Introduction:

• CLIC accelerator

• Experimental environment

• CLIC detector requirements and concept
pp and $e^+e^-$ collisions

**pp collisions:**
Interesting events need to be found in huge number of collisions

**ee collisions:**
More “clean”, all events usable

8 orders of Magnitude!
Hadron and e^+e^- colliders

**Hadron colliders:**

- Proton is compound object
  - Initial state unknown
  - Limits achievable precision
- High-energy circular colliders possible
- High rates of QCD backgrounds
  - Complex triggers
  - High levels of radiation

**e^+e^- colliders:**

- e^+e^- are pointlike
  - Initial state well-defined ($\sqrt{s}$, polarisation)
  - High-precision measurements
- High energies ($\sqrt{s} \geq 380$ GeV) require linear colliders
- Clean experimental environment
  - Less / no need for triggers
  - Lower radiation levels
Studies of high-energy $e^+e^-$ colliders

Compact Linear Collider (CLIC): CERN
$\sqrt{s} = 380$ GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km

Future Circular Collider (FCC-ee): CERN
$\sqrt{s} = 90 - 365$ GeV
Circumference: 97.75 km

International Linear Collider (ILC):
Japan (Kitakami)
$\sqrt{s} = 250 - 500$ GeV
Length: 20 km, 31 km

Circular Electron Positron Collider (CEPC): China
$\sqrt{s} = 90 - 240$ GeV
Circumference: 100 km
Compact Linear Collider (CLIC):
- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV
- Length: 50 km (for 3 TeV)
- $P(e^-) = \pm 80\%$
CLIC acceleration scheme

**Drive beam supplies RF power:**
- 12 GHz bunch structure
- Low energy: 2.4 GeV - 240 MeV
- High current: 100 A

**Main beam for physics:**
- High energy: 9 GeV - 1.5 TeV
- Current: 1.2 A
The CLIC Test Facility (CTF3)

CTF3 successfully demonstrated:
- Drive beam generation
- RF power extraction
- Two-beam acceleration up to a gradient of 145 MeV/m

- CTF3 completed its mission in 2016
- A new facility since 2017 (based on the CTF3 probe beam): CERN Linear Electron Accelerator for Research (CLEAR)
2-beam acceleration module in CTF3
CLIC accelerating structures

- R&D programme established
  gradient $O(100\text{MV/m})$

- Shorter pulses have less breakdowns

- 12 GHz (X-band)

- Break down rate (BDR): $p \leq 3 \cdot 10^{-7} \text{ m}^{-1} \text{pulse}^{-1}$
CLIC would be implemented in several energy stages

**Updated baseline scenario:**

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [GeV]</th>
<th>$L_{\text{int}}$ [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 (and 350)</td>
<td>1000</td>
</tr>
<tr>
<td>1500</td>
<td>2500</td>
</tr>
<tr>
<td>3000</td>
<td>5000</td>
</tr>
</tbody>
</table>

• The strategy can be adapted to possible discoveries at the (HL-)LHC or the initial CLIC stage(s)

• 1 year = $1.2 \times 10^7$ seconds (based on CERN experience)
CLIC at 380 GeV

Compact Linear Collider (CLIC)
- **380 GeV** - 11.4 km (CLIC380)
- Drive/main beam injector
- **LHC** - existing infrastructure

CERN
IP
LHC
Geneva
CLIC at 3 TeV

Compact Linear Collider (CLIC)
- **380 GeV** - 11.4 km (CLIC380)
- **1.5 TeV** - 29.0 km (CLIC1500)
- **3.0 TeV** - 50.1 km (CLIC3000)

LHC
CERN
Geneva

31/08/2018
Philipp Roloff
Physics at CLIC
• **Ongoing:** detailed bottom-up estimate of cost and power

• **Current estimate:** $O(6 \text{ GCHF})$ for 380 GeV stage, power $O(200 \text{ MW})$

• Considerable savings compared to CERN-2016-004 identified (2016 numbers were extrapolated from 500 GeV CLIC (CDR 2012) - 6.7 GCHF)
Comparison to other $e^+e^-$ collider options

**Linear colliders:**
- Can reach the highest energies
- Luminosity rises with energy
- Beam polarisation at all energies

