creation of extended look-up tables.
6. PARTICLE IDENTIFICATION, SPECTRA

6.1.2 Fit of the amplitudes

We want to fit the $A_i$ particle abundances so that the fit function $T^i = \sum_{j=1}^{N} A_j \hat{p}_j^i$ describes the measured histogram $M^i$ with a minimal $\chi^2$:

$$\chi^2 = \sum_{i=1}^{N} \frac{(T^i - M^i)^2}{\sigma_{i^2}}$$

where (from now on) $\sigma^i$ refers to the counting error of the content of the $i^{th}$ bin in the measured histogram (in Gaussian approximation $\sigma^i = \sqrt{M^i}$). The $\chi^2$ should have a minimum in $A_k$ (k=1..4):

$$\frac{\partial \chi^2}{\partial A_k} = 2 \sum_i \frac{1}{\sigma_{i^2}} (T^i - M^i) \hat{p}_k^i = 0.$$  

We can separate the two terms to the two sides of the equation and substitute the definition of $T^i$:

$$\sum_{i,l} \frac{A_l \hat{p}_l^i \hat{p}_k^i}{\sigma_{i^2}} = \sum_i \frac{M_i \hat{p}_k^i}{\sigma_{i^2}}.$$  

Let us denote the right side by the vector $V_k$, and the left side by $m_{k} A_i$, defining the symmetric matrix $m$ matrix by $m_{k} := \sum_i \hat{p}_l^i \hat{p}_k^i / \sigma_{i^2}$.

An element of the $V$ vector represents how the measured histogram and a lineshape for a given particle species overlap, while the $m$ matrix is the overlap matrix of the lineshapes for different species. If we had extremely good resolution on dE/dx measurement, the species would not overlap and $m$ would be diagonal. This is not the case, and what we have is a real matrix equation:

$$m_{k} A_i = V_i$$

with a solution

$$A_i = m_{k}^{-1} V_i.$$  

The matrix inversion can be carried out numerically in all practical cases. The result is the $A_i$ particle abundances in our histogram.

It is easy to show that the inverse error matrix happens to be identical to $m$. Since

$$\chi^2 = \sum_{i} \frac{1}{\sigma_{i^2}} (\sum_k A_k \hat{p}_k^i - M^i)^2,$$

one can construct the inverse error matrix by derivation:

$$\frac{\partial}{\partial A_j} \chi^2 = \sum_i \frac{1}{\sigma_{i^2}} (\sum_k A_k \hat{p}_k^i - M^i) \hat{p}_j^i$$

$$\frac{\partial^2}{\partial A_i A_j} \chi^2 = \sum_i \frac{1}{\sigma_{i^2}} \hat{p}_l^i \hat{p}_j^i \equiv m_{ij}.$$
This means, that the error matrix of $A_k$ is $m_{ij}^{-1}$, which we had to calculate anyway to obtain the result. The error of $A_k$ will be $\sqrt{m_{kk}^{-1}}$. For example, if there was no overlap between particles (diagonal $m$), it would be simply, as expected,

$$1/\sqrt{\sum_i p_k^i / \sigma_{ik}^2} \approx 1/\sqrt{\sum_i p_k^i / (A_k p_k^i)} = \frac{1}{\sqrt{1/A_k (\sum_i p_k^i)}} = 1/\sqrt{1/A_k} = \sqrt{A_k}$$

where we used that $p_k^i$ is normalized and $\sigma_{ik}^2 \approx A_k p_k^i$.

So far we did not really discuss the $\sigma^i$ errors of the bins. We can define $\chi^2$ as the contribution of the $i^{th}$ bin to the $\chi^2$ and express $\sigma_{ik}^2$ with it:

$$\chi^2 = \sum_i \chi^2_i = \sum_i \frac{(T_i^i - M^i)^2}{\sigma_{ik}^2} \rightarrow \frac{1}{\sigma_{ik}^2} := \frac{\chi^2_i}{(T_i^i - M^i)^2}$$

For $\sigma^i$ usually one takes the square root of the content of the bin ($\sigma_{ik}^2 \approx M^i$) when calculating the actual $\chi^2$ for a given fit. However, for small number of counts in a bin, the $\chi^2$ should be calculated in different way, since the counts distribute according to the Poissonian, not the Gaussian distribution. We can take for all (small and large) number of counts the formula suggested by [62]:

$$\chi^2_i := 2(T_i^i - M^i) + 2M^i \log(M^i/T^i)$$

(in case of $M = 0$, only the first term remains). This gives back the above usual result in the $T \approx M \gg 1$ limit (we omit the $i$ indices now). Let us define $\varepsilon \ll 1$ as $\varepsilon T := T - M$. In the usual way

$$\chi^2_{\text{usnu.}} = \frac{(T - M)^2}{\sigma^2} \approx \frac{(T - M)^2}{T} = \frac{\varepsilon^2 T^2}{T} = \varepsilon^2 T.$$ 

Since

$$\log \left( \frac{M}{T} \right) = \log \left( \frac{T - (T - M)}{T} \right) = \log(1 - \frac{\varepsilon T}{T}) = \log(1 - \varepsilon) \approx -\varepsilon - \frac{\varepsilon^2}{2},$$

our proper $\chi^2$ will become in the above limit

$$\chi^2 = 2(T - M) + 2M \log(M/T) = 2\varepsilon T + 2M(-\varepsilon - \frac{\varepsilon^2}{2}) = \varepsilon^2 T(1 + \varepsilon) \approx \varepsilon^2 T.$$ 

Therefore we use this, more general $\chi^2$ instead of the usual one.

The definition of the $m$ matrix implicitly contains the $A_k$ variables (in $\sigma_{ik}^2$), which are initially unknown. Therefore an iterative procedure is carried out, which converges extremely fast (after a few steps): $A_k \rightarrow \sigma_{ik} \rightarrow m \rightarrow m^{-1} \rightarrow A_k'$ and so on.

6.1.3 Fit of the peak positions

In the last section, we showed how to get the particle abundances for fixed set of $x_j$ peak positions. There is one more parameter to optimize, an overall width correction to our lineshapes.
It is always small, at most a few percent, which shows how precisely the error on the dE/dx of the tracks have been obtained before.

There are two different approaches which could be used in the fit of these 5 parameters.

The first is to compute the above $\chi^2$ expressed with the 5 parameters, and minimize this function in the five dimensional space. This cannot always be done, the resolution of the dE/dx measurement is not good enough to allow a stable minimization. This depends mainly on the relative abundance of the particles as well as on the total number of entries in the bin, therefore applies only in certain regions of momentum space.

To improve the situation, one needs to impose certain further constraints on the fit. Such an extra condition can be physical, like the symmetry of the particle production in a symmetric collision (like p+p or A+A), or more technical, like to fix the mean dE/dx for kaons ($x_K$) between that of the pions and protons in the same proportion as it is in the Bethe-Bloch parametrization (this way the kaon peak position is not independent any more, but it is a function of the pion and proton positions). Another example is, when above a certain momentum one excludes the existence of electrons, taking into account that electrons are not produced by the primary interaction but later in the detector and cannot fake primary particles with arbitrary momenta. These constraints are clearly needed and prevent us to carry out a fully automatic data analysis.

The second method uses an automatic fit of amplitudes, but the peak positions are optimized one by one with a human control and inspection. This is mainly intended as a source of experience one could gain about the features

![Graph](image_url)

**Fig. 47:** An example of a dE/dx fit (p+p reaction, positive particles with 9.4 GeV/c lab. momentum). The $\chi^2$ values as a function of the variation of the peak positions is shown below. This is a clear case where we reached the minimum of $\chi^2$. 
and eventual deviations of the data, to be able to judge on the level of systematic errors, or devising sophisticated constraints for a more automatic method. It also helps for example realize if bigger bins should be chosen in momentum or azimuthal angle to increase statistics in a bin. A friendly interface helps to move these positions and immediately see the consequences in terms of $\chi^2$ (Fig. 47). The time needed for a fit in a bin is no more than a few minutes.

The $\chi^2$ values as a function of the parameters (if moved alone, with the other parameters fixed) are plotted after each step, and after some iteration the overall $\chi^2$ minimum is reached. An example of such a fit is shown in Fig. 47, where we have found that in proton-proton collisions around 9.4 GeV/c momentum, the fraction of different positive particle types in the histogram is 9.85% protons, 7.9% kaons, 81.5% pions and 0.75% electrons. Errors coming from the fit of the peak positions can be estimated to be no more than two times of the errors coming from the amplitude fit (discussed above).

The next step towards particle spectra is the derivation of the appropriate phase space factors to be combined with the already known abundances in the momentum space bin.

6.2 Phase space factors for spectra

We shortly summarize, what kind of kinematical variables we shall use and how certain physical quantities are obtained from the data.

6.2.1 Variables, quantities

We will be interested in quantities in the center of mass coordinate frame. A Lorentz transformation with the parameter $\gamma$ brings the momentum components from the laboratory frame to the center of mass:

$$\begin{pmatrix} E \\ p_L \end{pmatrix} = \gamma \begin{pmatrix} 1 & -\beta \\ -\beta & 1 \end{pmatrix} \begin{pmatrix} E_{lab} \\ p_{L,lab} \end{pmatrix} \quad \text{and} \quad p_T = p_{T,lab}$$

where $p_L$ is the momentum component parallel to the beam, and $p_T$ is perpendicular to it. If a beam particle (with mass $m_1$) and a target ($m_2$) collides, we get $\beta = p_{lab}^{beam}/(m_2 + E_{lab}^{beam})$. At our 158 GeV/c beam momentum and proton target, this is practically the same for pion and proton beam. The $\gamma$ value is therefore $\gamma = 1/\sqrt{1 - \beta^2} = 9.2$ and the momenta of the approaching protons in the p+p reaction in the c.m. frame is $\beta \gamma m_{proton} = 8.58$ GeV/c, the total center of mass energy being $\sqrt{s} = (m_1^2 + m_2^2 + 2m_2E_{lab}^{beam})^{1/2} = 17.22$ GeV. We use the same Lorentz transformation in case of symmetric nucleus-nucleus collisions, and even in proton-nucleus collisions$^{20}$.

$^{20}$I did not take the mass of the heavy nucleus literally when calculating the boost to the center of mass
There are two simple possibilities to choose variables to parametrize the momentum space. The first one uses \((x_F, p_T, \phi)\), the second \((y, p_T, \phi)\) variables. The \(x_F = p_L/p_L^{max}\) is the Feynman-\(x\) variable, and \(p_L^{max}\) is the maximal allowed momentum for the particle\(^{21}\), \(p_T\) is the transverse momentum and \(\phi\) is the azimuthal angle in the cylindrical coordinate system. The \(x_F\) of a particle with \(p_L^{lab}\) longitudinal momentum and \(E^{lab}\) energy in the laboratory frame is \(x_F = (p_L^{lab}/\beta - E^{lab})/m_{\text{proton}}\). One apparently needs the particle mass (identification) to calculate \(x_F\).

The rapidity is defined as \(y \equiv \frac{1}{2}\ln \frac{E_{E+\nu}}{E_{E-\nu}}\) and it suffers only an additive translation under a Lorentz-boost applied on the momentum vector.

Both parametrizations have advantages and drawbacks, but finally the choice is largely a matter of taste. \(x_F\) have been used in the past decades in measurements verifying the idea of Feynman-scaling \([63]\) in hadronic reactions, and one might argue that it decouples \(p_T\) and \(p_L\) better than \(y\), which contains both of them in its definition. In rapidity, it is more difficult to study the phenomena at high (and close to beam) momenta, but more appropriate for certain studies in the central region, and various theoretical approaches prefer to use it.

In Fig. 48 we illustrate the relation between the \(x_F\) and \(y\) variables and the \(p_T\) and \(p_L\) momentum components (both in the center of mass and the laboratory frame). The aim was to point out the difference how \(x_F\) and \(y\) bins sample the momentum space.

### 6.2.2 Inclusive invariant cross sections

According to the common practice, we will quote cross sections in a Lorentz-invariant form, that is

\[
\sigma^{inv} = E \frac{d^3\sigma}{dp^3} \equiv \frac{E}{p_T} \frac{d^3\sigma}{d\phi dp_T dp_L},
\]

in any coordinate frame. This can be expressed by different set of variables\(^{22}\):

\[
E \frac{d^3\sigma}{dp^3} \equiv \frac{E}{p_T p_L^{max}} \frac{d^3\sigma}{d\phi dp_T dx_F} \equiv \frac{1}{m_T} \frac{d^3\sigma}{d\phi dm_T dy},
\]

where \(m_T\) denotes the transverse mass, \(m_T \equiv \sqrt{m^2 + p_T^2}\). For example, if we select tracks from the data in an \(x_F\) (assuming, say, a proton mass for each particle) and \(p_T\) bin, we have \(N\) system, since at this energy the proton typically does not interact with the nucleus as a whole. However using the \(p+p\) boost provides a good basis of comparison with the \(p+p\) and \(A+A\) data. This way, the \(p+A\) "center of mass\(^3\) system will represent a situation where a proton beam has the same momentum as a proton inside the nucleus.

\(^{21}\)This would be in principle the beam momentum (in the c.m. frame), but one usually takes into account the conservation laws in a few body final state which can decrease this value. For \(\sqrt{s} \to \infty\) (already for our beam energy), \(p_L^{max} \approx \sqrt{s}/2\).

