Physics at CLIC

7th international conference on High Energy Physics in the LHC era
UTFSM, Valparaiso, Chile

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Thanks to my CLICdp colleagues
Compact Linear Collider (CLIC)

- **380 GeV** - 11.4 km (CLIC380)
- **1.5 TeV** - 29.0 km (CLIC1500)
- **3.0 TeV** - 50.1 km (CLIC3000)
e+e- Colliders

CLIC: CERN; cm energy 0.38, 1.5, 3 TeV; length 11, 29, 50 km

FCC-ee: CERN; cm energy 90-350 GeV; circumference 97 km

ILC: Japan; cm energy 250-500 GeV (1 TeV) length: 17-31 km (50 km)

CEPC: China; cm energy 240 GeV circumference: 100 km
CLIC Collaborations

- CLIC accelerator collaboration: http://clic-study.web.cern.ch/
- CLIC detector and physics collaboration (CLICdp): http://clicdp.web.cern.ch/
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
Higgs Physics

- Production
- Higgsstrahlung at 350 GeV
- Higgsstrahlung at 250, 350, and 420 GeV
- Higgs physics above 1 TeV
- Double Higgs production
Higgs Physics at CLIC

Dominant processes:

- **Higgsstrahlung**
  \( \sigma \sim \frac{1}{s} \)
  Dominant up to \( \sim 450 \text{ GeV} \)

- **WW (ZZ) – fusion**
  \( \sigma \sim \log(s) \)
  Dominant above \( \sim 450 \text{ GeV} \)

- **ttH Production**
  Accessible at above \( \sim 500 \text{ GeV} \)
  Maximum at \( \sim 800 \text{ GeV} \)

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For unpolarized beams.

Hvv increases \( \times 1.8 \) for -80% e- polarization
(CLIC baseline)
Higgsstrahlung $e^+e^- \rightarrow ZH$ at $\sqrt{s}\sim 350$ GeV

ZH events, identified through recoil mass against Z.

$$m_{rec}^2 = s + m_Z^2 - 2\sqrt{s}E_Z$$

Model independent measurement

$$\sigma(e^+e^- \rightarrow ZH) \sim g_{HZZZ}^2$$

B(Z→ee)≈3.5%, very clean; \hspace{1cm} \Delta(\sigma_{HZ})=±3.8%

B(Z→μμ)≈3.5%, very clean; \hspace{1cm} \Delta(\sigma_{HZ})=±3.8%

B(Z→qq)≈70%, almost model independent; \hspace{1cm} \Delta(\sigma_{HZ})=±1.8%

\hspace{1cm} \Delta(g_{HZ})=±0.8%

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>56.1 %</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>23.1 %</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>8.5 %</td>
</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>6.2 %</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>2.8 %</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>2.9 %</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>0.23 %</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>0.16 %</td>
</tr>
<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>0.021 %</td>
</tr>
</tbody>
</table>

$\Gamma_H$ 4.2 MeV

EPJC 77, 475 (2017)
Higgsstrahlung $e^+e^- \rightarrow ZH$ at $\sqrt{s} \sim 250, 350, 420$ GeV

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>$\sigma$(HZ) (fb)</th>
<th>$\Delta \sigma_{\text{vis.}}$ (%)</th>
<th>$\Delta \sigma_{\text{invis.}}$ (%)</th>
<th>$\Delta \sigma$(HZ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>500</td>
<td>136</td>
<td>$\pm 3.63$</td>
<td>$\pm 0.45$</td>
<td>$\pm 3.65$</td>
</tr>
<tr>
<td>350</td>
<td>500</td>
<td>93</td>
<td>$\pm 1.71$</td>
<td>$\pm 0.56$</td>
<td>$\pm 1.80$</td>
</tr>
<tr>
<td>420</td>
<td>500</td>
<td>68</td>
<td>$\pm 2.42$</td>
<td>$\pm 1.02$</td>
<td>$\pm 2.63$</td>
</tr>
</tbody>
</table>
Higgs Physics above 1 TeV

Vector boson fusion.
- $e^+e^- \rightarrow H\nu\nu$; $e^+e^- \rightarrow He^e$
- High cross section.
- Combined with increased luminosity: access to rare Higgs decay.