**Circular colliders:**
- Large luminosity at lower energies
- Luminosity decreases with energy

**NB:** Peak luminosity at LEP2 (209 GeV) was $\approx 10^{32}$ cm$^{-2}$s$^{-1}$

CLIC is the only mature option for a multi-TeV $e^+e^-$ collider
CLIC experimental conditions

<table>
<thead>
<tr>
<th>CLIC at 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (cm(^{-2})s(^{-1}))</td>
</tr>
<tr>
<td>Bunch separation</td>
</tr>
<tr>
<td>#Bunches / train</td>
</tr>
<tr>
<td>Train duration</td>
</tr>
<tr>
<td>Train rep. rate</td>
</tr>
<tr>
<td>Crossing angle</td>
</tr>
<tr>
<td>Particles / bunch</td>
</tr>
<tr>
<td>(\sigma_x / \sigma_y) (nm)</td>
</tr>
<tr>
<td>(\sigma_z) ((\mu)m)</td>
</tr>
</tbody>
</table>

Drive timing requirements for CLIC detector

Very small beam profile at the interaction point

CLIC: trains at 50 Hz, 1 train = 312 bunches, 0.5 ns apart
Beam-induced backgrounds

Coherent $e^+e^-$ pairs:
7 $\cdot$ 10$^8$ per BX, very forward

Incoherent $e^+e^-$ pairs:
3 $\cdot$ 10$^5$ per BX, rather forward
→ Detector design issue (high occupancies)

$\gamma\gamma \rightarrow$ hadrons
• “Only” 3.2 events per BX at 3 TeV
• Main background in calorimeters and trackers
→ Impact on physics

$\gamma/\gamma^*$

$\gamma/\gamma^*$

Particles [1/BX]

3 TeV

BX = bunch crossing

Detector
Detector requirements

- **Momentum resolution**
  (e.g. Higgs recoil mass, $H \rightarrow \mu^+\mu^-$, leptons from BSM processes)
  \[
  \frac{\sigma(p_T)}{p_T^2} \sim 2 \times 10^{-5} \text{ GeV}^{-1}
  \]

- **Jet energy resolution**
  (e.g. $W/Z/h$ separation)
  \[
  \frac{\sigma(E)}{E} \sim 3.5 - 5\% \text{ for } E = 1000 - 50 \text{ GeV}
  \]

- **Impact parameter resolution**
  (b/c tagging, e.g. Higgs couplings)
  \[
  \sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3 \theta)}, \ a \approx 5 \mu m, \ b \approx 15 \mu m
  \]

- **Lepton identification, very forward electron tagging**
Detector requirements

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- **Lepton identification, very forward electron tagging**
CLIC detector concept

1.) Ultra low-mass vertex detector with $\approx 25 \times 25 \, \mu m^2$ pixels

2.) Main trackers: silicon-based (large pixels / short strips)

3.) Fine grained (PFA) calorimetry, $1 + 7.5 \, \lambda$

Instrumented return yoke for muon ID

Strong solenoid magnet (4 T)

Complex forward region with compact calorimeters

$\approx 11.4 \, m$
Background suppression

Beam-induced background from $\gamma \gamma \rightarrow$ hadrons can be efficiently suppressed by applying $p_T$-dependent timing cuts on individual reconstructed particles (= particle flow objects)

$e^+e^- \rightarrow t\bar{t}$ at 3 TeV with background from $\gamma \gamma \rightarrow$ hadrons overlaid

- **1.2 TeV background** in the reconstruction window ($\geq 10$ ns) around physics event
- **100 GeV background** after timing cuts
CLICdet performance in full simulation

**Tracking**

Transverse momentum resolution of $2 \times 10^{-5}$ GeV$^{-1}$ achieved for high-energy tracks in the barrel.

