Higgs Physics at CLIC

Strahinja Lukić
Vinča Institute, University of Belgrade, Serbia
On behalf of the CLICdp collaboration

ICHEP 2016, Aug 3-10, 2016, Chicago
The Compact Linear Collider

Dual-beam acceleration scheme

- RF power generated by a 100 A drive beam at 12 GHz
- Room-temperature cavities
- High gradient > 100 MV/m demonstrated
- Ultimate CM energy 3 TeV
Staged construction and physics program

- Three stages: 350 GeV, 1.4 and 3 TeV
  (Now being updated with 380 GeV in the first stage)
- Optimized for the key physics goals in the shortest time.

Higgs production statistics at each stage with unpolarized beams

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>350 GeV</th>
<th>1.4 TeV</th>
<th>3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_int</td>
<td>500 fb^{-1}</td>
<td>1.5 ab^{-1}</td>
<td>2 ab^{-1}</td>
</tr>
<tr>
<td>N_{ZH}</td>
<td>68,000</td>
<td>20,000</td>
<td>11,000</td>
</tr>
<tr>
<td>N_{H^+e^-}</td>
<td>17,000</td>
<td>370,000</td>
<td>830,000</td>
</tr>
<tr>
<td>N_{t\bar{t}H}</td>
<td>3,700</td>
<td>37,000</td>
<td>84,000</td>
</tr>
<tr>
<td>N_{HH^+e^-}</td>
<td>2,400</td>
<td>1,400</td>
<td></td>
</tr>
<tr>
<td>N_{H^+e^-}</td>
<td>225</td>
<td>1,200</td>
<td></td>
</tr>
</tbody>
</table>
Higgs program at CLIC

- Higgs recoil measurement allowing model-independent determination of Higgs couplings and width.
- Precise and model-independent couplings
- Precise mass
- Rare production processes, New Physics
Higgsstrahlung recoil measurement

- Reconstructing only the Z boson – Higgs recognized via the recoil mass
- $Z \rightarrow q\bar{q}$ analysis tailored for model independence
- $m_H$ measured with stat. precision of 110 MeV

<table>
<thead>
<tr>
<th>Reaction</th>
<th>BR</th>
<th>( \Delta \sigma_{HZ} / \sigma_{HZ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu^+ \mu^-$</td>
<td>\approx 3.5%</td>
<td>4.2%</td>
</tr>
<tr>
<td>$Z \rightarrow e^+ e^-$</td>
<td>\approx 3.5%</td>
<td>4.2%</td>
</tr>
<tr>
<td>$Z \rightarrow q\bar{q}$</td>
<td>\approx 70%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

Combined:

\[
\frac{\Delta g_{HZZ}}{g_{HZZ}} = 0.8\% 
\]

\[\frac{\Delta \sigma_{HZ}}{\sigma_{HZ}} = 1.65\% \]
σ × BR measurements

350 GeV
- HZ: H and Z decay candidates reconstructed
- Z decay + missing energy allows constraining $\text{BR}_{H \rightarrow \text{inv.}}$ to <1%
- $H\nu_e\bar{\nu}_e$: H decay candidate and invis. energy
- First set of precise model-independent measurements, including $\Gamma_H$

>1 TeV
- Large samples of Higgs boson in $W^+W^-$ fusion
- Excellent statistical precision
- Access to rare decays ($\mu^+\mu^-, \gamma\gamma, Z\gamma$)
Highlights above 1 TeV

- Precision measurements: $H \rightarrow b\bar{b}, c\bar{c}, g\bar{g}$
- Separation of hadronic flavours and gluons
  (Measurement of the $H \rightarrow c\bar{c}$ decay is a novelty w.r.t. the LHC)
- Very precise measurement of $\sigma_{H\nu\nu} \times \text{BR}_{H\rightarrow b\bar{b}}$: 0.3%
- Higgs mass measured to 33 MeV (1.4 and 3 TeV stages combined)
- Access to rare higgs decays ($H \rightarrow \mu^+\mu^-, H \rightarrow \gamma\gamma, H \rightarrow Z\gamma$)

Distribution of $m_{bb}$ for the selection of $H\nu\nu; H \rightarrow b\bar{b}$ events at 1.4 TeV

$m_{\mu^+\mu^-}$ for the selection of $H\nu\nu; H \rightarrow \mu^+\mu^-$ at 3 TeV and with $P(e^-) = -80\%$
Top Yukawa coupling

