Higgs physics at CLIC

Matthias Weber (CERN)
on behalf of the CLIC detector and physics (CLICdp) collaboration
Compact Linear Collider

Proposed $e^+e^-$ linear collider

- High acceleration gradient 100 MV/m
- Two beam acceleration scheme
- Staged construction up to 3 TeV
  - High precision physics
  - Higgs, top, BSM

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

Slightly different energies assumed in physics performance studies for first two stages 380 $\rightarrow$ 350 GeV, 1.5 TeV $\rightarrow$ 1.4 TeV
Higgs bosons in $e^+e^-$ collisions

<table>
<thead>
<tr>
<th>Energy stage</th>
<th># Higgs produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 GeV</td>
<td>1000000</td>
</tr>
<tr>
<td>1.4 TeV</td>
<td>430000</td>
</tr>
<tr>
<td>3 TeV</td>
<td>1400000</td>
</tr>
</tbody>
</table>

Numbers for unpolarised beams

Polarised beams can enhance production modes significantly

<table>
<thead>
<tr>
<th>Polarisation</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(e^-) : P(e^+)$</td>
<td>$e^+e^- \rightarrow ZH$</td>
</tr>
<tr>
<td>unpolarised</td>
<td>1.00</td>
</tr>
<tr>
<td>-80% : 0%</td>
<td>1.12</td>
</tr>
</tbody>
</table>

All results shown in the following are based on realistic full detector simulations including the impact of beam-beam effects

No triggers

$\Rightarrow$ all Higgs events used

Event selection efficiency

20-60 %
**Higgs production**

**Higgsstrahlung** $e^+e^- \rightarrow ZH$
Dominant at first energy stage $\sigma \sim 1/s$

**WW fusion** $e^+e^- \rightarrow Hv_\ell \nu_\ell$
Dominant above 500 GeV, large statistics at high energy stages $\sigma \sim \log(s)$

**ttH production** $e^+e^- \rightarrow ttH$
Accessible at second energy stage
Direct extraction of top Yukawa coupling

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**Graphical Representation**

- **Higgsstrahlung**
- **WW fusion**
- **ttH production**

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**CLICdp**

- Single Higgs production

**Legend**
- $e^+e^- \rightarrow ZH$, $\sqrt{s} = 350$ GeV
- $e^+e^- \rightarrow Hv_\ell \nu_\ell$, $\sqrt{s} = 350$ GeV
- $e^+e^- \rightarrow Hv_\ell \nu_\ell$, $\sqrt{s} = 1.4$ TeV
- $e^+e^- \rightarrow Hv_\ell \nu_\ell$, $\sqrt{s} = 3$ TeV
Recoil Method: ZH with $Z \rightarrow l^+l^-$ (l=e,μ)

Higgsstrahlung dominant production process at 380 GeV:
Recoil mass measurement only possible in $e^+e^-$ collisions

ZH event identified from Z-recoil mass
→ Model independent measurement of $\sigma(ZH)$ and $m_H$

$\Delta \sigma \ (HZ)/\sigma \ (HZ) = \pm \ 3.8 \%$

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Recoil Method with $Z \rightarrow qq$

Fine grain calorimetry of CLIC detector ideal for particle flow reconstruction to achieve high precision in hadronic channels

$$\Delta\sigma (HZ) / \sigma (HZ) = \pm 1.8 \% \quad (Z \rightarrow qq, 350 \text{ GeV})$$

**signal**

**background**

![Signal and Background Plots]
Simultaneous extraction:

- Three decay modes bb/cc/gg 
  \( \rightarrow \) precise flavour tagging
- Production Mode: ZH or WW fusion 
  \( \rightarrow \) Higgs \( p_T \) spectrum

\[ \sqrt{s} = 350 \text{ GeV}, \, L=500 \text{ fb}^{-1} \]

\[ \begin{array}{cccc}
\text{Decay} & \text{Statistical uncertainty} \\
& \text{Higgsstrahlung} & \text{WW-fusion} \\
H \rightarrow b\bar{b} & 0.86 \% & 1.9 \% \\
H \rightarrow c\bar{c} & 14 \% & 26 \% \\
H \rightarrow gg & 6.1 \% & 10 \% \\
\end{array} \]

