Higgs and BSM physics at CLIC

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on behalf of the CLICdp collaboration
Future linear electron-positron collider providing high luminosity: few x $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

CLIC would be implemented in energy stages, defined by physics and technical considerations.

Staged construction gives access to three centre of mass energies:

Stage 1: $500 \text{ fb}^{-1}$ at $\sqrt{s} = 350 \text{ GeV}$
- SM Higgs and top physics, top threshold scan

Stage 2: $1.5 \text{ ab}^{-1}$ at $\sqrt{s} = 1.4 \text{ TeV}$
- Improved Higgs precision, top Yukawa coupling, first BSM searches

Stage 3: $2 \text{ ab}^{-1}$ at $\sqrt{s} = 3 \text{ TeV}$
- Rarest Higgs processes, double Higgs production, best BSM sensitivity

Each stage corresponds to 4-5 years data taking.
Detectors, beam conditions and backgrounds

Physics studies in this talk use the CLIC_SiD and CLIC_ILD detector concepts

CLIC beams consist of short dense bunch trains
- enables power-pulsing, triggerless readout
- results in pile-up of beam-induced backgrounds

All studies use full physics and detector simulation

All reconstructed particles

After background reduction from time and momentum cuts
Single Higgs production at CLIC

Large samples of Higgs bosons will be produced at CLIC

<table>
<thead>
<tr>
<th></th>
<th>350 GeV</th>
<th>1.4 TeV</th>
<th>3 TeV</th>
</tr>
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<tbody>
<tr>
<td>ZH</td>
<td>68,000</td>
<td>20,000</td>
<td>11,000</td>
</tr>
<tr>
<td>Hvv</td>
<td>17,000</td>
<td>370,000</td>
<td>830,000</td>
</tr>
<tr>
<td>Hee</td>
<td>3,700</td>
<td>37,000</td>
<td>84,000</td>
</tr>
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Polarising the electron beam (80%) enhances WW-fusion by a factor 1.8

but benchmark studies assume unpolarised beams

Measurements at high √s require good detectors in the forward region
Higgsstrahlung at $\sqrt{s} = 350$ GeV

Identify HZ events from only the Z recoil mass: model independent measurement of $g_{HZZ}$

- very clean for $Z \rightarrow \mu\mu$, ee decays: 2% uncertainty on $g_{HZZ}$
- also possible for hadronic Z decays with minimal bias: 0.9% uncertainty on $g_{HZZ}$

Combined uncertainty 0.8% on model independent measurement of $g_{HZZ}$

Cross section x branching ratio measurements:

- precision at few % level

Constrain the invisible Higgs decay < 1% at 90% CL

<table>
<thead>
<tr>
<th>Stat precision</th>
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<tbody>
<tr>
<td>$\sigma(ZH) \times \text{BR}(H \rightarrow \tau\tau)$</td>
</tr>
<tr>
<td>$\sigma(ZH) \times \text{BR}(H \rightarrow bb)$</td>
</tr>
<tr>
<td>$\sigma(ZH) \times \text{BR}(H \rightarrow cc)$</td>
</tr>
<tr>
<td>$\sigma(ZH) \times \text{BR}(H \rightarrow gg)$</td>
</tr>
<tr>
<td>$\sigma(ZH) \times \text{BR}(H \rightarrow WW^*)$</td>
</tr>
<tr>
<td>$\sigma(Hvv) \times \text{BR}(H \rightarrow bb)$</td>
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</table>
Precision Higgs measurements at $\sqrt{s} > 1$ TeV

$H \rightarrow bb, cc, gg$

Separation of the different hadronic final states uses precise flavour tagging

Very challenging at the LHC

Higgs mass can be extracted from the $H \rightarrow bb$ invariant mass distribution: $\pm 33$ MeV at 3 TeV

<table>
<thead>
<tr>
<th>$\sigma(Hvv)\times BR(H \rightarrow ff)$</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>0.2%</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>2.7%</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

$H \rightarrow bb, cc, gg$

Separation of the different hadronic final states uses very precise flavour tagging

Very challenging at the LHC

Higgs mass can be extracted from the $H \rightarrow bb$ invariant mass distribution: $\pm 33$ MeV at 3 TeV

Unpolarised beams
Rare Higgs decays at $\sqrt{s} > 1$ TeV

$\sigma(\text{Hvv}) \times \text{BR}(H \rightarrow \mu \mu)$
- $\text{BR} \sim 0.022\%$
- requires precise tracking
- 38% at 1.4 TeV, 16% at 3 TeV

$\sigma(\text{Hvv}) \times \text{BR}(H \rightarrow \gamma \gamma)$
- $\text{BR} \sim 0.23\%$
- reconstructed $\gamma \gamma$ mass resolution 3.3 GeV
- 15% at 1.4 TeV

$\sigma(\text{Hvv}) \times \text{BR}(H \rightarrow Z \gamma)$
- $\text{BR} \sim 0.16\%$
- hadronic $Z$ decays used
- 42% at 1.4 TeV
Top Yukawa coupling at $\sqrt{s} = 1.4$ TeV

The $ttH$ cross section is directly sensitive to the top Yukawa coupling. $ttH$ production peaks at ~800 GeV, measured at 1.4 TeV. But main backgrounds also falling.