\(^{22}\)This can be checked simply by introducing the new variables and applying the corresponding Jacobian determinants.
Fig. 48: Illustration of $x_F$ (upper panels) and $y$ (lower panels) variables for protons in a p+p reaction with 158 GeV/c beam momentum. Constant $x_F$ and $y_{cm}$ lines are drawn on the $(p_T^{lab}, p_T)$ (left side) and on the $(p_T^{cm}, p_T)$ plane (right side).

particles in total with $E^i$ energy and $p_T^i$ transverse momentum in the c.m. frame (i=1..N), and our bin width is $\Delta x_F$ and $\Delta p_T$, and we have $N_{ev}$ events in our data sample and a $\sigma_{\text{trig}}$ trigger cross section, and we measured (fitted using a dE/dx histogram) that the fraction of protons is $F_{prot}$ (0<$F_{prot}$<1), the invariant production cross section will be

$$\sigma^{inv}_{prot} = \frac{F_{prot} \sum_{i=1}^{N} E^i / p_T^i}{2\pi p_T^{max} \Delta x_F \Delta p_T N_{ev} \sigma_{\text{trig}}}$$

Note that $\sum_{i} E^i / p_T^i$ has to be calculated, and not $N \sum_{i} E^i / \sum_{i} p_T^i$. The reason is simple: imagine a $p_T$ bin between 0 and $p_T^0$, where $\sigma^{inv} \approx \sigma_0 =$ constant and $E^i \approx$ constant, thus the number of particles in any $p_T$ bin is $N_{p_T} \propto p_T d p_T$. If we calculate $\sigma^{inv}$ from the data in a correct way, we get back $\sigma_0$ (since $1 / \Delta p_T \int_0^{\Delta p_T} \frac{1}{p_T} p_T^{N_{p_T}} = 1 / \Delta p_T \int_0^{\Delta p_T} d p_T = 1$), but in a wrong way we obtain $3\sigma_0/4$ (because $N^2 / \Delta p_T / \int_0^{\Delta p_T} p_T d p_T N_{p_T} = (\int_0^{\Delta p_T} p_T d p_T)^2 / \Delta p_T / \int_0^{\Delta p_T} p_T^2 d p_T = 3/4$).

In the end, we have two possibilities to present invariant cross sections as a function of,
say, $x_F$ and $p_T$: either by selecting tracks in $(x_F, p_T)$ bins, and apply the formula above, or by using other binning, like $(p^{lab}_T, p_T)$, calculate the invariant cross section using the appropriate Jacobian determinant, and transforming the location of the bin from the $(p^{lab}_T, p_T)$ plane to the $(x_F, p_T)$ plane (since the value of the invariant cross section does not depend on the reference frame). In the second case, a trivial (1 dimensional) Jacobian has to be applied, yielding the transformation (all quantities are in the laboratory frame):

$$\frac{\partial p_L}{\partial p} = \frac{\partial (p^2 - p_T^2)}{\partial p} = \frac{p}{\sqrt{p^2 - p_T^2}} = \frac{p}{p_L} \Rightarrow \frac{1}{dp_L} = \frac{p_L}{p} \frac{1}{dp};$$ therefore

$$\sigma^{inv} = E \frac{d^3\sigma}{dp^3} = E \frac{d^2\sigma}{2\pi p_T dp_T dp_L} = E p_L \frac{d^2\sigma}{2\pi p_T dp_T dp}.$$

### 6.2.3 Number densities

In many cases it is useful to present results in particle number densities like $dN/dx_F$ or $dN/dy$ per event (collision). The integral of these distributions over the full $x_F$ or $y$ range gives the total number of particles produced in a reaction.

In case of central Pb+Pb (or central p+Pb) collisions, for example, the notion of "event" is unambiguous: all central collisions produce such response in the trigger and detector system, that it passes the necessary conditions to be recorded, and no such event will be lost for the analysis. However, in case of the the proton-proton collisions, there are many events where the two protons interacted (they should be counted in the total cross section) but the momentum transfer is small, and the scattered protons hit the veto detector in the trigger system (indicating "no interaction") or they miss the TPC volumes (recall the large gap between the TPCs necessary because of measurements with lead beam) and the event reconstruction does not provide useful data for this reaction.

Evidently, the detector will see only a (large) part of the inelastic cross section, where more particles are produced with smaller momenta, and a (small) part of diffractive cross section, but it will miss most of the elastic scatterings. All this has two consequences:

- the trigger cross section has to be calculated for proton-proton collisions to have any physical result concerning particle spectra,
- one should choose a standard "event" as a reference when presenting some quantity per event.

Our choice will be the *inelastic event*: we will take this as a reference when presenting results. We assume, that none of the vetoed and not reconstructed events would contribute into the momentum bins where we have measured cross sections (that is, they are not appearing in the geometrical TPC acceptance). Thus, for example, the proton production cross section
in an $x_F$ bin is (using the notations of the last section):

$$\frac{d\sigma_p}{dx_F} = \frac{F_{prot}N}{N_{ev}\Delta x_F}\sigma_{trig}$$

and since the inelastic cross section is $\sigma_{inel}^{tot}$ (known from other measurements and compilations, tables), the number density of protons per (inelastic) event will be

$$\frac{dN_p}{dx_F} = \frac{F_{prot}N}{N_{ev}\Delta x_F}\sigma_{trig}^{tot}/\sigma_{inel}^{tot}.$$  

The typical (proton-proton) trigger cross section for our liquid hydrogen target is 28.5 mbarn, while the inelastic cross section is 31.62 mbarn and the total cross section is 38.55 mbarn at 158 GeV/c beam momentum.

### 6.3 Trigger cross section

We briefly summarize the calculation of our trigger cross section for proton-proton data.

The interaction cross section is defined by a general formula expressing a number of interactions in an intersection region of two beams:

$$dN_{int} = \sigma_{int}n_1n_2 | \vec{v}_1 - \vec{v}_2 | dVdt,$$

where $dN_{int}$ is the number of interactions in the volume element $dV$ and during a time interval $dt$, $n_1$ and $n_2$ are the beam densities (number of particles in the unit volume) and $\vec{v}_1$, $\vec{v}_2$ are velocities of the beam particles, finally $\sigma_{int}$ is the cross section of the interaction.

In our experiment the beam with velocity $v$ and density $n_1$ collides with a fixed target with $n_2$ density. Integrating over the homogenous interaction region, we obtain

$$\Delta N_{int} = \sigma_{int}n_2n_1vS\lambda dt$$

where $S$ is the surface, $\lambda$ is the length of the target, $n_1v$ is the beam flux, $n_1vS$ is the number of beam particles traversing the target in a unit time interval. Integrating over the measurement time, one can express $\sigma_{int}$:

$$N_{int} = \sigma_{int}N_{beam}n_2\lambda \rightarrow \sigma_{int} = \frac{1}{\lambda n_2} \frac{N_{int}}{N_{beam}},$$

$N_{beam}$ being the total number of beam particles.

We give an example of an application of the above formula to our conditions. In NA49, there are two scintillator counters used as a trigger for proton-proton collisions. The first is placed in front of the target in order to detect beam particles, the second counts protons penetrating the target without interaction, working in anticoincidence. The $\sigma_{trig}$ trigger cross
section measures the probability of a specific interaction; an interaction which satisfies the above trigger condition.

The target density $n_2$ can be expressed with the $N_A$ Avogadro constant, $\rho$ density and $A$ atomic molar weight of the target: $n_2 = N_A \rho / A$. Thus $\sigma_{\text{trig}}$ can be obtained from the $N_{\text{trig}}$ number of triggers and $N_{\text{beam}}$ number of beams:

$$\sigma_{\text{trig}} = \frac{A}{\rho \lambda N_A} \frac{N_{\text{trig}}}{N_{\text{beam}}}.$$

An example of the mean $N_{\text{trig}}/N_{\text{beam}}$ ratio was 2.476%. Part of these triggers were caused by interactions with the walls of the target and other materials. By emptying the target volume, and measuring only these interactions, we got a trigger rate of 0.77%. We can refine our last formula to include this information, finally giving the real trigger cross section:

$$\sigma_{\text{trig}} = \frac{A}{\rho \lambda N_A} \left( \frac{N_{\text{trig}}}{N_{\text{beam}}} \text{full} - \frac{N_{\text{trig}}}{N_{\text{beam}}} \text{empty} \right).$$

With $\rho = 0.07$ g/cm$^3$, $\lambda = 14$ cm, $A = 1$ g/mol and $N_A = 6.022 \times 10^{23}$ mol$^{-1}$ this formula gives $\sigma_{\text{trig}} = 2.89 \times 10^{-26}$ cm$^2 = 28.9$ mbarn.

A small Monte-Carlo study has been performed to estimate the part of elastic and diffractive cross section rejected by the trigger. Elastic events have been generated according to a $d\sigma_{\text{el}}/dt \propto e^{-11t}$ law, and diffractive events were approximated by the $d\sigma_{\text{el}}/dt \propto e^{-6.5t}$ dependence$^{23}$. Scattered protons were tracked through the magnetic field and rejection rate of the trigger has been estimated to be $\approx 80\%$ for elastic and $\approx 60\%$ for diffractive events. Taking the $\sigma_{\text{el}}^{\text{tot}} = 7$ mbarn and $\sigma_{\text{diff}}^{\text{tot}} \approx 6.5$ mbarn estimates, the total rejection was $\approx 9.5$ mbarn. Together with $\sigma_{\text{trig}} = 28.9$ mbarn, we get $\approx 38.4$ mbarn for the total cross section, to be compared with the table value of 38.55 mbarn. This rough estimation verifies that the difference between $\sigma_{\text{tot}}$ and $\sigma_{\text{trig}}$ can be properly accounted for.

### 6.4 Corrections

One should mention the types of corrections which are relevant for particle spectra. The first one is the geometrical acceptance of the TPC system, which limits the momentum space region where particle tracks can be reconstructed. The second is a correction related to the finite size of the $H_2$ target and the resolution of the vertex (interaction) point reconstruction. Finally we discuss a more physical correction for the particles not produced primarily, but being daughters of weakly decaying ones.

---

$^{23}$t is a Mandelstam variable defined as $(p_1 - p_2)^2$ where the four-momentum of the beam proton is $p_1$ before, and $p_2$ after the scattering.
### 6.4.1 Acceptance and efficiency

The acceptance of the NA49 TPC detectors is determined from the data itself. The momenta of the tracks in the data span a momentum space region which corresponds to the sensitive volume of the chambers. The acceptance can be looked up from a table constructed from this information, and by specifying the momentum vector and charge of the track, it gives the value of the number of pad-rows the track is expected to cross in the TPC. This should be close to the number of clusters on the track, since one cluster is normally found in each pad-row. This number is in turn related to the precision of the dE/dx measurement for the given track, therefore regions of "good" dE/dx resolution can be identified immediately. Tracks crossing the sensitive volume have practically 100% chance to be reconstructed in p+p, p+A reactions (except edge effects). There are two simple methods to use the acceptance table:

- one can select momentum regions where the acceptance is 100%, and constrain the analysis to use only this region
- based on the azimuthal symmetry, average the acceptance between $\phi = 0^\circ$ and $360^\circ$ in a certain $(p, p_T)$ bin, and divide the total number of found particles by this average.

![Graph of geometrical acceptance of TPCs for protons](image)

**Fig. 49**: Geometrical acceptance of the TPCs for protons, averaged over the azimuthal angle. The area of the boxes is proportional to the acceptance. At $x_F < 0.1$, the identification via dE/dx is not possible because of the crossing of Bethe-Bloch functions for protons and pions.

The second method has certain difficulties, since the decay products of strange particles (like a proton from a $\Lambda$ baryon) seem to come from the primary interaction point (main vertex) with some probability. This chance however is not azimuthally symmetric in the momentum space, and a precise angle dependent correction would complicate the analysis.
For some correlation studies the acceptance correction departs from these trivial considerations.

Fig. 49 shows the geometrical acceptance for (anti)protons, averaged over the azimuthal angle, in \((p_T, p_T^L)\) and \((p_T, x_F)\) variables. At least 30 clusters are required for the tracks. One should note that even if there is geometrical acceptance backward of the center off mass \((X_F < 0)\), the intersection of the Bethe-Bloch functions for protons and pions makes the identification via \(dE/dx\) not feasible below \(x_F \lesssim -0.1\).

The efficiency correction is much different in a low and a high track density environment. For Pb+Pb reactions, tracks are embedded artificially into real events, and the whole event is reconstructed again; then the probability to find the embedded track is obtained in bins of momentum space. The method is computationally rather expensive.

A different strategy can be followed in p+p, p+A collisions, since in this case there are almost no losses of tracks in the reconstruction. Much stronger quality measures can be applied, and the tracking efficiency can be improved much easier. After the final tracking software for p+p and p+A reactions became available, an extended eye-scan has been performed to assure tracking quality and discover eventual problems. It was found that the deviation of the efficiency from 100% is on the percent level (inside the geometrical acceptance), therefore no further simulation effort was needed to produce corrected results.

### 6.4.2 Target correction

There is a correction which is relevant only in case of low multiplicity reactions (p+p, p+A), and connected to events not reconstructed properly (we will discuss the example of p+p collisions). The event reconstruction efficiency depends on the multiplicity\(^{24}\), since the main vertex (interaction point) cannot be always reconstructed by extrapolating a small number of tracks to the target position. One should account for these lost events, which do not enter the subsequent analysis.