**Jet energy resolution**

CLICdp work in progress

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31/08/2018

Philipp Roloff

Physics at CLIC
Flavour tagging in full simulation

Example b- and c-tagging performances in $e^+e^- \rightarrow q\bar{q}$ events

$\sqrt{s} = 200$ GeV

CLICdp-Note-2014-002
Higgs physics:

• Single Higgs production

• Double Higgs production

• EFT analysis
Single Higgs production

**Higgsstrahlung:** $e^+e^- \rightarrow ZH$
- $\sigma \sim 1/s$, dominant up to $\approx 450$ GeV

**WW fusion:** $e^+e^- \rightarrow H \nu\bar{\nu}_e$
- $\sigma \sim \log(s)$, dominant above 450 GeV
- Large statistics at high energy

**ttH production:** $e^+e^- \rightarrow t\bar{t}H$
- Accessible $\geq 500$ GeV, maximum $\approx 800$ GeV
- Direct extraction of the top-Yukawa coupling
Using $Z \rightarrow e^+e^-$, $\mu^+\mu^-$:
- HZ events can be identified from the Z recoil mass
  → Model-independent measurement of the $g_{HZZ}$ coupling
- Best precision at 240/250 GeV (tracking resolution, beam energy spectra)

Using $Z \rightarrow q\bar{q}$:
- Almost model-independent measurement of $g_{HZZ}$ possible using hadronic Z decays
  → Substantial improvement in precision possible
- Better precision at 350 GeV found than at 250 GeV or 420 GeV

CLIC coupling sensitivity (1)

- No assumptions on additional Higgs decays (requires lepton collider)
- Correlations included where relevant
- All results limited by 0.6% from $\sigma(HZ)$ measurement
- The Higgs width is extracted with $4.7 - 2.5\%$ precision

CLIC coupling sensitivity (2)

Model dependent fit:
\[ K_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}} \]

Only SM Higgs decays:
\[ \frac{\Gamma_{H,md}}{\Gamma_H^{SM}} = \sum_i K_i^2 BR_i \]

**BR**\(_i\): SM branching fractions (prediction)

- Already the first CLIC stage significantly better than HL-LHC for several couplings
- The full program enhances the precision further
- \(\mu\mu, \gamma\gamma\) and \(Z\gamma\) would benefit from HL-LHC + CLIC combination

ATLAS-PHYS-PUB-2014-016
Double Higgs production

\( e^+e^- \rightarrow ZHH: \)
- Cross section maximum \( \approx 600 \text{ GeV} \), but very small number of events (\( \sigma \leq 0.2 \text{ fb} \))

\( e^+e^- \rightarrow HH\nu_e\bar{\nu}_e \) (CLIC):
- Allows simultaneous extraction of triple Higgs coupling, \( \lambda \), and quartic HHWW coupling
- Benefits from high-energy operation

**Projected precisions:**
- \( \Delta(\lambda) = 14\% \) for CLIC from total cross section assuming 5 ab\(^{-1}\) at 3 TeV
  \( \rightarrow \Delta(\lambda) \approx 10\% \) from differential distributions


<table>
<thead>
<tr>
<th>Model</th>
<th>( \Delta g_{hhh}/g_{hhh}^{SM} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>(-18%)</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>tens of %</td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>(-2%^a) (-15%^b)</td>
</tr>
<tr>
<td>NMSSM</td>
<td>(-25%)</td>
</tr>
</tbody>
</table>

Effective Field Theory:

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i \]

- Model-independent framework for probing indirect signs of new physics
  \[ \rightarrow \text{very useful for comparison of future collider options} \]
- **Input to fit:** Higgs measurements using WW-fusion and Higgsstrahlung,
  \[ e^+e^- \rightarrow W^+W^- \]
CLIC sensitivities to dimension-6 operators

Individual energy stages

- EFT analysis of Higgs and $W^+W^-$ production
- Lighter (darker) green bars include (omit) Higgsstrahlung at high energy
- Precision enhanced by higher centre-of-mass energy
- Sensitivity to new physics scales $\Lambda=O(10)\text{ TeV}$ for individual operators, reduces to $O(1)\text{ TeV}$ for global fit

JHEP 05, 096 (2017)
Combination of successive energy stages

→ The **global fit benefits from** the inclusion of earlier energy stages

- EFT analysis of Higgs and $W^+W^-$ production

**JHEP 05, 096 (2017)**
Top physics:

• Top quark mass

• Top electroweak couplings
Top-quark pair production

$e^+e^- \rightarrow t\bar{t}$:
- Production threshold at $\sqrt{s} \approx 2m_{top}$
- 380 GeV is near the maximum
  $\rightarrow$ large event samples (for rare decays etc.)