- 6 jet + lepton + missing energy final state (semi-leptonic)
- 8 jet final state (fully hadronic)

Combined uncertainty on the top Yukawa coupling 4.5%
Comparable to other measurements at 1 TeV
The HHvv cross section is sensitive to the Higgs self-coupling and the quartic coupling

Only 225 (1200) HHvv events at $\sqrt{s} = 1.4 \ (3) \ $TeV

► high luminosity and high energy crucial

Events forced to 4-jet topology

Jets paired by hemisphere/to minimise mass $\chi^2$

Template fit to extract sensitivity

\begin{tabular}{|c|c|c|}
\hline
 & 1.4 TeV & 3 TeV \\
\hline
$\Delta(g_{HHWW})$ & 7% & 3% \\
$\Delta(\lambda)$ & 32% & 16% \\
$\Delta(\lambda) \ P(e) = -80\%$ & 24% & 12% \\
\hline
\end{tabular}
Model-independent fit to Higgs properties

**Fully model independent fit**
- only possible at lepton colliders
- stems from model independent measurement of $g_{HZZ}$
- Higgs width extracted with 5-3.5% precision

**Model dependent fit**
- as at LHC (no invisible H decays)
- sub-% precision at high energy
- Higgs width extracted with <1% precision
- but results depend strongly on fit assumptions

-80% electron beam polarisation at 1.4, 3 TeV
Prospects for BSM physics at CLIC

Direct searches via pair-production of new particles up to the kinematic limit $M < \sqrt{s} / 2$

- three SUSY models used to benchmark performance:
  - CDR model 1, $\sqrt{s} = 3$ TeV
    - squarks
    - heavy Higgs
  - CDR model 2, $\sqrt{s} = 3$ TeV
    - smuons, selectrons
    - gauginos
  - CDR model 3, $\sqrt{s} = 1.4$ TeV
    - smuons, selectrons, staus
    - gauginos

Indirect searches via precision measurements of known variables, comparison with SM

- sensitive to, for example, $Z'$ bosons and composite Higgs
Sleptons and gauginos at $\sqrt{s} = 3$ TeV

Slepton signature very clean: leptons and missing energy

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

Masses from end-points of energy spectra

▷ for slepton masses $\sim 1$ TeV, precisions of $< 1\%$ achievable

Chargino and neutralino pair production: four jets and missing energy

$$e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$
$$e^+ e^- \rightarrow \tilde{\chi}_2^+ \tilde{\chi}_2^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 h h$$
$$e^+ e^- \rightarrow \tilde{\chi}_2^+ \tilde{\chi}_2^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 Z h$$

Masses from end-points of energy spectra

▷ for gaugino masses of few hundred GeV, precisions of 1-1.5%
Heavy Higgs bosons at $\sqrt{s} = 3$ TeV

Heavy Higgs bosons (~degenerate in mass) would produce complex final states of heavy-flavour jets

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

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

Separation requires heavy-flavour tagging

- accuracy of Higgs mass measurements $\sim 0.3\%$
Indirect searches

Precision studies of di-muon pair production
- total cross section
- forward-backward asymmetry
- left-right asymmetry (requires beam polarisation)

Sensitive to $Z'$ bosons, reach up to 10s of TeV

Composite Higgs theories (bound state of fermions)
- $m_p$: mass of the vector resonance
- $\xi$: strength of Higgs interactions

CLIC reach from single Higgs production provides an indirect probe of Higgs composite scale up to 70 TeV
Summary

CLIC offers a strong physics programme throughout its three energy stages

Higgs physics at CLIC
- model independent measurement of $g_{HZZ}$
- high statistics: precision measurements and rare decays
- top Yukawa coupling and Higgs self-coupling
- combined, model independent fit of Higgs parameters

BSM physics at CLIC
- direct searches possible up to the kinematic limit
- mass measurements of SUSY particles with %-level precision
- indirect searches increase reach to tens of TeV

Thanks for your attention!
If you want to know more

CLIC CDR vol 2
Physics and Detectors
CERN-2012-003
arxiv: 1202.5940

CLIC CDR vol 3
The CLIC Programme
CERN-2012-005
arxiv: 1209.2543

CLIC Snowmass White Paper
Physics at CLIC
arxiv: 1307.5288
Optimising the first energy stage

Higgs mass measurement (Higgsstrahlung):
- $\sqrt{s} = 250$ GeV: $\Delta m_H \sim 30$ MeV
- $\sqrt{s} = 350$ GeV: $\Delta m_H \sim 120$ MeV

Alternatively: WW-fusion $+$ H → bb:
- $\sqrt{s} = 350$ GeV: $\Delta m_H \sim 50$ MeV (tbc)

Higgs couplings:
- Requires access to Higgsstrahlung and WW-fusion: $g_{HZZ}$, $g_{HWW}$, $\Gamma_H$, couplings to fermions...
- $\sqrt{s} = 350$ GeV a good compromise
- But results may profit from higher energy&luminosity

Top physics:
- Threshold scan requires $\sqrt{s} = 360$ GeV

CLIC with $\sqrt{s} > 1$ TeV will give best perspectives. But in some areas the first energy stage can already improve significantly on HL-LHC:
- Top $A_{fb}$ and top couplings to Z, $\gamma$, W need $\sqrt{s} > 400$ GeV
- It might be worth adapting the first stage to enable these studies