The NA49 \(H_2\) target is a cigar shaped 20 cm long mylar\(^{25}\) vessel filled by liquid hydrogen. To avoid interactions of beam and mylar or other material in the beam line, we apply a geometrical cut on the \(z\) position of the reconstructed vertex (\(z\) is the direction of the beam), and discard events with vertex outside a 18 cm long window, thus limiting the contamination of this background to the 1% level.

The smaller multiplicity our event has, the worse vertex resolution is observed, and the more

---

\(^{24}\)And on other event characteristics as well. For example, an event with two slow tracks in the magnetic field will be reconstructed easier than an event with one fast (seen outside the field) and one slow track. We discuss here only the dependence on multiplicity (number of charged tracks).

\(^{25}\)The composition of mylar is 63% C, 33% O, 4% H
events get lost due to this vertex cut, as Fig. 50 shows. We have to correct for triggered events having no detected tracks in the TPCs ("zero prongs"), which do not go into the analysis but increase the trigger cross section.

The following steps are needed to calculate the correction factors:

- From the empty target (ET) and full target (FT) trigger rates, a proper normalization of the two contributions has to be obtained, in each multiplicity bin. (The empty target events are mostly p+C and p+O collisions, where the beam hits the mylar windows of the target, and p+p and p+C(O) collisions have different multiplicity distributions.)

- From the subtracted FT−ET vertex-z distribution, the number of real p+p events outside and inside the cuts can be determined, and the correction for the vertex "smearing" can be obtained.

- From the comparison of multiplicity distributions of FT−ET and the smearing corrected events used in the analysis (with at least 1 track) the event reconstruction efficiency can be determined as a function of multiplicity. Similarly, the above mentioned "zero prong correction" can be derived from the number of events in this histogram with 0 tracks (this is a special case of the reconstruction "efficiency").

The number of real p+p interactions can be expressed by the \( w \) vertex corrections and number of events used in the analysis, in multiplicity bins:

\[
N_{p+p\,evts}^{\text{mult.}} = N_{\text{evts in analysis}}^{\text{mult.}} \times w(\text{mult.})
\]

where \( w(\text{mult.}) \) is the final correction factor: the combination of smearing and reconstruction efficiency corrections.

In the analysis, all tracks should be weighted by this correction, corresponding to the event (multiplicity) the track belongs to. On the number of events not only these weights should be applied, but the zero prong correction (\( C_0 \)) as well. This means that the calculation of invariant cross section has to be modified. Taking our earlier example of an \((x_F, p_T)\) bin:

\[
\sigma^{\text{inv}}_{p_T} = \frac{F_{p_T} \sigma_{\text{trig}}}{2 \pi p_T^{\text{max}} \Delta x_F \Delta p_T} \frac{\sum_{i=1}^{N} E_i / p_T^i}{N_{ev}} \Rightarrow \sigma^{\text{inv}}_{p_T} = \frac{F_{p_T} \sigma_{\text{trig}}}{2 \pi p_T^{\text{max}} \Delta x_F \Delta p_T} \frac{\sum_{i=1}^{N} w(m^i) E_i / p_T^i}{C_0 \sum_{j=1}^{N_{ev}} w(m^j)}
\]
where $w(m')$ is the correction factor for an event with $m'$ multiplicity, and $N_{ev}$ is the total number of events in our data sample.

An example of the correction factors (for p+p reaction) can be seen in Fig. 51.

In case of $p+A$ collisions, the Centrality Detector was included in the trigger, to be able to collect reasonable statistics of very central events as well. For all trigger conditions, empty target runs were recorded, and similarly, the correction factors calculated. Different correction tables for the various collision centralities have to be used.

For $d+p$ collisions, events with proton spectator have been identified in the Veto Proportional Chamber and the Ring Calorimeter; these events are neutron-proton interactions. The vertex corrections can be calculated for these events in a similar way.

6.4.3 Feed-down from weak decays

A significant complication of measuring particle spectra (like $p, \pi$) is that some of these particles can be daughters of other, weakly decaying ones (like $\Lambda, \Sigma, K^0$), and we do not want to include these in the spectrum. Opposed to former spectrometer experiments with long arms, where most of these daughters have been detected, in NA49 only a fraction of these are reconstructed on vertex (looking like particles from the interaction). The probability of finding these cases depends on the complicated details of the geometrical acceptance and the momentum distribution of the daughter particles as well as on the reconstruction software, the conditions to assign a track to the main vertex, and different cuts applied. Therefore, two steps have to be taken to estimate this feed-down correction:

- An estimate of the relevant parent particle ($\Lambda, \Sigma$ etc.) spectra should be constructed. These can be collected from publications of earlier experiments or measured within NA49. Where none of these could be found, some assumptions are made.

- Calculating the probability that a parent particle will decay into $p, \bar{p}$ daughters which will be later reconstructed and assigned to the main vertex (though coming from a subsequent
decay). This point involves a reconstruction of simulated events containing the relevant parent particles.

For the first point, available data have been collected on momentum distributions, and the VENUS event generator was used to obtain detailed $p_T$ distributions.

For the second point, the decaying particles were tracked through the TPCs using a GEANT code applied to the NA49 detectors, and these events were reconstructed using the same software as in the real data, applying the same cuts.

It was found (as expected) that the feed-down contamination does not reflect the azimuthal symmetry in the momentum space (due to the detection and reconstruction effects), therefore a $\pm 50^\circ$ window\textsuperscript{25} was selected in the $\phi$ azimuthal angle to evaluate the correction. This implies that in the data analysis one should use the same selection for consistency.

Different reactions and beam energies studied by the NA49 experiment requires the estimation of these feed-down corrections in each case. Fig. 52 shows an example for 158 GeV/c $p + p$ interactions.

The following channels have been considered contributing to the $p, \bar{p}$ spectra (in $p + p$, $\pi^- + p$ and $\pi^+ + p$ interactions): $\Lambda^0 \rightarrow p + \pi^-; \ \bar{\Lambda}^0 \rightarrow \bar{p} + \pi^+; \ \Sigma^+ \rightarrow p + \pi^0; \ \Sigma^- \rightarrow \bar{p} + \pi^0$.

\textsuperscript{25}The direction of 0$^\circ$ is by convention the horizontal bending direction of the magnets. In top view, it is to the right for negative, to the left for positive particles with respect to the downstream $z$ direction. Particles having $-90^\circ < \phi < 90^\circ$ are called good side tracks (the magnetic field bends them towards the same $x$ direction as they started out), the rest are wrong side tracks.

Fig. 52: An example of feed-down correction. Contributions of $\Lambda$ and $\Sigma$ decays to the measured $p$ (upper panel) and $\bar{p}$ (lower panel) spectra are shown in $p+p$ reaction at 158 GeV/c beam momentum, as a function of $x_F$. Only those (anti)protons are included, which were tagged by the reconstruction software as particles coming from the primary vertex. These spectra should be subtracted from the measured ones.
6. PARTICLE IDENTIFICATION, SPECTRA

Below we give a summary about the available experimental data and various assumptions used to construct these corrections in $p+p$ and $\pi+p$ interactions. We need the total multiplicity and the shape of the $x_F$ spectra of the weakly decaying particles we considered.

- In $p+p$ interactions, the $\Lambda$ cross sections are best known. From the $\sqrt{s}$ dependence in [64], one can estimate a total multiplicity of $n_\Lambda = 0.09/\text{event}$. [65] provides information on $\Lambda$ spectra at 360 GeV/c measured by the EHS experiment.

Antilambdas are much poorer measured; from [64], [66] (at 405 GeV beam energy), [67] (at $\sqrt{s} = 63$ GeV) one can conclude that $\bar{\Lambda}$ and $\bar{p}$ have similar $x_F$ spectra, and a total number of $n_\bar{\Lambda} = 0.013/\text{event}$ have been taken.

For $\Sigma^+$ we used [68] ($p+p$ data at 405 GeV beam energy) where a ratio of $n_{\Sigma^+}/n_\Lambda = 0.38$ was found. Keeping the same ratio for our 158 GeV beam energy, we assumed $n_{\Sigma^+} = 0.034/\text{event}$. As nothing is known about $\Sigma^-$, we assumed a spectrum similar to $\bar{\Lambda}$ and an absolute yield of $n_{\bar{\Sigma}^-} = 0.0049/\text{event}$ given by our $n_\Lambda/n_{\bar{\Lambda}} \approx n_{\Sigma^+}/n_{\bar{\Sigma}^-}$ assumption.

- For $\pi^\pm + p$ interactions, parametrizations for multiplicities of $\Lambda$, $\bar{\Lambda}$ can be found in [69] at 40 GeV/c beam momentum.

For $\Sigma^+$ and $\Sigma^-$ the same assumptions are used as in the $p+p$ case: $n_{\Sigma^+}/n_\Lambda = 0.38$ and $n_\Lambda/n_{\bar{\Lambda}} \approx n_{\Sigma^+}/n_{\bar{\Sigma}^-}$. The following multiplicities have been derived: $n_\Lambda = 0.072$, $n_{\bar{\Lambda}} = 0.020$, $n_{\Sigma^+} = 0.027$, $n_{\bar{\Sigma}^-} = 0.076$ per event at 158 GeV/c beam momentum.

- There are indications that $\Lambda$ spectra and multiplicities are similar in $\pi^+p$ and $\pi^-p$ interactions ([70], measured at 18.5 GeV/c beam momentum), thus we assumed they are the same. In [69], [71] (at 16 GeV/c beam momentum) and [72] (at 100, 200 and 360 GeV/c) one can find momentum distributions.

For the $\Sigma^+$ distribution we have chosen a distribution which is the same as in $p+p$ in the backward ($p$) hemisphere, and the same as $\Lambda$ in $\pi^\pm p$ reactions in the forward ($\pi^\pm$) hemisphere. For $\Sigma^-$, similarly to the $p+p$ reaction, the shape of the $\bar{\Lambda}$ distribution is used.

As a result, corrections are given in units of $dN/dx_F$ (Fig. 52). This represents the amount of (anti)protons misinterpreted by the software, as coming from the primary interaction, and it is to be subtracted directly from the measured $p$ and $\bar{p}$ $dN/dx_F$ spectra. Generally one can say that the correction for protons, relative to the total measured proton yield, as a function of $x_F$, reaches a maximum of $\approx 7.5\%$ for $p+p$ interactions and $\approx 11\%$ in $\pi^\pm + p$ interactions at 158 GeV/c beam momentum. Antiprotons receive bigger, a maximum of around 16% feeddown correction for all studied interactions. Since these corrections are relatively small, the systematic errors we make by applying these with all the assumptions made, are estimated to be less than $\approx 2\%$ in all cases.
All data on hadronic beams presented in this thesis are feed-down corrected. For more
detailed description of feed-down corrections in various interactions we refer to [73].

6.5 Available data sets

Finally, in Table 6 we summarize the data sets of NA49 which were taken so far, and the ion-
ization measurement was calibrated by the method described and developed in the framework
of the present thesis (most of them in year 2000).

They include several different beam and target types and different trigger conditions. The
largest event sample is collected in p+p and p+Pb events\(^{27}\). The number of events refers to
the 'clean' sample of events ready for analysis after all the selection cuts applied.

The interaction type in the first column gives the projectile (left) and the target particle
(right side). The trigger was either a minimum bias type (imposing as few constraints as pos-
sible, though a condition that an 'interaction' happened was always required) or we prescribed
a given number of hits in the Centrality Detector in case of nuclear targets. Reactions with 40,
100, 158 GeV/c beam momenta were studied.

The ionization measurements have been calibrated in more than 6 million events in total,
thus prepared for the use of particle identification in all kinds of physical analysis.

\(^{27}\)We do not include here Pb+Pb collisions which have been treated in a different way.
<table>
<thead>
<tr>
<th>collision</th>
<th>trigger</th>
<th>beam energy</th>
<th>year of meas.</th>
<th>number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>1996</td>
<td>417 708</td>
</tr>
<tr>
<td>p+p</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>653 982</td>
</tr>
<tr>
<td>p+p</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>2000</td>
<td>1 469 613</td>
</tr>
<tr>
<td>p+p</td>
<td>min. bias</td>
<td>100 GeV/c</td>
<td>1998</td>
<td>261 304</td>
</tr>
<tr>
<td>d+p</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>2000</td>
<td>472 047</td>
</tr>
<tr>
<td>d+p</td>
<td>min. bias</td>
<td>40 GeV/c</td>
<td>1999</td>
<td>239 153</td>
</tr>
<tr>
<td>π⁺+p</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>2000</td>
<td>639 134</td>
</tr>
<tr>
<td>π⁻+p</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>2000</td>
<td>447 327</td>
</tr>
<tr>
<td>p+Pb</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>64 376</td>
</tr>
<tr>
<td>p+Pb</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>33 243</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥1</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>224 884</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥2</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>246 619</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥2</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>63 875</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥3</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>35 214</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥4</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>18 134</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥7</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>287 421</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥7</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>57 341</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥2</td>
<td>250 GeV/c</td>
<td>1997</td>
<td>43 790</td>
</tr>
<tr>
<td>p+Pb</td>
<td>NCD ≥7</td>
<td>250 GeV/c</td>
<td>1997</td>
<td>23 549</td>
</tr>
<tr>
<td>π⁺+Pb</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>37 614</td>
</tr>
<tr>
<td>π⁺+Pb</td>
<td>NCD ≥1</td>
<td>158 GeV/c</td>
<td>1999</td>
<td>62 189</td>
</tr>
<tr>
<td>π⁺+Pb</td>
<td>NCD ≥2</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>50 525</td>
</tr>
<tr>
<td>π⁺+Pb</td>
<td>NCD ≥7</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>27 592</td>
</tr>
<tr>
<td>K⁺+Pb</td>
<td>NCD ≥1</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>2 830</td>
</tr>
<tr>
<td>p+Al</td>
<td>min. bias</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>38 817</td>
</tr>
<tr>
<td>p+Al</td>
<td>NCD ≥1</td>
<td>158 GeV/c</td>
<td>1997</td>
<td>68 077</td>
</tr>
<tr>
<td>C+C</td>
<td>central</td>
<td>158AGeV/c</td>
<td>1998</td>
<td>46 254</td>
</tr>
<tr>
<td>Si+Si</td>
<td>central</td>
<td>158AGeV/c</td>
<td>1998</td>
<td>53 682</td>
</tr>
<tr>
<td>Pb+Pb</td>
<td>peripheral</td>
<td>158 GeV/c</td>
<td>2000</td>
<td>1 419</td>
</tr>
</tbody>
</table>

Table 6: NA49 datasets, for which the ionization (dE/dx) have been calibrated by the method described in this thesis. Note the remarkable versatility of the collected information.
7. Results

7.1 Baryons in p+p and n+p interactions

7.1.1 $p$ and $\bar{p}$ spectra in p+p collisions

In the previous chapter we discussed all the main steps from the detector response to the various corrections of the data.