Fit templates using 2D distributions of 
bb vs cc likelihoods

EPJC 76, 72 (2016)  
arXiv:1708.08912
Invisible Higgs decays identified with recoil mass technique in a model independent way

At first energy stage 350 GeV, L=500 fb\(^{-1}\)

BR(H\(\rightarrow\)inv) < 0.97 % at 90 % CL

Example: Recoil mass from Z\(\rightarrow\)qq, assuming 100 % invisible Higgs decays
Higgs coupling: projected sensitivity

- Precision of all results limited by 0.8% of $\sigma(ZH)$ cross section measurement
- No assumptions on additional Higgs decays
- Relevant correlations included
- **Higgs width** extracted with 6.7 (350 GeV) – 3.5% precision (all three stages)

$$\begin{align*}
\sigma(ZH) & \sim g_{HZZ}^2 \\
\sigma(ZH) \times BR(H \rightarrow VV/ff) & \sim g_{HZZ}^2 g_{HVV/Hff}^2 / \Gamma_H \\
\sigma(H_{\nu e \nu e}) \times BR(H \rightarrow VV/ff) & \sim g_{HWW}^2 g_{HVV/Hff}^2 / \Gamma_H
\end{align*}$$

based on EPJC 76, 72 (2016)
Higgs coupling: projected sensitivity (2)

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

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

\[ BR_i: \text{SM branching fractions} \]

Based on EPJC 77, 475 (2017)
ATLAS-PHYS-PUB-2014-016
Top Yukawa coupling

$\sigma(ttH)$ directly sensitive to top Yukawa coupling $g_{ttH}$

Studied in two final states:
- $ttH \rightarrow bqq blv bb$
- $ttH \rightarrow bqq bqq bb$
  $\rightarrow$ similar sensitivity

$\sqrt{s} = 1.4$ TeV, $L = 1.5$ ab$^{-1}$

$\Delta g_{ttH}/g_{ttH} = 3.8\%$

$\sigma(ttH)$ sensitive to CP mixing in $ttH$ coupling

$- ig_{ttH}(\cos\phi + i \sin\phi \gamma_5)$

Top physics at high-energy CLIC

# 527 by U. Schnoor
Double Higgs Production

e^+e^- \rightarrow HH\nu\nu: sensitive to quartic coupling $g_{HHWW}$ and Higgs self-coupling $\lambda$, profits from operation at high energy

\[ \Delta \lambda / \lambda = 16\% \text{ for } P(e^-) = -80\% \text{ from the total cross section} \]
\[ \Delta \lambda / \lambda \approx 10\% \text{ for } P(e^-) = -80\% \text{ from diff. distributions} \]

Sizeable deviations of Higgs self-coupling from SM expectation in several BSM scenarios

<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>

Measurement performed in HH$\rightarrow$bbbb final state
Conclusion and Summary

- A lepton collider is capable to enhance the understanding of the Higgs boson significantly beyond the precision of the HL-LHC

- Precise measurements of many Higgs couplings, Higgs mass and Higgs width using \textit{Higgsstrahlung} and \textit{WW} fusion processes

- Cross section and total Higgs width measured in a model-independent way

- Access to $ttH$ at second energy stage at CLIC

- \textbf{Double Higgs production} measurement profits from highest possible energies
BACKUP
**pp and $e^+e^-$ production cross sections**

**pp collisions:**
Small signal in vast amount of background, triggers needed

**$e^+e^-$ collisions:**
Less amount of background, no need for triggers, “clean” environment
Lepton vs Hadron colliders

Protons are compound objects:
- Unknown initial state
- Limits achievable precision

