CLIC overview

Philipp Roloff (CERN)
on behalf of the CLICdp collaboration

07/09/2017
Corfu Summer Institute:
Workshop on the Standard Model and Beyond
Introduction:

• CLIC accelerator

• Staged implementation

• Detector requirements and concept
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 ($\sqrt{s} > 350$ GeV) require linear colliders

- Clean experimental environment
  → Less / no need for triggers
  → Lower radiation levels
pp and $e^+e^-$ collisions

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

**$e^+e^-$ collisions:**
More “clean”, all events usable
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
$\sqrt{s} = 90 - 350$ GeV
Circumference: 97.75 km

International Linear Collider (ILC): Japan (Kitakami)
$\sqrt{s} = 250 - 500$ GeV (1 TeV)
Length: 17 km, 31 km (50 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
  (in several stages)
- 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
CLIC layout at 3 TeV

- Drive Beam
  - Drive beam accelerator: 2.4 GeV, 1.0 GHz
  - 540 klystrons, 20 MW, 148 μs
  - 2.5 km delay loop
  - CR1: 293 m, CR2: 439 m

- Main Beam
  - Booster linac: 2.86 to 9 GeV

- e⁻ main linac: 12 GHz, 72/100 MV/m, 21 km
- e⁺ main linac

- TA: turnaround
- CR: combiner ring
- DR: damping ring
- PDR: predamping ring
- BC: bunch compressor
- BDS: beam delivery system
- IP: interaction point
- Ump

- 540 klystrons: 20 MW, 148 μs
- 2.5 km delay loop
- Circumferences: 73 m

07/09/2017  Philipp Roloff  CLIC overview
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)**
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
CLIC staged implementation

CLIC would be implemented in several energy stages

Baseline scenario:

<table>
<thead>
<tr>
<th>Stage</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$L_{\text{int}}$ ($\text{fb}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>350</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

→ The strategy can be adapted to possible LHC discoveries at 13/14 TeV!
New baseline scenario

- Initial stage at 380 GeV optimised for Higgs and top measurements (including $t\bar{t}$ threshold scan)
- Baseline scenario of 22 years presented in CERN-2016-004

**NB:** Many physics studies in the following assume a slightly different scenario (500 fb$^{-1}$ at 350 GeV, 1.5 ab$^{-1}$ at 1.4 TeV, 3 ab$^{-1}$ at 2 TeV)
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
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)

  $$\sigma(d_0) = \sqrt{a^2 + b^2 \cdot GeV^2 / (p^2 \sin^3 \theta)}, \quad a \approx 5 \mu m, \quad b \approx 15 \mu m$$

- **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 ≈ 25 x 25 μm² pixels

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

3.) Fine grained (PFA) calorimetry, 1+7.5 λ

Strong solenoid magnet (4 T)

Instrumented return yoke for muon ID

Complex forward region with compact calorimeters

≈11.4 m
Higgs physics:

• Single Higgs production
  • EFT analysis
• Double Higgs production
Single Higgs production

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

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

**$t\bar{t}H$ production:** $e^+e^- \to t\bar{t}H$
- 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

Higgs properties at CLIC

Fully model-independent analysis only possible at lepton colliders

NB: All projections are based on benchmark studies using full detector simulations

BSM potential of Higgs production & $e^+e^- \rightarrow W^+W^-$

**Effective Field Theory:**

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

- **Standard Model**
- **Dimension-6 operators**
- **Scale of new decoupled physics**

- **Model-independent framework for probing indirect signs of new physics**
  \( \rightarrow \text{very useful for comparison of future collider options / parameters} \)

- **Input to fits:** Higgs production in Higgsstrahlung and WW fusion, $e^+e^- \rightarrow t\bar{t}H$, weak boson pair production: $e^+e^- \rightarrow W^+W^-$
Comparison of different collider options

Many EFT parameters can be measured significantly better at CLIC compared to the HL-LHC

$H \rightarrow c \bar{c}$ only accessible in at lepton colliders

arXiv:1704.02333
see also JHEP 1705, 096 (2017)
Double Higgs production

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

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

Projected precisions:
- \(\Delta(\lambda) = 16\%\) for CLIC from total cross section assuming 3 \(a b^{-1}\) at 3 TeV
  \((\rightarrow \Delta(\lambda) \approx 10\%\) from differential distributions\)