In this section we present longitudinal momentum spectra of protons and antiprotons in p+p and n+p collisions. Following the common practice of the similar experimental studies completed in the 1970's, we use the Feynman-x variable $(x_F = p_L/p_L^{max})$ to characterize the longitudinal momentum. It was predicted long time ago by Feynman [63], that at asymptotic beam energies, particle distributions approach an energy-independent function in this variable. We will present spectra at two beam energies (100 and 160 GeV), together with results of earlier experiments.

The momentum space was sliced in the laboratory frame to bins of $x_F$ (see Fig. 48), and particles with $p_T < 2 GeV/c$ were all included in the analysis. As the $p_T$ spectrum of the produced hadrons suffers a strong exponential cut-off, where the mean $p_T$ of the protons is around 500 MeV, the omitted particles contribute less than 0.5% of the above integral, which we can neglect.

Such acceptance region was chosen for the analysis in the TPCs, where in a given $x_F$ bin all particles with $0 < p_T < 2 GeV/c$ transverse momentum had more than 30 clusters (measured space and ionization points) on their trajectory, as given by the acceptance tables. Indeed, only typically less than 0.5% of the tracks in the bin failed to have this minimum number of clusters in the data, which has been regarded as a negligible amount, compared to the other experimental errors.

As discussed in the last chapter, the feed-down correction was calculated for an azimuthal angle bin of $\pm 50^\circ$ around the $x$ direction called "good side". Therefore, in cases where one had ample statistics (see Table 6 for details), like in p+p and p+Pb data at 158 GeV/c beam momentum, we used only this window for the analysis. In the other reactions, like in n+p, $\pi^+\text{Pb}$, $\pi^\pm p$ and in 100 GeV/c p+p, a slightly extended azimuthal angle window was used, to gain as much in statistics as possible for the fitting of the dE/dx distributions. These windows are illustrated in Fig. 53 as a function of $x_F$ of the protons. In these cases, the same feed-down corrections were used as in the $\pm 50^\circ$ wedge.

In case of the data with 100 GeV/c beam, the acceptance extends farther in the $x_F$ space, since the same magnetic field was set in the spectrometer. Note that below $x_F = -0.1$, the acceptance is still sufficient but the particle identification is not any more possible because of
Fig. 53: Acceptance windows in azimuthal angle used in the analysis of data sets with poorer statistics. Otherwise, a ±50° window was used. Note the difference of acceptance at the two beam energies.

the crossing Bethe-Bloch functions for different particles.

In Fig. 54, we present the proton and antiproton spectra after all the corrections in proton-proton collisions with 158 GeV/c beam momentum, for an average inelastic event. One should note that the symmetry axis is $x_F = 0$, and that we can not measure the diffractive peak of the proton spectrum above $x_F = 0.9$\textsuperscript{28}.

One can observe a remarkably flat proton momentum distribution, with a bump around $x_F = 0$ (midrapidity). This reflects the effect of baryon pair production: its shape is rather similar to the antiproton spectrum. One usually takes the $p - \bar{p}$ difference to obtain the net proton spectrum. The antiproton distribution cuts off exponentially rather than Gaussian-like. At $x_F = 0.4$ it reaches one percent of the central yield. At midrapidity, there are substantially more protons than antiprotons, their ratio being $\bar{p}/p = 0.227 \pm 0.009$.

7.1.2 $p$ and $\bar{p}$ spectra in n+p collisions

One can repeat the analysis for the neutron-proton events recorded by the NA49 experiment. Here the neutron is the beam and the proton is the target particle. A deuteron beam was shot on a liquid hydrogen target, and events with a proton spectator were selected, therefore only the neutron-proton collisions entered the analysis. The complicated trigger composed of the on-line interaction trigger for the $d + p$ interaction and the off-line selection of $n + p$ events resulted

\textsuperscript{28}The reason for this is that because of the data taking with heavy ion beams, one cannot close the gap between the TPCs in order to cover the full kinematical range, and the study of diffractive peak would need a modified trigger and reconstruction. But this peak was extensively measured during the past decades in other experiments.
in a 98% trigger efficiency of the $n + p$ interactions. This means that we recorded almost all elastic events as well. Particles from those events do not enter the detector acceptance, and we make these data comparable with the $p + p$ events by normalizing our spectra to the inelastic events (cross section) in both cases. Clearly, because of this slight difference in the trigger, the most reassuring procedure would be to select spectator neutrons from the $d + p$ events, and this way analyzing the $p + p$ events. This selection is not possible at the moment as cleanly as the proton spectator selection. Therefore we compare the $n + p$ events with $p + p$ events from proton beam data.

The neutron spectator was detected in the Ring Calorimeter behind the TPC system, and its energy was measured with a precision of 20-25%. Since the spatial separation of the proton and neutron spectators on the Calorimeter surface was smaller than a cluster of cells responding to a hit (due to the large cell size of the detector), the neutrons could be differentiated from the proton spectators only with the help of the new Veto Proportional Chamber, described in Chapter 4. Positive particles leave a substantial charge deposit in the Veto Chamber, allowing us to require such a signal for proton spectator candidates. Since the yield of positive particles other than proton spectators close to beam momentum is rather small, even the above energy resolution of the Calorimeter was sufficient to achieve a reliable proton spectator selection. The amount of events containing no proton spectator in the selected sample was estimated to be only 1% in [74]. The main source of this background are $p+p$ events with a diffractive proton
close to beam momentum and small (less than 150 MeV/c) $p_T$. The validity of the applied cuts was verified with a comparison to p+p events (with proton beam): only 1% of the true p+p events survive the requirements of detecting a "spectator" proton.

To summarize, this high energy neutron "beam" and the measurement of n+p collisions (in the n hemisphere) is a unique achievement and provides an indirect way to measure the n and π spectra in p+p collisions, as it will be shown.

The feed-down correction for the n + p interactions was estimated in the following way: in the backward (p) hemisphere, the corrections derived for p + p interactions have been used for the feed-down received by the p and π spectra. In the forward (n) hemisphere, the correction for the p spectrum was taken to be the same as for the p + p → n + X spectrum. Similarly, the correction for p + p → π + X was used for the n + p → π + X spectrum. This assumption is not necessarily valid, but gives a useful estimate.

To construct the feed-down corrections for the p + p → n + X, p + p → π + X spectra, we had to take into account the TPC acceptance. The TPC does not detect neutral particles, but now (in p + p) the n and π spectra play the role of the n + p → p + X and n + p → π + X spectra measured in the TPCs. Therefore, we should estimate how much of these n, π particles would be seen in the TPC system by geometrical acceptance, and how many of those would be reconstructed on the main vertex of the event.

Precisely the following information was available: the spectra of p and π particles originating from the Λ and Σ decays separately in p + p interaction, including the TPC acceptance and reconstruction effects, be denoted by Λ(p), Σ+(p) etc. We know the following branching ratios: Λ → pπ−(64%), Λ → nπ0(36%), Σ+ → pπ0(52%), Σ+ → nπ+(48%), Σ− → nπ−(100%), and similarly for the antiparticles. Thus, the spectra of n and π coming from these decays (and assuming TPC acceptance) has to be expressed with the above known quantities. Thus, the neutron correction reads:

$$\frac{36}{64} \Lambda(p) + \frac{48}{52} \Sigma^+(p) + \Sigma^-(n) \approx \frac{36}{64} \Lambda(p) + \frac{48}{52} \Sigma^+(p) + \frac{100}{52} \Sigma^+(p) \approx \frac{36}{64} \Lambda(p) + \frac{148}{52} \Sigma^+(p),$$

and the antineutron correction becomes

$$\frac{36}{64} \Lambda(\bar{p}) + \frac{48}{52} \Sigma^-(\bar{p}) + \Sigma^+(\bar{n}) \approx \frac{36}{64} \Lambda(\bar{p}) + \frac{48}{52} \Sigma^- (\bar{p}) + \frac{100}{52} \Sigma^- (\bar{p}) \approx \frac{36}{64} \Lambda(\bar{p}) + \frac{148}{52} \Sigma^- (\bar{p}).$$

The relative feed-down correction of neutrons is on the level of 10, for antineutrons 15 percent, thus even a 30% error in the above approximation causes only 3-5% error in the final result.\(^\text{29}\)

The results are presented in Fig. 55, where the larger error bars reflect the relatively low number of events remaining after the selection cuts for proton spectator (125k events, in contrast to the 2.5M p+p events).

\(^{29}\)A more precise feed-down correction calculation is still to be worked out, but even the above estimate was good enough to present these very new data with a reasonable precision.
Fig. 55: $p$ and $\bar{p}$ Feynman-$x$ spectra in neutron-proton collisions at 158 GeV/c beam energy, presented in both linear and logarithmic scale. The $dN/dx_F$ yields are given for an average inelastic event.

While the proton yield at $x_F = 0$ (midrapidity) is similar in $n + p$ and $p + p$ collisions, the antiproton spectra exceed that of the $p+p$ reaction, and is somewhat asymmetric. This indicates that the neutron beam produces more antiprotons than the proton beam on the proton target. A comparison will be presented after the discussion on isospin symmetry, in Fig. 57.

Besides the applied vertex corrections responsible for the correct normalization of the data, the overall normalization of the $n+p$ data was checked with two methods. First, as we will show in the next chapter, neutron data from the Ring Calorimeter coincides well with the indirectly inferred neutron spectrum based on the $n + p \rightarrow p + X$ spectrum. Secondly, the measured yields of charged pions ($\pi^+ + \pi^-$) at $x_F = 0$ are the same within a couple of percent in the $p + p$ and $n + p$ reactions.

7.1.3 Baryon spectra in p+p collisions

To construct the neutron and antineutron spectra in p+p collisions, two assumptions are needed, both being rather natural:

- The isospin symmetry is fulfilled, so that the $n + n \rightarrow p + X$ and the $p + p \rightarrow n + X$ spectra are identical, similarly so for $n + n \rightarrow \bar{p} + X$ and $p + p \rightarrow \bar{n} + X$.

- The particle production originating from the fragmentation of the beam particle is not (significantly) affected by the isospin of the target baryon. This means that the sum of $n + n \rightarrow p + X$ and $p + p \rightarrow p + X$ spectra is equal to the sum of $n + p \rightarrow p + X$ and $p + n \rightarrow p + X$.
spectra\(^30\). Therefore the \(p + p \rightarrow n + X\) and \(p + p \rightarrow \bar{n} + X\) spectra can be obtained as:

\[
(p + p \rightarrow n + X) \equiv (n + n \rightarrow p + X) = (n + p \rightarrow p + X) + (p + n \rightarrow p + X) - (p + p \rightarrow p + X)
\]

\[
(p + p \rightarrow \bar{n} + X) \equiv (n + n \rightarrow \bar{n} + X) = (n + p \rightarrow \bar{n} + X) + (p + n \rightarrow \bar{n} + X) - (p + p \rightarrow \bar{n} + X)
\]

One could rephrase the above statement: the particle spectra are composed of a target and a projectile part, and these contributions do not depend on the type of the other initial particle. This two-component picture will be further examined in the chapter on the comparison of \(\pi + p\) and \(p + p\) interactions; for the moment this 'factorization' is an assumption.

Let us concentrate on what is needed to evaluate the above equations. For example, in order to get the \(n\) density at a given \(x_F\) in \(p + p\) collisions, we need to add up the measured \(p\) density in \(n + p\) collisions at \(x_F\) and at \(-x_F\), and subtract the \(p\) density in \(p + p\) collisions at \(x_F\). The procedure is illustrated schematically in Fig. 56.