$e^+e^- \rightarrow t\bar{t}H$:
- Maximum near 800 GeV

$e^+e^- \rightarrow t\bar{t}v_e\bar{v}_e$ (Vector Boson Fusion):
- Benefits from highest energies
- Potential high-energy probe of the top Yukawa coupling
• Measurement at different centre-of-mass energies in the $t\bar{t}$ production threshold region (data also useful for Higgs physics)

• Expected precision on 1S mass: $\approx 50$ MeV (currently dominated by theory NNNLO scale uncertainty)

• Theoretical uncertainty in the order of 10 MeV when transforming the measured 1S mass to the $\overline{\text{MS}}$ mass scheme
  

• Other methods: ISR photons, direct reconstruction (less precise)

• Precision at the HL-LHC limited to several hundred MeV

arXiv:1807.02441
Top electroweak couplings

- Top quark pairs are produced via $Z/\gamma^*$ in electron-positron collisions
- The general form of the coupling can be described as:

$$\Gamma_{\mu}^{t\bar{t}V}(k^2, q, \bar{q}) = -ie \left\{ \gamma_\mu \left( F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2) \right) + \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left( F_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2) \right) \right\}$$

- New physics would modify the $t\bar{t}V$ vertex
- CLIC typically 1-2 orders of magnitude better than HL-LHC

CERN-2016-004

Boosted top reconstruction

$e^+e^- \rightarrow t\bar{t} \rightarrow q\bar{q}q\bar{q}b\bar{b}$ at $\sqrt{s} = 3$ TeV

- Hadronic decays of high-energy top quarks do not lead to three separated jets

- Instead, reconstruction of the top in a “large” jet and identification of substructure compatible with $t \rightarrow Wb \rightarrow q\bar{q}b$

- Studied $\approx 10$ years for the LHC, new and active effort for CLIC including different approaches

Example:
- John Hopkins top tagger
- High efficiency achieved in physics analyses (also due to moderate backgrounds in $e^+e^-$ collisions)

arXiv:1807.02441
Global EFT analysis of $\bar{t}t$ production

- High energy dramatically improves the sensitivity for the 4-fermion Operators $C_{lq,B}$, $C_{lq,W}$ and $C_{lt,B}$
- The global fit requires at least 2 energy stages

arXiv:1807.02441
Top-quark compositeness

Sensitivity to top-quark compositeness scales in the order of 10 TeV!

**Green area:** from $t \bar{t}H$ coupling

**Orange area:** from $t \bar{t}$ global fit

arXiv:1807.02441
Direct BSM searches
Direct searches

• Direct observation of new particles coupling to $\gamma^*/Z/W$ → precision measurement of new particle masses and couplings

• The sensitivity often extends up to the kinematic limit (e.g. $M \leq \sqrt{s} / 2$ for pair production)

• Very rare processes accessible due to low backgrounds (no QCD) → CLIC especially suitable for electroweak states

• Polarised electron beam and threshold scans might be useful to constrain the underlying theory
**Direct observation of sparticles**

**Example:** Phenomenological MSSM with 11 parameters

- Global fit to current experimental data (LHC results, low-energy and flavour experiments, CDM measurements)
- In this model, many gaugions and sleptons are accessible at CLIC, stop and sbottom are possible
  → Direct discoveries are (still) a **main motivation for high-energy CLIC operation**

```
• Blue lines: best fit values
• Orange bands: 68% & 95% CL ranges
```

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31/08/2018
Philipp Roloff
Physics at CLIC
Reconstruction of SUSY particles

Endpoints of energy spectra:

- $m(\tilde{\mu}_R) : \pm 5.6\text{ GeV}$
- $m(\tilde{e}_R) : \pm 2.8\text{ GeV}$
- $m(\tilde{\nu}_e) : \pm 3.9\text{ GeV}$
- $m(\tilde{\chi}_1^0) : \pm 3.0\text{ GeV}$
- $m(\tilde{\chi}_1^\pm) : \pm 3.7\text{ GeV}$

slepton masses: 1.0 - 1.1 TeV

$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

Jet reconstruction

Precision on the measured gaugino masses (few hundred GeV): 1 - 1.5%

- $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0W^+W^-$
- $e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow hh\tilde{\chi}_1^0\tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow Zh\tilde{\chi}_1^0\tilde{\chi}_1^0$