High QCD background rates
- Triggers needed
- High levels of radiation

High energy circular colliders feasible

$e^+e^-$ point like
- Well defined initial state (polarisation, $\sqrt{s}$)
- High precision measurements

Cleaner experimental environment
- Triggers less readout possible
- Low levels of radiation

High energies ($\sqrt{s} > 350$ GeV) require linear collider
CLIC related contributions at ICHEP

Daniel Schulte: “The CLIC accelerator project status and plans” #884

Eva Sicking: “The CLIC detector” #528

Ulrike Schnoor: “Top-quark physics at high-energy CLIC operation” #527

Aleksander Zarnecki: “Top quark physics at the first CLIC stage” #526

Roberto Franceschini: “BSM searches at CLIC” #525
CLIC project 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 Session, July 7
ICHEP 2018
Matthias Weber
CERN
Systematic uncertainties

Example: analysis $\sigma(H\nu_e\nu_e) \times BR(H\rightarrow bb)$ statistical uncertainty 0.3 %

- Luminosity spectrum reconstructed from Bhabha scattering events $\rightarrow$ expected uncertainties lead to 0.15 % syst on $\sigma(H\nu_e\nu_e) \times BR(H\rightarrow bb)$
- Total luminosity: luminometer expected to reach accuracy of a few permille
- Beam polarisation: expected to be controlled to 0.2% using single $W,Z,\gamma$ events with missing energy $\rightarrow$ syst uncertainty of 0.1 % on $\sigma(H\nu_e\nu_e) \times BR(H\rightarrow bb)$
- Jet energy scale: calibrated using $e^+e^-\rightarrow Z\nu_e\nu_e$, with $Z\rightarrow bb$
  biggest challenge for mass measurement, statistical uncertainty at 3 TeV is 44 MeV, systematic error of that scale requires JES uncertainty of 0.035 %
- Flavour tagging efficiency mostly affects the event rate $\rightarrow$ b-tagging uncertainties lead to an syst uncertainty of 0.25 %
Recoil Method with $Z \rightarrow qq$

Optimization study for first CLIC stage

At 350 GeV highest precision in Hadronic $Z$ decays

At 250 GeV largest signal cross-section, but background more signal like

At 450 GeV lower cross-section and worse jet energy resolution

Slightly beyond 350 GeV optimal for top physics as well

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

EPJC 76, 72 (2016)
arXiv:1509.02853
Higgs mass measurements

Di-jet invariant mass for $H \rightarrow bb$
selection at $\sqrt{s} = 1.4$ TeV

Reconstructed invariant mass for
$H \rightarrow ZZ^* \rightarrow q\bar{q}l^+l^-$ selection at
$\sqrt{s} = 1.4$ TeV
Signal & background templates for hadronic H decays

bb likelihood vs cc likelihood for $e^+e^- \rightarrow ZH$ hadronic Higgs decay study