Since we generally cannot identify particles far in the backward hemisphere, one more assumption is needed to derive the spectra in \(p + n\) collision (where \(p\) would be the beam and \(n\) the target). We assume that below \(x_F = -0.1\), the proton (and antiproton) spectra of \(p + p\) and \(n + p\) interactions do not differ. Experimentally, one can observe from Fig. 54 and 55 that around \(x_F = -0.1\) this assumption is already satisfied, since the spectra in the two reactions do not differ significantly there. Going more backward (decreasing \(x_F\)) the spectrum obviously gets more and more independent of the projectile, and more and more similar to the target fragmentation region. Thus, the assumption is justified within errors. We refer to section 7.3 for further discussion of this factorization. One can also identify in NA49 the protons far backward\(^31\) \((x_F \ll -0.1)\) in the \(p + p\) and the \(n + p\) interactions and verify this equality there. As a result of the above assumption, our equations get simpler:

\[
(p + p \rightarrow n + X)\bigg|_{x_F} \equiv (p + p \rightarrow n + X)\bigg|_{-x_F} = (n + p \rightarrow p + X)\bigg|_{-x_F} + (n + p \rightarrow p + X)\bigg|_{+x_F} - (p + p \rightarrow p + X)\bigg|_{-x_F} = (n + p \rightarrow p + X)\bigg|_{+x_F}
\]

\(^{30}\)In these formulae, the left initial particle represents the beam, and the right one stands for the target particle: the \(n + p\) and \(p + n\) collisions differ only by a mirroring (sign change) in the \(x_F\) variable.

\(^{31}\)This is possible at low laboratory particle momenta, where the \(\propto 1/\beta^2\) part of the Bethe-Bloch function separates the particle species much better than in the region of the relativistic rise.
and similarly for the antiparticles. This result is quite natural: it tells only that the $p + p \rightarrow n + X$ and $n + p \rightarrow p + X$ spectra are the same in the projectile hemisphere, sufficiently far from $x_F = 0$.

![Graph of $dN/dx_F$ vs $x_F$ for neutrons and antineutrons in proton-proton collisions at 158 GeV/c beam energy.](image)

**Fig. 57:** $n$ and $\pi$ Feynman-$x$ spectra in proton-proton collisions at 158 GeV/c beam energy, presented together with the $p$ and $\bar{p}$ spectra. The $dN/dx_F$ yields are given for an average inelastic event.

Now the above calculation can be carried out using our results in Fig. 54 and Fig. 55, leading to the neutron and antineutron spectra in $p+p$ collision, shown in Fig. 57. It is visible that the antineutron yield exceeds the antiproton yield by about 25-30% at $x_F=0$, which is not expected and not reproduced by models made for hadronic interactions. The antiprotons and antineutrons are compared separately in Fig. 58.

The proton and neutron central yield is similar, and the neutron spectrum decreases almost linearly.

The neutron spectrum is also obtained from the Ring Calorimeter data, completely independently from the method above\(^{32}\). The sum of $n$ and $\bar{n}$ was measured (there is no way to separate the two), thus the data were corrected such that the

\(^{32}\text{Details on the neutron analysis with the Ring Calorimeter can be found in [75].}\)
$p + p \rightarrow \overline{\pi} + X$ spectrum was subtracted from the $n + \overline{\pi}$ spectrum obtained from the Ring Calorimeter. This is also presented in Fig. 57, and shows an excellent agreement with the neutron spectrum derived with the method described above.

We have so far omitted the strange baryons, and only presented non-strange ones. The detection and analysis of strange and multistrange baryons is not a part of the present thesis, but for completeness, one has to take them into account to construct the net baryon spectrum in $p + p$ collisions.

![Graph](image)

Fig. 59: Net baryon Feynman-$x$ spectra in proton-proton collisions at 158 GeV/c beam energy. On the left, net proton, neutron and $\Lambda$, on the right panel net baryons, taking into account $p, \overline{\pi}, n, \pi, \Lambda, \overline{\Lambda}$ spectra measured by NA49. The $dN/dx_F$ yields are given for an average inelastic event.

Strange baryon analysis is available in NA49, where $\Lambda$ and $\overline{\Lambda}$, and even $\Xi^-$ and $\Xi^+$ spectra have been obtained, using a so called "V0" search, that is, finding charged daughters of weakly decaying baryons by geometrical and kinematical constraints. The preliminary results were presented in [76]. For our presentation only the $\Lambda$ results are included, since the $\Xi$ yields are only a few percent of the $\Lambda$ yields. The $x_F$ spectra were taken from a simulation using VENUS, and normalized to the midrapidity yields measured by NA49 (0.019 and 0.006 for $\Lambda$ and $\overline{\Lambda}$, respectively).

Fig. 59 shows the net baryon spectrum $(p - \pi + n - \pi + \Lambda - \overline{\Lambda})$ in $p + p$ collisions at 158 GeV/c beam momentum, in the $x_F < 0.6$ momentum range. The notion of "net protons" $(p - \overline{\pi})$ was designed to refer to the not pair produced (valence) proton spectrum. However in the $n \neq \overline{\pi}$ situation, the net protons as defined above does not correspond to the not pair produced ones precisely.
7. RESULTS

The net baryon spectrum is a quantity which can be fairly compared to heavy ion collisions; there one has similar number of neutrons and protons initially, thus \( p - \bar{p} \) represents well the net nonstrange baryons.

Note, that the integral of the net baryon spectrum has to be equal to 2, since we started from the collision of two protons. Only a part of the integral is contained in Fig. 59, the rest mainly comes from the contribution of the diffractive peak in the proton spectrum, a feature of the \( p + p \) collisions known as the leading particle effect. However, the acceptance of the NA49 TPC-s does not cover this region \(^{33}\).

7.1.4 Comparison with earlier measurements

There are a large number of earlier measurements (1965-1991) devoted to the investigation of inclusive proton and antiproton cross sections in \( p + p \) collisions. The \( \sqrt{s} \) total energy of these collisions range from 5 to 63 GeV, the latter achieved by the CERN Intersecting Storage Rings (ISR), while the others employed fixed targets, like the NA49 experiment with its intermediate, 14-17 GeV total energy. In the early phase of these efforts, the aim was the exploration of basic properties of soft interactions, verification of Feynman-scaling for different final state particles, search for resonance states, observation of leading particle effect; later more specific observables appeared, using polarized beams etc.

There are two important classes these experiments belong to: the first type consists of bubble chamber experiments (like \([77]\), with good momentum space coverage, but statistics limited by the number of exposures taken and processed. Investigations of the recoil proton spectrum (small momenta in the laboratory frame) are ideal with those. The other class is single arm spectrometers; those are applied in many high energy and collider experiments, like ones at the ISR (like \([78, 79, 80]\)). These feature good momentum resolution and sometimes reliable particle identification, but corrections for daughters of weak decays are difficult or impossible to apply because of the small area covered by the detectors, relatively far from the collision point. By moving the spectrometers, the inclusive spectra could be traced, but no information was available on the internal correlations in \( p + p \) events in most cases. Absolute normalization of the cross sections was a major challenge in these experimental configurations, an overall scale error reaching 5-20% typically.

The variables used by those experiments were adjusted to the geometrical setup; with a spectrometer, the laboratory momentum (with modulus \( P \)) of the particles and the scattering angle \( \Theta \) could be measured thus spectra in the \( d^2 \sigma/d\Omega dP \) are presented as a function of \( \Theta \), where \( \Omega \) stands for the solid angle (for example in \([81]\)). This can be converted into invariant

\(^{33}\)We can again refer to the large gap between the TPC-s around the beam, which is there to allow for runs with heavy ion beams without overloading the TPC sensitive volume. This is the missing acceptance region.
(differential) cross sections as $\sigma_{\text{inv}} \equiv E \frac{d^3\sigma}{dp^3} = \frac{E}{P} \frac{d^3\sigma}{dM^2}$. The measured points in the momentum space are arranged naturally on a $\Theta$-$P$ lattice, and when converting values to the center of mass system, these do not span a rectangular $p_L-p_T$ grid, thus interpolations are needed. The other type of variables are $s$, $t$ and $M_z$, with definitions $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$, $M_z^2 = (p_1 + p_2 - p_3)^2$ (where the $p_1$ four-momentum belongs to the beam, $p_2$ to the target and $p_3$ to the detected particle) called total energy, momentum transfer, and missing mass (squared). Cross sections are presented as $\frac{d^3\sigma}{dM^2}$ (like in [82]), and from the above definitions, we get for the invariant cross sections $\sigma_{\text{inv}} = E \frac{d^3\sigma}{dp^3} = \frac{\beta}{\pi} \frac{sd^3\sigma}{dM^2}$ where $\beta = p_1/(m + E_1)$ the velocity of the center of mass frame in the laboratory. Again, a rectangular $t$ vs. $M_z^2$ grid is not a rectangular $p_L$ vs. $p_T$ grid, though $x_F \approx 1 - M_z^2/s$. The third type of variables are the rather generally used $x_F = p_L/p_L^\text{max}$ or sometimes $x_F = 2p_L/\sqrt{s}$ and $p_T$ or $p_T^2$ (also the $y$ rapidity appears in a few cases). We will prefer the latter variables to be compared with the measured data. Earlier results in the other types of variables can be converted and interpolated into these, but we will restrict ourselves to the cases where $x_F$ spectra are (almost) directly measured.

The momentum space region of $x_F \approx 0$ (or $y \approx 0$) is frequently covered by experiments, thus first we concentrate on central proton and antiproton density, as a function of $\sqrt{s}$, and give an overview of existing measurements. In most cases, the invariant cross section was measured as a function of $p_T$:

$$\sigma_{\text{inv}} = E \frac{d^3\sigma}{dp^3} = \frac{E \sigma_{\text{tot}}}{2 \pi p_T dp_T dx_F p_T^\text{max}} = \frac{\sigma_{\text{tot}}}{2 \pi p_T dp_T dy}.$$ 

To obtain $dN/dx_F$ or $dN/dy$ values from these $p_T$ spectra, a simple fit was performed with the form of $\sigma_{\text{inv}} = A \exp(-\sqrt{m^2 + p_T^2}/T)$ to the measured data, where $m$ is a mass parameter (not necessarily a physical mass) describing the low-$p_T$ shape of the function. Although this functional form resembles the one appearing in interpretations of the data in the thermodynamical picture, we do not associate any physical meaning to these parameters, we only facilitate the $p_T$ integration by using them, in situations where not the entire $p_T$ range is covered by data points. Finally, the $dN/dx_F$ value can be calculated numerically as

$$dN/dx_F = \int_0^\infty 2 \pi p_T p_T^\text{max} E \sigma_{\text{tot}} \sigma_{\text{inv}}(p_T) dp_T \quad \text{or} \quad dN/dy = \int_0^\infty \frac{2 \pi p_T}{\sigma_{\text{tot}} \sigma_{\text{inv}}}(p_T) dp_T.$$

$\sigma_{\text{tot}}^\text{inel}$ values are taken from [83]. In the following we review the relevant papers for $x_F = 0(= y)$.

The lowest energy data we present is from [77], a bubble chamber experiment at the CERN PS, which collected 290 (560) thousand events at 12 (and 24) GeV beam energy. In Fig. 60, the above fit to the data points is illustrated. As a result, we get $dN/dx_F|_{x_F=0} = 0.55(3)$ and $0.51(3)$ at 12 and 24 GeV, respectively. The method is applied similarly to the following experiments as well.
Ref. [84] describes a spectrometer experiment at the Argonne zero-gradient synchrotron. We find results on proton cross sections at 12.5 GeV beam energy in the form of $d^2\sigma/d\Omega dP$. After conversion and interpolation, we find a similar result as above, $dN/dx_F|_{x_F=0}=0.48(3)$.

In the three publications of ref. [85] inclusive cross sections of $p$ and $\bar{p}$ can be found in the $0.5 < p_T < 4.2$ GeV/c transverse momentum range at 70 GeV beam energy, measured with a double-arm spectrometer at the IHEP accelerator. Using the $m=m_{proton}$ parameter in the fit to estimate the not covered low-$p_T$ region, we get $dN/dx_F|_{x_F=0}=0.38(8)$ for protons and $0.035(4)$ for antiprotons.

Ref. [86] contains only the antiproton density, which is $0.36(4)$ at 360 GeV beam energy, based on 8600 events measured by the NA23 collaboration at CERN using the Rapid Cycling Bubble Chamber and the European Hybrid Spectrometer (EHS) setup.

The NA27 experiment at CERN is one of the latest inclusive spectrum measurements in $p+p$ interactions [87], analyzing 472000 events with the EHS facility at 400 GeV/c beam energy. Particle identification capabilities were similar in quality to the NA49 spectrometer. The full $x_F$ region is covered by the experiment, however trigger inefficiencies at higher $x_F$ are present. At $x_F = 0$, the proton and antiproton densities are $0.69(2)$ and $0.29(2)$, respectively.

![Graph](image)

**Fig. 60:** Examples of fitting the transverse momentum spectra of earlier datasets to obtain $p_T$-integrated particle densities at $x_F=0$. Data are from [77] (left) and [78, 79, 80] (right panel). Units on the vertical axes is invariant cross section. The inset shows the data from [79] extending to $p_T=4$ GeV/c.

CERN ISR collider experiments dominate the highest energy measurements. One of them is described in [88]. We find proton and antiproton $p_T$ distributions in the 0.2-1.2 GeV range at
the two energies $\sqrt{s} = 30.6$ and 52.8 GeV, at the angle of 89 degrees with respect to the beam - this corresponds to $x_F = 0$. The fit gives proton densities of 1.08(6) and 1.86(9), antiproton densities of 0.48(7) and 0.99(9) at the two energies.

Three other publications, [80], [78] and [79] investigated the $p + p$ scattering at the energies $\sqrt{s} = 23, 31, 45, 53$ and 63 GeV, and at $x_F = 0$ they cover different ranges of $p_T$: the 0.12-0.5, 0.25-1.3 and 0.2-4 intervals, respectively.