- Extracted directly from the measurement of the $t\bar{t}H$ cross section
- Complex final states with 6 or 8 jets, including 4 b quarks
- Jet clustering and flavor tagging capabilities of the detector are crucial here
- Measurement precision at a 1.4 TeV CLIC:

\[
\frac{\Delta \sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}} = 8.4\% \quad \Rightarrow \quad \frac{\Delta g_{Htt}}{g_{Htt}} = 4.4\%
\]

See talk by F. Żarnecki in the "Top quark and EW Physics" session
Higgs self coupling

The $H H \nu_e \bar{\nu}_e$ final state is sensitive to the Higgs self coupling $\lambda$ and to the quartic $g_{H H W W}$ coupling.

- Extracted using generator
- High energy and luminosity crucial, polarization important

Statistical uncertainty of $\frac{\Delta \lambda}{\lambda}$ (preliminary):

<table>
<thead>
<tr>
<th>$E_{CM}$</th>
<th>$P(e^-) = 0$</th>
<th>$P(e^-) = -80%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 TeV</td>
<td>32%</td>
<td>24%</td>
</tr>
<tr>
<td>3 TeV</td>
<td>16%</td>
<td>12%</td>
</tr>
</tbody>
</table>
Model-independent fit

Higgs couplings and width from the comprehensive set of measurements ($\sigma_{HZ}$ and all $\sigma \times BR$)

$$\chi^2 = \sum_i \frac{(C_i/C_i^{\text{measured}} - 1)^2}{\Delta F_i^2}$$

- E.g. $C_{ZH;H\rightarrow b\bar{b}} = g_{HZZ}^2 g_{Hbb}/\Gamma_H$
- $\Delta F_i$ – Measurement uncertainties
- Minimal model assumptions (e.g. narrow $\Gamma_H$)
- Higgsstrahlung recoil ($g_{HZZ}$)
  Limits the precision of all other parameters

Relative precision of determination of Higgs couplings in the model-independent fit at the successive operation stages of CLIC. At each stage data from all previous stages are included in the fit.
Model-dependent fit

- LHC-style analysis
- $C_i = \kappa_i^2 = \Gamma_i / \Gamma_i^{\text{measured}}$
- Main assumption: There are no invisible Higgs decays
- $\Gamma_{H,md} = \Gamma_H^{SM} \sum_i \kappa_i^2 \text{BR}_i$

Relative precision of determination of Higgs width parameters in the model-dependent fit at the successive operation stages of CLIC. The total width $\Gamma_{H,md}$ is derived from the fitted values $\kappa_i$. At each stage data from all previous stages are included in the fit.
A staged operation offering very competitive Higgs physics program already at the first stage:

- Model-independent measurement of the Higgs couplings and total decay width.
- Constraint on invisible Higgs decays $\Gamma_{\text{invis}}/\Gamma_H < 0.01$ at 90% C.L.

The full dataset brings in addition:

- Measurement of most Higgs couplings with a percent precision
- Access to rare Higgs decays
- Higgs mass determined with precision down to 33 MeV
- Direct measurement of the Top yukawa coupling
- Measurement of the trilinear Higgs coupling

CLIC Higgs physics paper to be public soon!
Backup slides
New CLICdp detector model

- Triggerless readout
- High granularity for background suppression and particle-flow analysis
- Power pulsing
- Optimization based on experience with CLIC_ILD and CLIC_SiD:
  - Single detector
  - Beam background reduction by time stamping requires an all Silicon tracker
  - More forward coverage
  - A more realistic design of the vertex detector: Spiral geometry for air cooling, realistic thickness and support structure
  - Lighter return yoke than in the 2-detector scheme
Polar angle distributions for single Higgs events at $\sqrt{s} = 350$ GeV, 1.4 TeV and 3 TeV, including the effects of the CLIC beamstrahlung spectrum and ISR. The distributions are normalised to unity.
### Measurement precision at 350 GeV