Complex final states:

- $e^+e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b}$
- $e^+e^- \rightarrow H^+H^- \rightarrow tb\bar{t}b$

$\approx 0.3\%$ precision on heavy Higgs masses
Exploration of future upgrades

- Exploration of novel acceleration methods for high-energy upgrades started → make sure CLIC is consistent with this

- Plasma-based acceleration demonstrated gradients of 50 GV/m
- Dielectric structures could lead to reduced cost

Main challenges:
- Preservation of beam quality has to be explored theoretically and experimentally
- Efficiency and beam stability
- Many technical challenges

Daniel Schulte, ICHEP 2018

Might be possible to reuse drive beam
SM processes at very high energies

Example: the knowledge of the Higgs self-coupling could be improved with respect to 3 TeV CLIC with a few ab$^{-1}$ at 10 TeV
Electroweak states at 10 TeV

- The pair production cross section is flat almost up to the kinematic limit
- Discovery potential even beyond FCC-hh
CLIC timeline

2013 - 2019 Development Phase
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start
Ready for construction; start of excavations

2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion
CLIC collaborations

**CLIC accelerator collaboration**

≈ 70 institutes from ≈ 70 countries
(incl. Argonne National Laboratory)

- CLIC accelerator design and development
- Construction and operation of CTF3

http://clic-study.web.cern.ch

**CLIC detector & physics (CLICdp)**

Collaboration: 30 institutes from 18 countries
(incl. Argonne National Laboratory)

- Physics prospects and simulation studies
- Detector optimisation and R&D for CLIC

http://clicdp.web.cern.ch
Summary and conclusions

• CLIC is the only mature option for a multi-TeV electron-positron collider

• Very active R&D projects for accelerator and physics/detector

• Energy-staging → optimal for physics:

<table>
<thead>
<tr>
<th>Energy</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 GeV</td>
<td>Optimised for precision SM Higgs and top physics</td>
</tr>
<tr>
<td>1.5 TeV, 3 TeV</td>
<td>Best sensitivity for BSM searches, rare Higgs processes and decays</td>
</tr>
</tbody>
</table>

• 380 GeV CLIC could be ready for physics in 2035 – at “affordable” cost

• The energies of the TeV stages will depend on the LHC results
Backup slides
**Closer look at $\sqrt{s} < 500$ GeV**

- $\sqrt{s} = 240/250$ GeV: 
  (CEPC, FCC-ee, ILC)
  Maximum of the Higgsstrahlung cross section

- $\sqrt{s} = 350/380$ GeV: 
  (FCC-ee, ILC, CLIC)
  Also allows to access the WW fusion process
  → Additional information for combined analysis
σ x BR measurements

At 350 GeV:
Higgsstrahlung

\[ \sigma \sim g_{HZZ}^2 g_{HVV/Hff}^2 / \Gamma_H \]

+ BR(H→inv.) < 0.97% at 90% CL

At 350 GeV and higher:
WW fusion

\[ \sigma \sim g_{HWW}^2 g_{HVV/Hff}^2 / \Gamma_H \]
Invisible Higgs decays

The recoil mass technique also allows to identify invisible Higgs decays in a model-independent manner.

**Example:**
\[ \text{BR}(H \rightarrow \text{inv.}) < 0.97\% \text{ at } 90\% \text{ CL for CLIC at } 350 \text{ GeV} \]
Top electroweak couplings

- Top quark pairs are produced via Z/γ* in electron-positron collisions

- The general form of the coupling can be described as:

\[
\Gamma^{t\bar{t}V}_{\mu}(k^2, q, \bar{q}) = -ie \left\{ \gamma_{\mu} \left( F^V_{1V}(k^2) + \gamma_5 F^V_{1A}(k^2) \right) + \frac{\sigma^{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left( i F^V_{2V}(k^2) + \gamma_5 F^V_{2A}(k^2) \right) \right\}
\]

- New physics would modify the t\bar{t}V vertex

[Graph showing cross section as a function of \( \sqrt{s} \) in GeV]

Results: form factors

• The expected precisions for CLIC are 1-2 orders of magnitude better than for HL-LHC
• Interesting top physics program at the first CLIC stage at 380 GeV!
What about $t\bar{t}$ at high energy?