The study in [80] aimed to explore the low $p_T$ intervals with high precision, reaching a normalization error as small as 4% for protons. This region represents the majority of the particle yield. [79] shows significantly higher cross sections than [78] at $p_T < 0.5$ GeV/c, while the errors of the latter datapoints are larger. (An illustration is shown in the right panel of Fig. 60 for the proton data at $\sqrt{s} = 45$.) For these reasons, [80] was used in the low $p_T$, [79] in the high $p_T$ region for the fit.

All the mentioned datapoints together with those from NA49 are presented in Fig. 61. The NA49 points fit well into the trend shown by the other measurements, connecting the early fixed target (low energy) and collider (high energy) experiments.

Fig. 61: The central proton and antiproton density in a collection of earlier experiments, in terms of $dN/dx_F$ at $x_F = 0$ (left panel) and $dN/dy$ at $y = 0$ (right panel). Note that the NA49 data (results from this thesis) are feed-down corrected. The data refer to average inelastic events.

Let us note the points corresponding to the measurement of the LEBC-EHS collaboration at $\sqrt{s} = 27.4$ GeV [87] (Aguilar-Benitez et al.). These are not consistent with the other presented data, giving significantly smaller values for the proton and antiproton density, as well as for their difference. According to [20], authors of the HIJING model used these data to adjust
cross sections associated with the new interaction via gluonic junctions. As we will see in Fig. 65, HIJING somewhat underestimates the net proton density at the NA49 energies, but indeed is in agreement with EHS [87].

The second possibility to review earlier measurements is to collect complete measured $x_F$ spectra. It is very difficult to construct this quantity because of the $p_T$-integration: a good acceptance coverage is essential, especially around the 500 MeV average transverse momentum of the $p$, $\bar{p}$ particles. In NA49, this presents no problem: acceptance down to $p_T = 0$ is naturally given, as well as up to a few GeV/c, since the $p_T = 0$ configuration is not related to any geometrical borderline in the experimental setup. Thus, only a few experiments give integrated $dN/dx_F$ values, usually as a result of a fit on the $p_T$ spectra similarly to our method described above, but with various fit functions. Two simple functional forms are the exponential and the Gaussian one (in the $\sigma_{inv}$ variable, as a function of $p_T$), used for example by [89], an extensive study of many types of hadronic reactions at the Fermilab Single Arm Spectrometer at 100 and 175 GeV/c beam momentum (in 1982). Both NA49 and other experiments suggest an exponential tail up to a few GeV/c $p_T$ in the proton and antiproton spectra, while at low $p_T$ the spectra 'flatten out' and reach $p_T = 0$ with a vanishing first derivative (at $x_F = 0$). Thus the shape is most likely neither of the mentioned ones; this observation motivated the $\exp(-m_T/T)$ parametrization we used. The available data on the $dN/dx_F$ spectra are as follows:

We have already mentioned ref. [87]; both proton and antiproton spectra can be found there, at 400 GeV beam energy.

At lower energies, [77] provides proton $x_F$ spectra in the $x_F=0...0.9$ range. More precisely, the integral $\int \sigma_{inv} (p_T) dp_T^2$ is given for various $x_F$ values. To calculate the $dN/dx_F$ values, the following approximation had to be used:

$$\int_0^\infty \frac{E d\sigma}{2 \pi d p_T d x_F p_L^{max}} 2p_T dp_T = \frac{\sigma_{inv}^{tot}}{\pi p_L^{max} d x_F} \int_0^\infty \sqrt{(x_F p_L^{max})^2 + m^2 + p_T^2} \frac{dN}{dp_T} dp_T \approx \frac{\sigma_{inv}^{tot} \langle E \rangle}{\pi p_L^{max} d x_F}$$

Where $\langle E \rangle \approx \sqrt{m^2 + (0.5 \text{GeV}/c)^2 + (x_F p_L^{max})^2}$ average energy was used.

For the [89] Fermilab analysis 100 and 175 GeV beam energy was chosen. Two important comments have to be placed regarding the interpretation of integrated $dN/dx_F$ yields. In the paper, the quantity $x_F \frac{d\sigma}{dx_F}$ is presented, which is not equal to the product of $x_F$ and $\frac{d\sigma}{dx_F}$ (as often interpreted when quoting [89]); instead, defined by the integral $2 \pi \int_0^\infty E \frac{d\sigma}{dp_T} p_T dp_T$, which is $\pi$ times the detailed formula above. Thus, it is approximately $\sigma_{inv}^{tot} \langle E \rangle \langle p_L^{max} \rangle dN/dx_F$. At large $|x_F|$ values, indeed $\langle E \rangle \langle p_L^{max} \rangle \approx x_F$, but at $|x_F| \approx 0$ it is larger than $x_F$. Thus dividing the presented $x_F \frac{d\sigma}{dx_F}$ by $x_F$ overestimates the particle density at low $x_F$. Also high $x_F$ values, detailed study of $p_T$ shapes and refitting of the differential $p_T$ spectra results significantly smaller $dN/dx_F$ values than in the paper. Refitted values are also included in Fig. 62, as well as original datapoints divided by $x_F$. 
7. RESULTS

High energy data from the Fermilab 30 Inch Bubble Chamber is also available [90], with good \( p_T \) coverage (0...1.1 GeV/c) at beam momenta of 102, 205, and 405 GeV/c, in the \( x_F \) range of 0.6 < \( x_F \) < 1.0.

All the mentioned \( x_F \) spectra are presented in Fig. 62, together with the NA49 data at 158 GeV/c. Low energy data are denoted by open points. One can observe a gradual decrease of the \( x_F \approx 0.8 \) region with increasing beam energy. Data from [89] exhibits approximate Feynman-scaling, as well as NA49 data. Higher energy data from [90] in the high \( x_F \) region can be consistently viewed as the continuation of the spectrum measured by NA49. NA49 data are likely the most precisely measured spectra at its energy range.

![Graph showing proton \( x_F \) spectra from earlier datasets.](image)

Fig. 62: Proton \( x_F \) spectra from earlier datasets. Red and blue lines represent NA49 158 and 100 GeV data (results from this thesis), black line the 400 GeV EHS data. Lower energy data are open, high energy data are closed points. In this case, the feed-down correction is not applied to the NA49 data.

Many other earlier publications contain important information on proton and antiproton yields in \( p+p \) inelastic scattering; their systematic overview and partial re-evaluation is beyond
the scope of the presentation in this thesis.

After the summary of earlier datasets, we turn now to the discussion of phenomenological model predictions compared to the NA49 data. We believe that the data presented in this thesis could contribute to a more critical revision of the compilations of $p+p$ data these models rely on.

7.1.5 Comparison with phenomenological models

We discussed a few phenomenological models in Chapter 2, and at this stage we can compare them with the experimental results. As a basis of the comparison we choose the directly measured proton and antiproton spectra, and the somewhat indirectly obtained neutron and antineutron spectra. The result is presented in Fig. 63 for event generators. Several conclusions can be drawn from the comparison:

- While the proton yields are fairly reproduced at $x_F = 0$ by the VENUS and HIJING models, they tend to keep a similar structure of the spectrum for the neutrons, not in agreement with the data.

- UrQMD overestimates the central proton yield, however, gives an excellent description of the neutrons. Again, the shape of the spectra it predicts for $p$ and $n$ are rather similar.

To summarize, data favor significantly different shapes for the proton and neutron $x_F$ distributions, while the event generators tend to keep a similar functional shape. Therefore the agreement with the data cannot be perfect in any of the studied cases.

The following can be stated about the antiparticles:

- Central $\bar{p}$ and $\bar{n}$ yields are fairly reproduced by all the models.

- There is a significant difference between the shapes of the $x_F$ spectra. Both the data shows and the models predict a spectrum exponentially falling with $x_F$ for $\bar{p}$ and $\bar{n}$, but the slope of this exponential decay differs between event generators. This slope is perfect in case of HIJING, while UrQMD and VENUS give a flatter, and even flatter distribution, respectively, than the data shows. The deviation from the data is very significant, can reach a factor of 3-4 at $x_F \approx 0.3...0.4$.

- Finally, all the models predict almost exactly the same spectrum for antiprotons and antineutrons, which feature originates from the fact that baryon pair production is isospin-symmetrically included: the isospin of the projectile and the beam is not correlated with the isospin of the pair-produced baryons. However, as we mentioned earlier, data suggests a larger $\pi$ than $\bar{p}$ yield, by about 25-30%, which indicates such a correlation.

To summarize, both the baryons and the antibaryons indicate a difference between isospin states, which implies a correlation between the isospin of the initial and the final baryons. This is not fully reproduced by the mentioned phenomenological models.
Fig. 63: Comparison of non-strange baryon and antibaryon Feynman-x spectra with a few phenomenological models in a p+p collision with a 158 GeV/c beam momentum. On the upper panels protons and antiprotons, on the lower panels neutrons and antineutrons are shown, both on a linear and a logarithmic scale. Note that the symmetry axis is at $x_F = 0$ and only the $x_F$ range was plotted where the NA49 experiment has acceptance and particle identification in the $0 < p_T < 2$ GeV/c range.
One can also consider the ALCOR hadronization model [24] for a comparison. Since ALCOR was designed for heavy ion collisions, and not for small systems like a p + p collision, we cannot expect good agreement, only some trends could be demonstrated. However, if one adjusts the parameters to the values $f_s = 0.08$, $P_{\text{stop}} = 0.06$ and $N_{\Lambda n}$=0.72, a good description of the baryons in the Table 7 is achieved. It is rather surprising that this hadronization model, designed for heavy ion collisions, is able to describe the p + p data at midrapidity with a 10-20% precision. The simultaneous description of p + p and A + A data with the same parameter set is not possible; the $f_s$ parameter had to be decreased from 0.22 to 0.08, the $P_{\text{stop}}$ parameter from 0.17 to 0.06. The model clearly formulates the difference between the physics of elementary $p + p$ and the nuclear A + A collisions concerning stopping and strangeness production in terms of the above two parameters.

Resonance excitation models could eventually give a qualitative explanation for the observed differences between spectra (yield) of different isospin states in the final state by assuming baryon pairs other than $p\bar{p}$ and $n\bar{n}$. Let us imagine a simplistic example, where the projectile proton gets excited (at least in some fraction of the events) to a high-mass positive baryon state (resonance), and subsequently decays into two high-mass objects, a mesonic and baryonic one. There are two possibilities to arrange the charge (isospin) between them: one of them is positive, the other is neutral like $p \rightarrow B^+ \rightarrow M^+ B^0$ or $p \rightarrow B^+ \rightarrow M^0 B^+$. Let us concentrate on baryon pair production. This can naturally originate from the decay of the mesonic resonance, depending on the charge: $M^+ \rightarrow p\bar{n}$ and $(M^0 \rightarrow p\bar{p}$ or $M^0 \rightarrow n\bar{n})$. At the same time, $B^0$ or $B^+$ can give a leading (high momentum) baryon (likely $n$ or $p$, respectively). As can be seen, this would prefer more $\bar{n}$ than $\bar{p}$ to be produced. Moreover, a correlation is expected: if the leading baryon is a proton, one expects symmetric $(\bar{n} \approx \bar{p} \approx p_{\text{pair}} \approx n_{\text{pair}})$ baryon pair production, but if the leading baryon is a neutron, $p_{\text{pair}} \approx \bar{n}$ is expected (where $p_{\text{pair}}$ stands for pair produced protons). Such a correlation is verified experimentally, as will be shown in the next chapter.

Naturally, pion emission in the intermediate steps can wash out this isospin (charge) correlation, still, a remnant is observed in the data. Further support for this idea can be a recent

| $dN/dy|_{y=0}$ | $\Lambda$ | $\bar{\Lambda}$ | $p$ | $\bar{p}$ | $n$ | $\bar{n}$ | $\Xi^-$ | $\Xi^+$ |
|----------------|---------|----------------|-----|-------|-----|---------|--------|--------|
| NA49 data      | 0.0190  | 0.0060         | 0.071 | 0.016 | 0.072 | 0.020  | 0.00070 | 0.00033 |
| ALCOR          | 0.0176  | 0.0052         | 0.0738 | 0.0165 | 0.0613 | 0.0165 | 0.00105 | 0.00039 |

Table 7: Comparison of midrapidity yields (dN/dy/event) of various baryons, between the measured data ($p+p$ collision at 158 GeV/c beam momentum) and the ALCOR model, for parameter values of $f_s = 0.08$, $N_{\Lambda n} = 0.72$, and a fraction of stopped valence quarks $P_{\text{stop}} = 0.06$. No errors included: the table is meant to be only an illustration. Most of the NA49 data are preliminary.
7. RESULTS

observation of a narrow \(p\bar{p}\) state of mass 2.02 GeV/c² at CERN [91]. Furthermore, simulations based on the above excitation and subsequent cascade decay scenario reproduce other features of the \(p+p\) interactions, like the \(< p_T > - x_F\) ("sea-gull") correlation, the strong anticorrelation between the \(x_F\) of leading proton and the number of \(\pi\)'s in the event, as pointed out in [92].

7.1.6 Energy dependence

We could include in the discussion here two different beam energies at which \(p+p\) collisions were measured at NA49. We compare \(x_F\) distributions of protons and antiprotons at these energies, and we present a summary of experimental data about the \(p\) and \(\bar{p}\) yield at \(x_F = 0\), compared to the event generators.

![Graph of proton and antiproton Feynman-x spectra](image)

Fig. 64: Comparison of proton and antiproton Feynman-x spectra at 100 and 158 GeV/c beam momentum with the HIJING model prediction (the histogram corresponds to 158, the lines to 100 GeV/c). Note that the symmetry axis is at \(x_F = 0\). The \(\sqrt{s}\) values corresponding to the two beam energies are 13.76 and 17.22 GeV.