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Observable</th>
<th>Stat. precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(ZH) \times BR_{H \rightarrow \text{invisible}}$</td>
<td>$\Gamma_{\text{inv}}$</td>
<td>0.6 %</td>
</tr>
<tr>
<td>$\sigma(ZH) \times BR_{H \rightarrow b\bar{b}}$</td>
<td>$g_{HZZ}^2 g_{Hbb}^2 / \Gamma_H$</td>
<td>0.85 %</td>
</tr>
<tr>
<td>$\sigma(ZH) \times BR_{H \rightarrow c\bar{c}}$</td>
<td>$g_{HZZ}^2 g_{Hcc}^2 / \Gamma_H$</td>
<td>10.4 %</td>
</tr>
<tr>
<td>$\sigma(ZH) \times BR_{H \rightarrow gg}$</td>
<td>$g_{HZZ}^2 g_{Hcc}^2 / \Gamma_H$</td>
<td>4.5 %</td>
</tr>
<tr>
<td>$\sigma(ZH) \times BR_{H \rightarrow \tau^+\tau^-}$</td>
<td>$g_{HZZ}^2 g_{H\tau\tau}^2 / \Gamma_H$</td>
<td>6.2 %</td>
</tr>
<tr>
<td>$\sigma(ZH) \times BR_{H \rightarrow WW^*}$</td>
<td>$g_{HZZ}^2 g_{HWW}^2 / \Gamma_H$</td>
<td>5.1 %</td>
</tr>
<tr>
<td>$\sigma(H_{\nu_e \bar{\nu}<em>e}) \times BR</em>{H \rightarrow b\bar{b}}$</td>
<td>$g_{HWW}^2 g_{Hbb}^2 / \Gamma_H$</td>
<td>1.9 %</td>
</tr>
<tr>
<td>$\sigma(H_{\nu_e \bar{\nu}<em>e}) \times BR</em>{H \rightarrow c\bar{c}}$</td>
<td>$g_{HWW}^2 g_{Hcc}^2 / \Gamma_H$</td>
<td>14.5 %</td>
</tr>
<tr>
<td>$\sigma(H_{\nu_e \bar{\nu}<em>e}) \times BR</em>{H \rightarrow gg}$</td>
<td>$g_{HWW}^2 g_{Hcc}^2 / \Gamma_H$</td>
<td>5.8 %</td>
</tr>
</tbody>
</table>

**CLIC BR measurement precision at 350 GeV with 500 fb$^{-1}$ (Preliminary)**

---

S. Lukić, ICHEP 2016, Aug 3-10, 2016, Chicago
### $\sigma \times \text{BR}$ Measurement precision above 1 TeV

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Observable</th>
<th>Stat. precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow b\bar{b}}$</td>
<td>$g_{HWW}^2 g_{Hbb}^2 / \Gamma_H$</td>
<td>0.4 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow c\bar{c}}$</td>
<td>$g_{HWW}^2 g_{Hcc}^2 / \Gamma_H$</td>
<td>6.1 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow gg}$</td>
<td>$g_{HWW}^2 g_{Hgg}^2 / \Gamma_H$</td>
<td>5.0 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow \tau^+\tau^-}$</td>
<td>$g_{HWW}^2 g_{H\tau\tau}^2 / \Gamma_H$</td>
<td>4.2 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow \mu^+\mu^-}$</td>
<td>$g_{HWW}^2 g_{H\mu\mu}^2 / \Gamma_H$</td>
<td>38 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow \gamma\gamma}$</td>
<td>$g_{HWW}^4 / \Gamma_H$</td>
<td>15 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow Z\gamma}$</td>
<td>$g_{HWW}^4 / \Gamma_H$</td>
<td>42 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow WW^*}$</td>
<td>$g_{HWW}^2 / \Gamma_H$</td>
<td>1.0 %</td>
</tr>
<tr>
<td>$\sigma_{H_e^0 \bar{\nu}<em>e} \times \text{BR}</em>{H \rightarrow ZZ^*}$</td>
<td>$g_{HWW}^2 g_{HZZ}^2 / \Gamma_H$</td>
<td>5.6 %</td>
</tr>
<tr>
<td>$\sigma_{He^+ \bar{e}^-} \times \text{BR}_{H \rightarrow b\bar{b}}$</td>
<td>$g_{HZZ}^2 g_{Hbb}^2 / \Gamma_H$</td>
<td>1.8 %</td>
</tr>
</tbody>
</table>

Notes:

* Extrapolated from 1.4 TeV

---

S. Lukić, ICHEP 2016, Aug 3-10, 2016, Chicago

Higgs Physics at CLIC