Dependence of $\sigma(e^+e^- \to t\bar{t})$ on dimension-6 operators:

$$\frac{1}{\sigma} \frac{\partial \sigma}{\partial \tilde{C}_i} \bigg|_{\tilde{C}_i=0, \forall i} \equiv S_i^\sigma$$

- **Four-fermion operators:**
  - Sensitivity rises steeply with energy
  - Best measured at high energy

- **Vertex operators:**
  - Sensitivity flat in energy for several operators
  - Best measured at 380 GeV (most $t\bar{t}$ events)

The top pair production measurements at 380 GeV and at high energy provide complementary information.

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Durieux, Perelló, Vos, Zhang, to be published
Vector boson scattering

- Vector boson scattering (VBS) gives insight into the mechanism of electroweak symmetry breaking.

- Investigated processes for high-energy CLIC operation:

\[
\begin{align*}
    e^+e^- &\rightarrow W^+W^-\nu\bar{\nu} \\
    e^+e^- &\rightarrow ZZ\nu\bar{\nu}
\end{align*}
\]

- Search for additional resonances or anomalous couplings.

- The sensitivity rises steeply with the centre-of-mass energy.

\[
\begin{align*}
    \mathcal{L}_{S,0} &= F_{S,0} \quad \text{tr} \left[ (D_\mu H)^\dagger D_\nu H \right] \quad \text{tr} \left[ (D_-^\mu H)^\dagger D_-^\nu H \right] \\
    \mathcal{L}_{S,1} &= F_{S,1} \quad \text{tr} \left[ (D_\mu H)^\dagger D_-^\mu H \right] \quad \text{tr} \left[ (D_-^\nu H)^\dagger D_-^\nu H \right]
\end{align*}
\]

VBS: experimental aspects

- At CLIC fully hadronic events can be used (in contrast to hadron colliders):
  \[ W^+W^-\nu\bar{\nu}/ZZ\nu\bar{\nu} \rightarrow qqqq\nu\nu \]
  \[ \rightarrow \text{largest event samples and full kinematic information} \]

- Extract the operator coefficients \( \alpha_4 \) and \( \alpha_5 \) from invariant mass of the final-state bosons

- Most important background after event selection: \( e^\pm\gamma_{BS} \rightarrow qqqq\nu \)
  \( (\gamma_{BS}: \text{photon originating from Beamstrahlung}) \)

\[
\alpha_4 = F_{S,0} \frac{v^4}{16} \\
\alpha_5 = F_{S,1} \frac{v^4}{16}
\]
**VBS: results**

**CLIC, $\sqrt{s} = 1.4$ TeV**

1D fit (68% CL):
- $-0.0082 < \alpha_4 < 0.0116$
- $-0.0055 < \alpha_5 < 0.0078$

**CLIC, $\sqrt{s} = 3$ TeV**

1D fit (68% CL):
- $-0.00102 < \alpha_4 < 0.00112$
- $-0.00070 < \alpha_5 < 0.00074$

→ Sensitivity almost one order of magnitude better at 3 TeV
VBS: comparison to LHC

ATLAS, $\sqrt{s} = 8$ TeV

CLIC, $\sqrt{s} = 3$ TeV

1D fit (68% CL):
- $-0.00102 < \alpha_4 < 0.00112$
- $-0.00070 < \alpha_5 < 0.00074$

→ Sensitivity significantly better than 8 TeV LHC

arXiv:1610.07572
Precision study of $e^+e^- \rightarrow \mu^+\mu^-$

Minimal anomaly-free $Z'$ model:
Charge of the SM fermions under $U(1)'$ symmetry:
$$Q_f = g'_Y(Y_f) + g'_{BL}(B-L)_f$$

Observables:
- total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- forward-backward-asymmetry
- left-right asymmetry ($\pm 80\% e^-$ polarisation)