a) simulated data
$ZH; Z \rightarrow q\bar{q}, H \rightarrow jets$ candidates

b) fit template: $b\bar{b}$
$ZH; Z \rightarrow q\bar{q}, H \rightarrow b\bar{b}$

CLICdp $\sqrt{s} = 350$ GeV

c) fit template: $c\bar{c}$
$ZH; Z \rightarrow q\bar{q}, H \rightarrow c\bar{c}$

d) fit template: $g\bar{g}$
$ZH; Z \rightarrow q\bar{q}, H \rightarrow g\bar{g}$

e) fit template: other decays
$ZH; Z \rightarrow q\bar{q}, H \rightarrow others$

f) fit template: SM background

Higgs Session, July 7
ICHEP 2018
Overview: CLIC projections

$\sqrt{s} = 350$ GeV

$\sqrt{s} = 1.4$ & $3$ TeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measurement</th>
<th>Observable</th>
<th>$350\text{GeV}$</th>
<th>500 fb$^{-1}$</th>
<th>Statistical precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{H} \rightarrow \text{invisible})$</td>
<td>$m_H$</td>
<td>110 MeV</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{Z} \rightarrow 1^+1^-)$</td>
<td>$g_{\text{HZZ}}$</td>
<td>3.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{Z} \rightarrow \text{q}\bar{\text{q}})$</td>
<td>$g_{\text{HZZ}}$</td>
<td>1.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{H} \rightarrow \text{b}\bar{\text{b}})$</td>
<td>$g_{\text{HZZ}}g_{\text{Hbb}}/\Gamma_H$</td>
<td>0.86%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{H} \rightarrow \text{c}\bar{\text{c}})$</td>
<td>$g_{\text{HZZ}}g_{\text{Hcc}}/\Gamma_H$</td>
<td>14%</td>
<td></td>
<td></td>
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<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{H} \rightarrow \text{gg})$</td>
<td>$g_{\text{HZZ}}g_{\text{Hgg}}/\Gamma_H$</td>
<td>6.1%</td>
<td></td>
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<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{H} \rightarrow \tau^+\tau^-)$</td>
<td>$g_{\text{HZZ}}g_{\text{Htt}/\Gamma_H}$</td>
<td>6.2%</td>
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<tr>
<td>ZH</td>
<td>$\sigma(\text{ZH}) \times \text{BR}(\text{H} \rightarrow \text{WW}^*)$</td>
<td>$g_{\text{HZZ}}g_{\text{HWW}}/\Gamma_H$</td>
<td>5.1%</td>
<td></td>
<td></td>
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<tr>
<td>$\text{H}<em>{\text{V}}\text{V}</em>{\text{e}}$</td>
<td>$\sigma(\text{H}<em>{\text{V}}\text{V}</em>{\text{e}}) \times \text{BR}(\text{H} \rightarrow \text{b}\bar{\text{b}})$</td>
<td>$g_{\text{HWW}}g_{\text{Hbb}}/\Gamma_H$</td>
<td>1.9%</td>
<td></td>
<td></td>
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<tr>
<td>$\text{H}<em>{\text{V}}\text{V}</em>{\text{e}}$</td>
<td>$\sigma(\text{H}<em>{\text{V}}\text{V}</em>{\text{e}}) \times \text{BR}(\text{H} \rightarrow \text{c}\bar{\text{c}})$</td>
<td>$g_{\text{HWW}}g_{\text{Hcc}}/\Gamma_H$</td>
<td>26%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{H}<em>{\text{V}}\text{V}</em>{\text{e}}$</td>
<td>$\sigma(\text{H}<em>{\text{V}}\text{V}</em>{\text{e}}) \times \text{BR}(\text{H} \rightarrow \text{gg})$</td>
<td>$g_{\text{HWW}}g_{\text{Hgg}}/\Gamma_H$</td>
<td>10%</td>
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Unpolarised electron beam

- Expected to collect more data with $P(e^-) = -80\%$ at high energy

$^\dagger$: fast simulation

$^*$: extrapolated from 1.4 to 3 TeV

Comparison of different collider options

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

H → cc only accessible in at lepton colliders

arXiv:1704.02333
see also JHEP 1705, 096 (2017)
CLIC beam environment

Low duty cycle $\rightarrow$ power pulsing
High luminosity
Very small bunch size at IP
Very strong electromagnetic field from opposite beam $\rightarrow$ Beamstrahlung

- **Coherent** and **trident** $e^+e^-$ pairs very forward
- Contribution from **incoherent** $e^+e^-$ pairs ($3 \times 10^5$ per BX) in detector region
- Main background in calorimeters and tracker from $\gamma\gamma \rightarrow$ hadrons
  (3.2 evts per BX at 3 TeV)
$\rightarrow$ beam background reduced by $p_T$ and timing cuts