In Fig. 64 we compare the experimental results at 100 and 158 GeV/c beam momentum. The antiproton yield decreases substantially with the energy: at 100 GeV/c, we have only 65-70% of the antiprotons measured at the higher energy. The central proton yield decreases even faster; yielding a somewhat smaller central \(p - \bar{p}\) density at the smaller beam energy.

At the medium momentum range \((x_F \approx 0.4 - 0.5)\) the data indicates a slight increase of the proton yield at lower energy.

These trends are well reproduced by the HIJING model, which is included in Fig. 64 as an illustration, however it over-predicts the antiproton yield and proton yield at \(x_F \approx 0.4 - 0.5\).
significantly.

**Fig. 65:** Energy dependence of the central proton and antiproton density, as a function of $\sqrt{s}$. Lines show HIJING predictions, while the open squares refer to the NA49 data at $\sqrt{s}=13.76$ and 17.22 GeV.

The **energy dependence** of the central baryon density is relevant and interesting for elementary as well as heavy ion collisions. Fig. 65 illustrates the difference between using a $dN/dxF$ and the $dN/dy$ quantity to measure central baryon yields. While in rapidity (right panel), the central yield of net protons ($p - \bar{p}$) decreases with rising energy, the same quantity increases in $dN/dxF$ units. The decrease of rapidity density reflects a trivial effect: the rapidity region accessible for particles extends with rising $\sqrt{s}$. In $x_F$, however, the accessible region is always the [-1;+1] interval. One should get the total baryon number 2 by integrating between these borders. Thus, baryon number conservation is more naturally illustrated in $x_F$.

It may be instructive to show $p$ and $\bar{p}$ distributions at different $\sqrt{s}$ values in both $y$ and $x_F$ variable (Fig. 66). The $x_F$ spectrum of protons gradually decreases with increasing energy in the intermediate Feynman-x region up to $x_F \approx 0.9$, while features an approximate Feynman-scaling; it presumably converges for $\sqrt{s} \rightarrow \infty$. The high-$x_F$ diffractive and central regions increase. The central structure of the proton spectrum develops because of the baryon pair production: the antiproton yield also increases. The integral of the net baryon number certainly remains constant (two). The $p - \bar{p}$ density at $x_F = 0$ is slightly rising or remains constant with the energy (in HIJING, it definitely rises), while expressing it in terms of $dN/dy$, it definitely decreases. The energy dependence of neutrons and antineutrons is not known, and one has to take into account the strange baryons as well to state something on the energy dependence of the net baryon density at $x_F = 0 = y$. This would be probably more relevant and interesting
for comparisons with phenomenological models. If the asymmetric baryon pair production (appearing as $\pi \neq \bar{\pi}$) extends to higher energy as well, the $dN/dx_F$ net baryon density could even decrease with energy.

Concerning the trivial difference between the $y$ and $x_F$ variables, we note that a given $dx_F$ interval extends in $p_L$ with energy, proportionally to $\sqrt{s}$, while a $dy$ interval does not involve this energy scale. Therefore a central structure is lost in the $dN/dy$ plot. Feynman-scaling in the $x_F$ variable is much more apparent. These are some of the reasons to use $x_F$ instead of $y$ throughout this thesis.

### 7.2 Leading and central baryons in p+p interactions

After demonstrating the correlation between the isospin of the produced baryons and the initial ones, it is worthwhile to discuss another aspect of this possible correlation. The most easily measurable quantity for this is the proton and antiproton spectrum in proton-proton events, where a fast ("leading") proton or neutron is contained in the event. Due to acceptance constraints, and making sure that the event is still fully inelastic, we chose a Feynman-x bin for the leading baryon between $x_F=0.4$ and $0.6$. A particle was called leading proton, if it was found in this momentum range, and its ionization value was consistent with being a proton\[34\].

\[34\] The condition was $dE/dx < BB + 0.04$ where BB is the Bethe-Bloch value for protons. The cut is so relaxed because at the given high momentum range protons are much more abundant than kaons.
Fig. 67: Proton and antiproton spectra in events containing a leading proton (closed points) and neutron (open points) falling into the $0.4 < x_F < 0.6$ interval. Comparison of NA49 data (upper left), the HIJING (upper right), the UrQMD (lower left) and the VENUS (lower right) event generators at 158 GeV/c beam momentum.
Leading neutrons were selected with the energy measured in the Ring Calorimeter and the charge information given by the Veto Proportional Chamber (see Chapter 4). The spectra of the other (remaining) $p$ and $\bar{p}$ particles are shown in Fig. 67. Closed points represent events with leading proton selection: here, the proton and antiproton spectra converge to each other at around $x_F = 0.1$. However, a leading neutron in the event implies increased proton yield and considerably decreased antiproton yield. The size of the effect is much larger than the ones observed in the presented three event generators (see Fig. 67).

The Ring Calorimeter has a finite energy resolution, and this is taken into account in the results of the presented event generators. For a neutron with momentum $p$, the measured $E$ energy in the calorimeter has a probability density of $\propto \exp(-\left(\log(E/p)\right)^2/2C^2)$, where $C \approx 0.23$. The chance for neutrons from an event generator to fall into the given $x_F$ bin was calculated according to the above formula, and the spectra were obtained applying these weights - simulating the situation we had in the data.

Thus, a leading proton in an event seems to prefer symmetric baryon pair production ($p \approx \bar{p}$), while a leading neutron is observed together with more protons than antiprotons produced. This observation is not reproduced by the presented color string models, but supports the existence of correlations of the type we discussed earlier in connection to a resonance excitation and decay scenario, and consistent with the $\pi > \bar{p}$ observation in the inclusive analysis.

Such situation could occur in the resonance excitation picture, where we have a high mass baryon resonance ($B^+$) excited from the projectile, decaying into a neutral mesonic $M^0$ and a positive baryonic $B'^+$ state, or vice versa, to a $M^+$ and a $B'^0$ state. In the first case, a leading proton could emerge from the decay of $B'^+$, and $M^0$ produces $p\bar{p}$ and $n\bar{n}$ pairs symmetrically. In the second case, a leading neutron is more preferred from the $B'^0$ decay, while $M^+$ produces to $p\bar{p}$ pairs most likely (see Fig. 68). All this would imply that more $\pi$ than $\bar{p}$ is measured on average in $p+p$ collisions, and also that a leading proton coincides with symmetric baryon pair production while a leading neutron is associated with a small number of $\bar{p}$ and increased number of $p$ baryons in the pair production - both phenomena demonstrated already experimentally in the thesis. Pion emission can certainly soften these charge (isospin) correlations with respect to what the above oversimplified explanation states,
but data suggest that the correlations do not vanish completely.

The backward region of the momentum space is affected only weakly by the leading particle selection, and a part of the forward proton and antiproton yield (close to $x_F = 0$) originates from the target "contribution". The size of this contribution is yet unknown, but we present an experimental estimate of it in the next section.

7.3 $\pi+p$ and $p+p$ interactions

For two important reasons, in this section we introduce an idea of a two-component (target and projectile) separation of the net proton spectrum in $p+p$ interaction. One of the motivations is that this way we can estimate, how much of this spectrum extends into the opposite hemisphere, affecting measurements as for example in the last section.

The other reason is to establish a tool to separate target and projectile hemispheres for studying baryon stopping in $p+p$ and $p+A$ collisions, where in the latter case we are interested mainly in the projectile component.

Let us imagine the inclusive $p-\bar{p}$ spectrum in $p+p$ collisions as a sum of a projectile and an identical (but reflected to $x_F=0$) target component (Fig. 69)\textsuperscript{35}. We know that at $x_F=0$ these components have $1/2$ of the inclusive value, and that far from $x_F=0$ they converge to the inclusive spectra.

Using pion beams, however, we can say more. The only assumption we need is that approximately the same process happens to the target proton, no matter whether the beam particle was a 158 GeV/c proton or a 158 GeV/c pion: the target component of $p-\bar{p}$ is independent of the beam particle. We know furthermore, that by charge conjugation symmetry, the $p-\bar{p}$ spectrum cannot have projectile component in the sum of $\pi^+ + p$ and $\pi^- + p$ reactions: the projectile component of $p-\bar{p}$ spectrum from $\pi^+ + p$ to $\pi^- + p$ reaction changes sign (since $\pi^+ \equiv \pi^-$ and $\bar{p} - \bar{p} \equiv -(p - \bar{p})$). Therefore, the $\pi + p \rightarrow p - \bar{p}$ inclusive spectrum is the same as the target component of the

\textsuperscript{35} A baryon pair production or "central" component is certainly allowed, but we quote here always $p-\bar{p}$ and not only $p$ spectra.
$p + p \rightarrow p - \bar{p}$ spectrum (where $\pi := (\pi^+ + \pi^-)/2$). Similarly, $[p + p] - [\pi + p] \rightarrow p - \bar{p}$ gives the projectile part of the $p + p \rightarrow p - \bar{p}$ spectrum.

Fig. 70: Proton (red) and antiproton (blue) Feynman-$x$ spectra in $\pi^+ + p$ (closed points) and $\pi^- + p$ (open points) collisions at 158 GeV/$c$ beam momentum.

Measured $\pi^\pm + p \rightarrow p$, $\bar{p}$ spectra are presented in Fig. 70. It is apparent, that the antiprotons are much more abundant and further extended towards high momenta, than in $p + p$ interactions: a higher amount of baryon pair production takes place. In $\pi^+ + p$ collisions, we find a significantly larger $p$ than $\bar{p}$ yield at high $x_F$ values, while in $\pi^- + p$ collisions the two are close to each other\(^\text{36}\). Therefore the target net proton contribution extends considerably to the projectile hemisphere. To quantify this, we can derive the target net proton contribution as discussed above, calculating the average $p - \bar{p}$ spectrum between $\pi^+ + p$ and $\pi^- + p$ interactions.

The result is presented in Fig. 71. On the right panel, the difference of the $p - \bar{p}$ spectrum in $p + p$ collisions and the latter is shown in the forward hemisphere, and the reflected $\pi + p \rightarrow p - \bar{p}$ spectrum in the backward hemisphere. The two join perfectly at $x_F = 0$, at a value which is precisely 1/2 of the inclusive net proton yield in $p + p$ interactions. This fact gives a strong support to the assumption that the proton undergoes the same processes independently of the beam particle ($p$ or $\pi$ with the same momentum).

To summarize, we created a way to quantify the contributions of the projectile and the target proton to the $p - \bar{p}$ spectrum in proton-proton collisions. In the next chapter, we demonstrate

\(^{36}\)The result in the $x_F > 0.2$ region is consistent with the expectation that the $\pi^+$ beam fragments into as many $p$ ($\bar{p}$) than the $\pi^-$ beam into $\bar{p}$ ($p$).
7. RESULTS

Fig. 71: On the left panel, $p - \bar{p}$ spectra in $\pi^+ + p$ (red) and $\pi^+ + p$ (blue) collisions at 158 GeV/c beam momentum, and the average of the two (black). On the right panel, the later is subtracted from the $p - \bar{p}$ spectrum of $p + p$ collisions (open black points), as well as reflected around $x_F = 0$ (closed black points), representing together the projectile part of the net proton spectrum (red) in $p + p$ collisions.

this idea applied to proton-nucleus interactions.

7.4 Baryon stopping in p+A interactions

One can apply the idea presented in the last chapter to proton-nucleus and pion-nucleus data, to estimate the part of the $p - \bar{p}$ spectrum which can be attributed to the proton projectile. This would indicate the amount of proton stopping in the nuclear matter. These stopping studies of the NA49 experiment [3] triggered a lot of interest from the theoretical side. In [93], the valon model of the nucleons is applied to these data.

The question of baryon stopping in $p + A$ collisions was earlier discussed in connection to predictions of the possible amount of baryon stopping and baryon density hoped to be reached in subsequent heavy ion collisions. Nuclear transparency and stopping power was discussed, and the importance of $p + A$ studies in the research of new physics to emerge in $A + A$ collisions was emphasized [94, 95]. An important earlier experiment provided inclusive cross sections in various colliding systems, but data were restricted to a certain $p_T$ value [96].

The NA49 collaboration contributes to these results with a practically full $p_T$ coverage. The data are especially valuable because they are presented in different centrality regions of the collision. The projectile, while scattering through the large $Pb$ nucleus, hits several nucleons, and depending on the impact parameter of the collision, a small (peripheral) or large (central)
number of grey protons are emitted in the laboratory momentum range of about 0.15 to 1 GeV/c. These are detected in the Centrality Detector and the TPC, and after corrections and comparison to the VENUS model, a correlation is given between the number of detected grey particles and the number of "elementary" collisions undergone by the projectile in the Pb nucleus (in a Glauber-picture). The data are divided into bins of number of gray particles, and an average number of collisions \( \nu \) is calculated to describe the centrality. Four bins are used, with 3.1 (peripheral), 4.6 (medium), 5.5 (central) and 6.3 (very central) "elementary" collisions. The bins are the same for \( p + Pb \) and \( \pi + Pb \) interactions.