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Top physics:

• Top quark mass

• Top electroweak couplings
### Top quark mass

**tt threshold scan:**

- 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 (independent of accelerator, 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

  \[ \text{Phys. Rev. Lett. 114, 142002 (2015)} \]

- Precision at the LHC limited to several hundred MeV

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**Graph:**

- $t\bar{t}$ threshold scan - Beneke et al. NNNLO - $\mu = 80$ GeV
- ISR + ILC LS, mass fit incl. scale uncertainties
- default - $m_t^{\text{PS}}$ 171.5 GeV
- best fit template, $m_t^{\text{PS}}$ 171.45 GeV
- mass variations $\pm 0.2$ GeV

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**Notes:**

- Preliminary based on CLIC/ILC Top Study EPJ C73, 2530 (2013)

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**Author:**

Frank Simon, topLC 2017
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:

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

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

CLIC 1-2 orders of magnitude better than HL-LHC

**Interesting top physics program at the first CLIC stage at 380 GeV**
Precision measurements and direct BSM searches:

- Vector boson scattering

- $Z'$ using $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \gamma\gamma$

- Direct BSM searches
Vector boson scattering

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

- Example processes investigated for high-energy CLIC operation:
  
  \[
  e^+e^- \rightarrow W^+W^-\bar{\nu}\bar{\nu} \\
  e^+e^- \rightarrow ZZ\bar{\nu}\bar{\nu}
  \]

- Search for additional resonances or anomalous couplings.

- At CLIC fully hadronic events can be used (in contrast to hadron colliders):
  
  \[
  W^+W^-\bar{\nu}\bar{\nu}/ZZ\bar{\nu}\bar{\nu} \rightarrow qqqqq\bar{\nu}\bar{\nu}
  \]

  \rightarrow largest event samples and full kinematic information.
VBS: results and 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
Other precision measurements benefiting from high energy

**Example:** $Z'$ using $e^+e^- \rightarrow \mu^+\mu^-$

HL-LHC sensitive up to $\approx 7$ TeV

CLIC provides discovery reach up to tens of TeV

$$Q_f = g_Y(Y_f) + g_{BL}(B-L)_f$$

arXiv:1208.1148

**Example:** $e^+e^- \rightarrow \gamma\gamma$

Unique to lepton colliders, CLIC about 15 times better than LEP 2

$\sqrt{s} = 3$ TeV, $L = 2$ ab$^{-1}$

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

Endpoints of energy spectra:

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

Jet reconstruction

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

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

Complex final states:

\[ e^+ e^- \rightarrow HA \rightarrow b\bar{b}b\bar{b} \]
\[ e^+ e^- \rightarrow H^+ H^- \rightarrow t\bar{b}t\bar{b} \]

\( \approx 0.3\% \) precision on heavy Higgs masses
The CLIC studies are carried by two active collaborations:
• CLIC accelerator collaboration: http://clic-study.web.cern.ch/
• CLIC detector and physics collaboration: http://clicdp.web.cern.ch/

Together ≈ 80 institutes

Upcoming events:
• LCWS 2017: http://agenda.linearcollider.org/event/7645/
• CLIC Workshop 2018: http://indico.cern.ch/event/656356/
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 Focus</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>

• The energies of the TeV stages will depend on the LHC results
Backup slides
CLIC accelerating structures

R&D programme established gradient O(100MV/m)

Shorter pulses have less breakdowns

Now focussing on:
• Further improvements
• Preparation for mass production
• Cost reduction

12 GHz (X-band)
Break down rate (BDR):
\[ p \leq 3 \cdot 10^{-7} \text{ m}^{-1}\text{pulse}^{-1} \]

\[ \approx 25 \text{ cm} \]
2-beam acceleration module in CTF3
## CLIC experimental conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (cm$^{-2}$s$^{-1}$)</td>
<td>$5.9 \cdot 10^{34}$</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>#Bunches / train</td>
<td>312</td>
</tr>
<tr>
<td>Train duration</td>
<td>156 ns</td>
</tr>
<tr>
<td>Train rep. rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>20 mrad</td>
</tr>
<tr>
<td>Particles / bunch</td>
<td>$3.72 \cdot 10^9$</td>
</tr>
<tr>
<td>$\sigma_x / \sigma_y$ (nm)</td>
<td>$\approx 45 / 1$</td>
</tr>
<tr>
<td>$\sigma_z$ ($\mu$m)</td>
<td>44</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