_ttH production._
- Extraction of top quark Yukawa coupling
- Best above 700 GeV
- $\Delta(g_{tt})=\pm4.2\%$, 1.4 TeV, 1.5 ab$^{-1}$

\[
\frac{g_{HWW}}{g_{HZZ}} = \cos^2 \theta_W
\]
Measured to $\sim1\%$ level
Double Higgs Production

\( e^+e^- \rightarrow ZHH \): Cross section maximum at \( \sim 600 \) GeV, but very small number of events.

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

Expected precision: \( \Delta(\lambda) = 16\% \) assuming 3 ab\(^{-1}\) at 3 TeV (10% using differential distributions).
Combined Higgs Couplings

- Full CLIC program: ~5 years at each stage, 80% e- polarization above 1 TeV.
- Model independent measurements: 1-2% for most the couplings.
- Accuracy on the Higgs width: ~3.5%
- Green circles: accuracy significantly better than HL-LHC.
- Red circles: accuracy comparable to HL-LHC.

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Top Physics

- Top quark mass
- Top quark electroweak couplings
Top Quark Mass

- CLIC will make a dedicated scan near the threshold for a top quark pair production.
- Cross section is very sensitive to the top quark pole mass.
- Uncertainty $\Delta m_t \sim 50$ MeV (dominated by theory).
- In $e^+e^-$ colliders top quark pairs appear through $Z/\gamma^*$ in the $s$-channel.
Top Quark Electroweak Couplings

- Top quark pairs are produced via $Z/\gamma^*$ in electron positron collisions
- New physics modifies the $ttV$ coupling, whose general form is,

$$\Gamma^{ttV}_\mu(k^2, q, \bar{q}) = -ie \left\{ \gamma^\mu \left( F^V_{1V}(k^2) + \gamma_5 F^V_{1A}(k^2) \right) + \frac{\sigma^{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left( iF^V_{2V}(k^2) + \gamma_5 F^V_{2A}(k^2) \right) \right\}$$

Green: CP conserved
Red: CP violated

arXiv:1608.07537
arXiv:1710.06737
Beyond the Standard Model

- Vector Boson Scattering
- Supersymmetry Direct Searches
- Non-doublet scalars
\[ \alpha_4 \mathcal{L}_4 = \alpha_4 \text{tr}[V_\mu V_\nu] \text{tr}[V^\mu V^\nu], \]
\[ \alpha_5 \mathcal{L}_5 = \alpha_5 \text{tr}[V_\mu V^\mu] \text{tr}[V_\nu V^\nu], \]

Anomalous couplings.

arXiv:1609.05122
Supersymmetry Direct Searches

- Direct observation of susy particles couplings to $\gamma/Z \rightarrow$ precision measurements of susy particle masses and couplings.

- The sensitivity often extends up to the kinematic limit (e.g. up to $\sqrt{s}/2$ for the mass of the new particle in the case of pair production).

- Very rare processes accessible due to low backgrounds (no QCD). CLIC is specially equipped for electroweak states.

- The possibility for polarized electron beams and threshold scans can potentially constrain even more the underlying theory.
Large part of the SUSY spectrum measured at <1% level.
Non-doublet scalar fields

The largest production mechanism at a hadron collider only works for a scalar $H$ with a large doublet component.

In particular, it does not work for a pure triplet commonly present in models that give mass to neutrinos.

This is an important production mode at an electron-positron collider.

It is not penalized if the field $H$ is purely triplet.

Conclusions

• CLIC is a mature option for a multi-TeV electron-positron collider
• It includes three stages, at 0.38, 1.5 and 3 TeV.
• It can study the Higgs boson with precision (relevant for physics beyond the SM).
• It can study the top quark mass and anomalous couplings.
• Double Higgs production can be achieved (relevant for the mechanism of SSB).
• Double vector boson fusion can be achieved, with anomalous coupling well determined.
• Supersymmetric partners can be studied with detail.
• Non doublet scalars are favored in electron-positron colliders

Thanks!