The assumption we need is similar as in the \( p + p \) case: the target contribution is identical for both beam particles, provided the centrality is the same. Thus, the \( \frac{\left[ (\pi^+ + Pb) + (\pi^- + Pb) \right]}{2} \rightarrow p - \bar{p} \) spectrum should correspond to the target contribution only. Subtracting this from the \( p + Pb \rightarrow p - \bar{p} \) spectrum, we get the projectile component of the net proton spectrum. The measured \( p \) and \( \bar{p} \) spectra are presented in Fig. 72 for \( p + Pb \) and \( \pi^+ + Pb \) reactions. We immediately observe that the proton spectra are strongly steepening (the proton stopping increases) as we move towards higher centralities, while the antiproton spectra do not show a significant change.

We should note here that the actual results to be presented are preliminary (and they are meant to demonstrate the above method only), for the reasons below:

- We only have \( \pi^+ + Pb \) data available, and not \( \pi^- + Pb \). To overcome this difficulty, for the present data we assumed that the difference in the \( p - \bar{p} \) spectrum between \( \pi^+ \) and \( \pi^- \) beams is the same as in case of proton target. (The antiproton spectrum is similar for all centralities in \( p + Pb \), the same is assumed for the baryon pair production attributed to the beam pion.)
More data with Pb target (also with \( \pi^- \) beam) is being taken in the 2001 fall period.

- The available statistics in \( \pi^+ + Pb \) is much smaller than with \( p \) beam, though being equally important for this study. This is what results in the large error bars. The subtraction of two large numbers (inclusive and target component) leads to a sizeable error on the projectile component of the spectra.

- The feed-down corrections in \( \pi^+ + Pb \) collisions were not available by the time of writing.

The assumption was used, that these corrections can be approximated by those applied to \( p + Pb \) collisions, multiplied by the ratio of corrections applied to \( \pi^+ + p \) and \( p + p \) reactions.

Keeping the above weaknesses in mind, we can still make the subtraction between the proton and pion induced reactions, and estimate the projectile component of the net proton spectra. The mentioned uncertainties do not affect the spectra at higher \( x_F \) values: the increasing degree of stopping with increasing centrality remains spectacular, as can be seen in Fig. 73. Other kind of interesting and valuable observables are the neutron spectra in \( p + Pb \) collisions: these are presented on the right panel of Fig. 73 (\( n - \pi \) spectra with the \( \pi \approx \bar{p} \) assumption). Neutrons
Fig. 72: Proton and antiproton Feynman-x spectra in peripheral (red), medium (blue), central (green) and very central (black) \(p+\text{Pb}\) (left) and \(\pi^+\text{Pb}\) (right) collisions at 158 GeV/c beam energy. For comparison, spectra in \(\pi^+p\) and \(p+p\) interactions are given (lines) as well (\(\bar{p}\) points were slightly shifted from each other for better visibility).

Fig. 73: Estimated projectile component of the \(p-\bar{p}\) spectrum in \(p+\text{Pb}\) collisions at 158 GeV/c beam momentum. Four different centrality bins are shown, together with a projectile component in \(p+p\) collisions (left panel). On the right panel, the \(n-\pi\) spectrum is shown (\(\bar{p} \approx \pi\) is assumed) as measured with the Ring Calorimeter, in \(p+p\) and \(p+A\) reactions (in the most central and most peripheral bins).
suffer a very similar stopping effect than the protons, depending strongly on the centrality of the collisions.

We can conclude that the extent of stopping baryons suffer in proton-nucleus collisions depends strongly on the impact parameter, thus minimum bias data are not sufficient to compare with heavy ion reactions neither with model calculations. A centrality dependent analysis can be found for example in [93]. In the last chapter, we compare stopping in different reactions.

7.5 Comparison of baryon stopping in p+A and A+A reactions

The above results concerning proton-nucleus data can be compared to heavy ion (Pb + Pb) collisions at 158 GeV/c beam energy per nucleon (taken from [97]). On the left panel of Fig. 74, p − \( \bar{p} \) spectra are shown in Pb+Pb collisions, in three different centrality bins. Centrality is characterized by the average number \( \nu \) of elementary collisions undergone by an average participant nucleon according to a Glauber calculation; our bins refer to \( \nu = 2.6 \) (peripheral), 3.6 (medium) and 4.6 (central), corresponding to a number of participant pairs of 181, 94, 36 respectively. Yields per event are divided by the number of participant pairs. This way, a common scale for comparison with the other interactions is established.

![Graph](image_url)

Fig. 74: On the left panel, \( x_F \) spectra of \( p - \bar{p} \) are shown in Pb+Pb interactions with 158 A·GeV/c beam momentum, together with the hypothetical "nucleon-nucleon" interaction. Lines are schematical estimates of the projectile contribution in Pb+Pb. On the left panel, these lines are compared to the projectile contribution of \( p - \bar{p} \) in p+Pb interactions.

As we have no "pionic nucleus" beam to extract the target component of the \( p - \bar{p} \) spectra...
in Pb+Pb collisions, similarly to the $p + p$ and $p + Pb$ cases, only the fact that the $Pb + Pb$ collision is symmetrical around $x_F = 0$ can be used. Thus, the projectile component is $1/2$ of the inclusive spectrum at $x_F = 0$, and converges to the inclusive values at $|x_F| \gg 0$. Based on these simple facts, the lines on the left panel of Fig. 74 are schematic estimates of the projectile component of the $p - \pi$ spectra. For comparison, the nucleon-nucleon ($N + N$) data are also indicated, where the $N$ nucleon is a mixture of 0.4 proton and 0.6 neutron corresponding to the nucleon content of the $Pb$ nucleus; the $N + N \rightarrow p - \pi$ spectrum is approximated by the following sum: $0.4 \times (p + p \rightarrow p - \pi) + 0.6 \times (n + n \rightarrow p - \pi) \equiv 0.4 \times (p + p \rightarrow p - \pi) + 0.6 \times (p + p \rightarrow n - \pi)$.

On the right panel of Fig. 74, we repeat the projectile components of the net proton spectra in $p + Pb$ collisions. Here, the fair basis of comparison is the $p + p$ reaction, while in case of Pb+Pb results, it is the $N + N$ reaction. Thus, we superimposed the lines representing the projectile $p - \pi$ spectra in $Pb + Pb$ scaled in a way that brings the (scaled) $N + N$ and the (not scaled) $p + p$ results to approximate overlap. This way it is attempted to account for the different isospin contents of the participants in the $p + Pb$ and $Pb + Pb$ interactions.

It is interesting to observe that the proton stopping reaches a much higher degree in $p + Pb$ than in $Pb + Pb$ collisions. In fact, the $Pb + Pb$ spectrum with $\nu \approx 4.6$ average number of elementary collisions, which is a central sample, lies rather close to the spectrum in $p + Pb$ with $\nu \approx 3.1$, which is a peripheral sample.

Note, that in the central $p + Pb$ collision, the proton passes through a $2R$ thick nuclear matter (where $R$ is the radius of the nucleus taken to be a sphere) while at the central $Pb + Pb$ collision the average participant traverses only a matter of $\approx 3R/2$ thickness, being less central than the central $p + Pb$ collision. But as we see in Fig. 74, the proton is ”stopped” significantly stronger in $p + Pb$ at $\nu = 4.6$ number of collisions (blue points), than in $Pb + Pb$ at the same $\nu = 4.6$ (green line). This result suggests that the $\nu$ is not the only parameter to characterize the stopping; indeed, in $Pb + Pb$ collisions the participants (except the first ones) collide with already wounded nucleons, while in $p + Pb$ the proton projectile meets always ”intact” nucleons which are not yet wounded (thinking in a Glauber picture). The first scenario may have a less effective stopping mechanism, as we might conclude from the above results.

Let us stress again that both the $Pb + Pb$ results and the $p, \pi + Pb$ data will be under reanalysis as the data with low luminosity (in the first case) and with larger statistics and $\pi^-$ beam (in the second case) will become available, and considerations and new corrections concerning the precise centrality determination in $p + A$ is under development as well.

### 7.6 Summary of the experimental results

As a summary, we can recall the aspects of baryon momentum transfer and antibaryon production in $p + p$, $p + A$ and $A + A$ interactions we discussed in this thesis.
• We measured with an unprecedented accuracy the inclusive longitudinal momentum spectra of protons and antiprotons in proton-proton collisions, as well as in neutron-proton collisions, with the neutron as a beam particle, at 158 GeV/c beam momentum.

• Using a few assumptions, which were consistent with the data, we derived neutron and antineutron momentum spectra in proton-proton collisions. We have found that antineutrons are significantly more abundantly produced than antiprotons. We concluded that both the baryon-antibaryon pair production and the proton and neutron spectra in the fragmentation regions exhibit a correlation with the isospin of the colliding baryons ($p$, $n$), features not reproduced by the presented known event generators.

• Studying the energy dependence in $p+p$ reactions, we verified the approximate Feynman-scaling, and found good qualitative agreement with phenomenological models. We also pointed out how the usage of different kinematical variables can lead to completely opposite conclusions about the energy dependence of the central baryon density.

• We studied the correlations between the isospin of the leading baryons and the momentum spectra of the other baryons in proton-proton collisions. We have found again a significant correlation; an influence of the isospin of the leading baryon on the isospin states of the other produced baryons. This is not expected to be included and indeed not reproduced by commonly used event generators.

• We introduced a new idea of separating the net proton distribution in $p+p$ interactions to the contributions of the target and projectile proton, using (net baryon-free) pion beams on the proton target. We have found the projectile component of the net proton spectrum in a consistent and plausible way. We observed a remarkably high amount of baryon-antibaryon production in pion-proton interactions.

• We applied the same method to the interactions with heavy nuclear target. Using $\pi + Pb$ and $p + Pb$ interactions, we separated the projectile contribution to the net proton spectrum, which is a convenient observable when studying baryon stopping in nuclear matter quantitatively. We observed a high degree of momentum degradation in central $p+Pb$ collisions.

• We compared the results in $p+A$ interactions with available data on $Pb+Pb$ collisions. In the latter case, an experimental way of projectile part separation cannot be established, but even with a certain degree of uncertainty, the observed proton stopping even in central $Pb+Pb$ interactions was found to be significantly smaller than in central $p+Pb$ collisions. This statement holds true even if we compare not central $Pb+Pb$ and central $p+Pb$ (the later being naturally more central) but the two interactions with the same average number of "elementary" collisions (same average thickness of traversed nuclear matter) undergone by an (average) projectile nucleon.
Acknowledgements

First of all, I would like to thank my advisor György Vesztergombi his continuous support and patience during the last years, and especially that he gave me the opportunity to start working in such a prestigious and inspiring international institution as CERN. He devoted enormous effort to expose his students to the competitive atmosphere of experimental particle research, while tirelessly making difficult compromises to keep them on reasonable tracks.

As the leader and organizer of the group in NA49 working on physics of interactions with elementary hadronic beams; the starter of the whole hadronic physics program; my closest advisor and instructor at CERN; most of the credit for the assistance I got is deserved by Hans Gerhard Fischer. I am especially grateful for his commitment to the complicated task of initiating and maintaining the $p + p$ and $p + A$ program in NA49.

I express my gratitude to my colleagues from Budapest: to Zoltán Fodor, Ferenc Siklér, Dezső Varga and especially to Dániel Barna for their helpfulness, assistance and encouragement.

I thank my collaborators and working group members in NA49 their hard work they devoted to the success of our experiment, their support and helpful discussions: Peter Seyboth and Reinhard Stock spokesmen; Latchezar Betev, Helena Bialkowska, Božena Boimska, Juraj Bracicak, Predrag Bunčić, Vladimir Černý, Marek Gaździcki, Claudia Höhne, Kreso Kadija, Christof and Günther Roland, Andrzej Rybicki, Thomas Sammer, Herbert Ströbele, Tatjana Šuša, Siegfried Wenig, and all the NA49 collaborators.

Michal Kreps, Ondřej Chvála and Ferenc Siklér provided an indispensable contribution to the software efforts of the NA49 working group as well as to the present thesis concerning feed-down corrections, vertex cut corrections and the increased quality measures of the tracking, respectively.

In the past three years I enjoyed the atmosphere and hospitality created by my colleagues and friends at the Department of Atomic Physics at the Eötvös Loránd University in Budapest: András Patkós (head of the department), Zsolt Szép, Szabolcs Borsányi and many others.

I acknowledge the travel grants and support of the Graduate School of Physics at the Eötvös Loránd University, as well as the OTKA Research Grant No. F 034707, and Prof. György Marx and András Patkós for creating excellent working conditions for me.

Finally, I am most thankful to my family and to my friends and especially to my grandfather for I could count and rely on them at all times; I benefited from the relations with them much more than they could do.
Bibliography


[41] Hans Bichsel Particle identification in TPC, Univ. of Washington, Seattle, Oct. 31, 1994
[42] Handbook of Chemistry and Physics, 64th ed., Boca Raton: CRC Press (1983);

[43] L. D. Landau On the energy loss of fast particles by ionization, J. Phys, USSR, 8, 201 (1944)


[48] I. Lehraus, R. Matthewson, W. Tejessy dE/dx measurements in Ne, Ar, Kr, Xe and pure hydrocarbons, Nuclear Instruments and Methods (Feb. 9, 1982)


[55] F. Lapigule, F. Pinz Simulation of the measurement by primary cluster counting of the energy lost by a relativistic ionizing particle in Argon, CERN, Geneva (1979)


[73] M. Kreps Feed-down correction for protons and antiprotons. NA49 internal note, July 16, 2001


V. V. Abramov et al. *Y. Fiz. 41* 700 (1985) (in Russian)  
V. V. Abramov et al. *ZETFP 33* 304 (1981) (in Russian)