If LHC discovers $Z'$ (e.g. for $M = 5$ TeV):
Precise measurement of the effective couplings

Otherwise:
Discovery reach up to tens of TeV (depending on the couplings)

Blaising, Wells, arXiv:1208.1148
New physics searches with $e^+e^- \rightarrow \gamma\gamma$: deviation from QED expectation

Events with small energy loss due to Beamstrahlung and ISR are selected → two back-to-back photons (track veto crucial)

Signal and main background

After selection:
e^+e^- → γγ: results and interpretation

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\Lambda_{\pm}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Born}} \pm \frac{\alpha^2 s}{2\Lambda_{\pm}^4} (1 + \cos^2 \theta)
\]

**Example:** QED cutoff parameter Λ (simplest Ansatz)

**CLIC:** \( L = 2 \text{ ab}^{-1}, \Delta L/L = 0.5\% \)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CLIC reach (95% CL)</th>
<th>LEP limit (95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED cutoff parameter Λ</td>
<td>6.33 TeV</td>
<td>≈390 GeV</td>
</tr>
<tr>
<td>(electron size)</td>
<td>(3.1 \cdot 10^{-18} \text{ cm})</td>
<td></td>
</tr>
<tr>
<td>Contact interactions: Λ'</td>
<td>20.1 TeV</td>
<td>≈830 GeV</td>
</tr>
<tr>
<td>Extra dimensions: ( M_s/\Lambda^{1/4} )</td>
<td>15.9 TeV</td>
<td>≈1 TeV</td>
</tr>
<tr>
<td>Excited electron: ( M(e^*) )</td>
<td>4.87 TeV</td>
<td>≈250 GeV</td>
</tr>
</tbody>
</table>

\( \text{CLIC}_dp \) \( \sqrt{s} = 3 \text{ TeV}, L = 2 \text{ ab}^{-1} \)

→ CLIC at 3 TeV factor 15 - 30 better than the LEP limits
Heavy electroweak states (1)

There is potential for a direct discovery at CLIC even without a signal at the HL-LHC.

**Example:** chargino + neutralino production and decay to W/Z

Indicative CLIC reach at $\sqrt{s} = 3$ TeV

(CMS-PAS-FTR-13-014)

(similar projection: ATL-PHYS-PUB-2014-010)
There is potential for a direct discovery at CLIC even without a signal at the HL-LHC

**Example:** stau pair production

Indicative CLIC reach at $\sqrt{s} = 3$ TeV

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**ATLAS Simulation Preliminary**

$\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$, $\mu > 200$

- $\sigma_{tag}$=30%, 5 σ discovery
- $\sigma_{tag}$=30%, 95% excl
- $\sigma_{tag}$=50%, 5 σ discovery
- $\sigma_{tag}$=50%, 95% excl
- $\sigma_{tag}$=30%, 95% excl
- $\sigma_{tag}$=20%, 95% excl

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ATLAS-PHYS-PUB-2016-021
CLIC cost estimate

Preliminary estimate (scaled from CDR) with room for improvement. New estimate will be provided for European Strategy Update.

<table>
<thead>
<tr>
<th>System</th>
<th>Value for 380 GeV (MCHF of Dec 2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main beam production</td>
<td>1245</td>
</tr>
<tr>
<td>Drive beam production</td>
<td>974</td>
</tr>
<tr>
<td>Two-beam accelerators</td>
<td>2038</td>
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<tr>
<td>Interaction region</td>
<td>132</td>
</tr>
<tr>
<td>Civil engineering &amp; services</td>
<td>2112</td>
</tr>
<tr>
<td>Accelerator control &amp; operation infrastructure</td>
<td>216</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>6690</strong></td>
</tr>
</tbody>
</table>

Value for the CLIC accelerator at $\sqrt{s} = 380$ GeV (11.4 km site length)

Lucie Linssen, EP seminar, January 24, 2017
CLIC accelerator R&D

Mechanical tests of 2-beam module  Prototype final focus quadrupole  Tunable permanent magnet

Accelerator structure, 1 disk  Brazing of a CLIC structure  Cut through a CLIC acceleration structure

31/08/2018  Philipp Roloff  Physics at CLIC