$\gamma/\gamma^*$
$q \bar{q}$

$\gamma\gamma \rightarrow$ hadrons

3 TeV

$10^{10}$
$10^8$
$10^6$
$10^4$
$10^2$
$10^{-2}$
$10^{-4}$
$10^{-6}$

Particles [1/BX]

$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$1$

$\theta$ [rad]

$\theta$ [rad]

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$1$

Coherent Pairs
Incoherent Pairs
Trident Pairs
$\gamma\gamma \rightarrow$ Hadrons

BX = bunch crossing
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)

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

1.2 TeV background in the reconstruction window ($\geq 10 \text{ ns}$) around physics event

100 GeV background after timing cuts
Closer look at $\sqrt{s} < 500 \text{ GeV}$

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

$\sqrt{s} = 350/380 \text{ GeV}$: (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

\[ \sigma \sim g_{HWW}^2 g_{HVV/Hff}^2 / \Gamma_H \]
Higgs properties at CLIC (1)

- Fully model-independent analysis only possible at lepton colliders
- All results limited by 0.8% from $\sigma(HZ)$ measurement
- The Higgs width is extracted with 6.7-3.5% precision
Higgs properties at CLIC (2)

Model dependent fit:

\[ \kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}} \]

\( \text{BR}_i \): SM branching fractions (prediction)

Only SM Higgs decays:

\[ \frac{\Gamma_{H,\text{md}}}{\Gamma_H^{SM}} = \sum_i \kappa_i^2 \text{BR}_i \]

- Significantly better than HL-LHC or not possible at hadron colliders
- Similar to HL-LHC
Invisible Higgs decays

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

Example:
BR(H→inv.) < 0.97% at 90% CL for CLIC at 350 GeV

Recoil mass from $Z \rightarrow q\bar{q}$ assuming all Higgs bosons decay invisibly.
CLIC sensitivities to dimension-6 operators

Individual CLIC energy stages

Sensitivity enhanced by higher centre-of-mass energy

JHEP 1705, 096 (2017)
What about $t\bar{t}$ at high energy?

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

\[
\frac{1}{\sigma} \left. \frac{\partial \sigma}{\partial \tilde{C}_i} \right|_{\tilde{C}_i=0, \forall i} \equiv S^\sigma_i
\]

- **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.
Boosted top reconstruction at CLIC

- 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
- Also useful for $t\bar{t}H$, top squarks, ... 

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

• At CLIC fully hadronic events can be used (in contrast to hadron colliders):
  \[ W^+W^-\nu\bar{\nu}/ZZ\nu\bar{\nu} \rightarrow q\bar{q}q\bar{q}\nu\nu \]
  → 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: \( e^\pm\gamma_{\text{BS}} \rightarrow q\bar{q}q\bar{q}\nu \)
  (\( \gamma_{\text{BS}} \): photon originating from Beamstrahlung)

\[
\begin{align*}
\alpha_4 &= F_{S,0} v^4/16 \\
\alpha_5 &= F_{S,1} v^4/16
\end{align*}
\]
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
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:
$e^+e^- \rightarrow \gamma\gamma$: 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 $\Lambda$
(simplest Ansatz)

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

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  $(3.1 \cdot 10^{-18} \text{ cm})$ | $\approx 390 \text{ GeV}$ |
| Contact interactions: $\Lambda'$      | 20.1 TeV              | $\approx 830 \text{ GeV}$ |
| Extra dimensions: $M_s / \Lambda^{1/4}$| 15.9 TeV              | $\approx 1 \text{ TeV}$  |
| Excited electron: $M(e^*)$            | 4.87 TeV              | $\approx 250 \text{ GeV}$ |

$\rightarrow$ 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

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>
</tr>
<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>TOTAL</td>
<td>6690</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 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