Higgs properties projections @ future e+e-

arXiv:1903.01629
1708.09079
1708.08912

ESG “Higgs @ FC”
arXiv:1905.03974

Junping Tian (U. Tokyo)

Snowmass Community Planning Meeting
“Higgs factories” session, October 6, 2020
proposals of future e+e- colliders

<table>
<thead>
<tr>
<th></th>
<th>√s</th>
<th>beam polarisation</th>
<th>∫Ldt (baseline)</th>
<th>R&amp;D phase</th>
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</thead>
<tbody>
<tr>
<td>ILC</td>
<td>0.1 - 1 TeV</td>
<td>e-: 80%</td>
<td>2 ab⁻¹ @ 250 GeV</td>
<td>TDR 2013</td>
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<tr>
<td></td>
<td></td>
<td>e+: 30% (20%)</td>
<td>0.2 ab⁻¹ @ 350 GeV</td>
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<td></td>
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<td></td>
<td>4 ab⁻¹ @ 500 GeV</td>
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<td></td>
<td>8 ab⁻¹ @ 1 TeV</td>
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<tr>
<td>CLIC</td>
<td>0.35 - 3 TeV</td>
<td>e-: (80%)</td>
<td>1 ab⁻¹ @ 380 GeV</td>
<td>CDR 2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e+: 0%</td>
<td>2.5 ab⁻¹ @ 1.5 TeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 ab⁻¹ @ 3 TeV</td>
<td></td>
</tr>
<tr>
<td>CEPC</td>
<td>90 - 240 GeV</td>
<td>e-: 0%</td>
<td>5.6 ab⁻¹ @ 250 GeV</td>
<td>CDR 2018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e+: 0%</td>
<td>16 ab⁻¹ @ Mz</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2.6 ab⁻¹ @ 2Mw</td>
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<tr>
<td>FCC-ee</td>
<td>90 - 350 GeV</td>
<td>e-: 0%</td>
<td>150 ab⁻¹ @ Mz</td>
<td>CDR 2018</td>
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<td></td>
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<td>e+: 0%</td>
<td>10 ab⁻¹ @ 2Mw</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>5 ab⁻¹ @ 250 GeV</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1.7 ab⁻¹ @ 365 GeV</td>
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</tr>
</tbody>
</table>

common: Higgs factory with O(10⁶) Higgs events
differ in energy reach, luminosity, polarization, project readiness
LHC (super Higgs factory \#10^8)

- \( \sqrt{s} = 13 \text{ TeV}, 79.8 \text{ fb}^{-1} \)
- ATLAS
  - Data
  - VH, H → bb (\( \mu = 1.16 \))
  - tt
  - Single top
  - Z+jets
  - Multijet
  - W+jets
  - Diboson

# of Higgs produced: \(~4,000,000\)

significance: \(5.4\sigma\)

[ATLAS, 1808.08238; CMS, 1808.08242]

e+e- (Higgs factory \#10^6)

\[ \sqrt{s} = 250 \text{GeV} \]
\[ \int Ldt = 250 \text{fb}^{-1} \]

full detector simulation

Events/1

# of Higgs produced: \(~400\)

significance: \(5.2\sigma\)

[Ogawa, PhD Thesis (Sokendai)]
goal of Higgs precision measurements @ e+e-

✓ to see new physics effects from deviation w.r.t. SM
⇒ need 1% or below sensitivity for m_{BSM}~1 TeV
✓ to identify the underling BSM model from deviation pattern
⇒ need meas. as model-independent as possible
complementarity: direct NP search & precision Higgs coup.

MSSM with $b$-$\tau$ unification

currently excluded by LHC searches

expected exclusion by HL-LHC searches

$\delta k_b / \%$

[Wells, Zhang, arXiv:1711.04774]
Higgs productions at e+e-

- two apparent thresholds: $\sqrt{s} \sim 250$ GeV for ZH, $\sim 500$ GeV for ZHH & ttH
- + another threshold for t t-bar, important for Higgs sector as well
Highlight a few measurements @ e+e-

- \( m_H, \) CP
- \( \sigma_{ZH} \)
- \( \text{Br}(H \rightarrow bb/cc/gg) \)
- \( \text{Br}(H \rightarrow \text{Invisible} / \text{Exotic}) \)
- total width \( \Gamma_H \)
- Higgs self-coupling

note the important synergy with LHC on \( \text{BR}(H \rightarrow \gamma\gamma/\gamma Z/\mu\mu) \)

unless stated, most features are common for e+e-

cautions: bias in selection
recoil mass technique: \( m_H \) & inclusive \( \sigma_{ZH} \)

\[
M_X^2 = \left( p_{CM} - (p_{\mu^+} + p_{\mu^-}) \right)^2
\]

- well defined initial states at e+e-
- Higgs is tagged without looking into H decay
- inclusive cross section of e^+e^- \( \rightarrow ZH \)
- key to determining absolute Higgs couplings

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\[\text{[ESG]}\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \Delta m_H ) / MeV</th>
<th>( \delta \sigma_{ZH} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEPC</td>
<td>5.9</td>
<td>0.5%</td>
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<tr>
<td>FCC-ee240</td>
<td>11</td>
<td>0.5%</td>
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<tr>
<td>ILC250</td>
<td>14</td>
<td>L:1.1%; R:1.1%</td>
</tr>
<tr>
<td>CLIC380</td>
<td>78 (23)</td>
<td>L:1.5%; R:1.8%</td>
</tr>
</tbody>
</table>

[Yan et al, arXiv:1604.07524]
Higgs decays to invisible or exotic

- Recoil technique allows Higgs to be fully reconstructed even if it decays invisibly

\[ \text{BR} \sim O(0.1\%) \]


Higgs decays to bb, cc and gg

- clean environment at e+e- allows excellent b- and c-tagging performance
- b-tag eff. typically > 80%
- c-tag eff. typically > 50%
- H→bb/cc/gg separation

**e+e- → ZH, H→2-jet: b-likeness vs c-likeness**


differential meas.: Higgs CP & anomalous couplings

through \( H \rightarrow \tau^+\tau^- \)
(or ttH)

\[ \mathcal{L}_{Hff} = - \frac{m_f}{\nu} H \bar{f} (\cos \Phi_{CP} + i \gamma^5 \sin \Phi_{CP}) f \] (CP-odd)

\[ \Delta \Phi_{CP} \sim 4.3^\circ \] [Jeans, Wilson, 1804.01241]

CP sensitive observable (\( \Delta \phi \)): transverse spin correlation of two \( \tau \)
differential meas.: Higgs CP & anomalous couplings

through HZZ
(or HWW)

\[ \mathcal{L} = m_Z^2 \left( \frac{1}{v} + \frac{a}{\Lambda} \right) H Z^\mu Z_\mu + \frac{b}{2\Lambda} H Z^{\mu\nu} Z_{\mu\nu} + \frac{\tilde{b}}{\Lambda} H Z^{\mu\nu} \tilde{Z}_{\mu\nu} \] (CP-odd)

\[ \Delta \tilde{b} \sim 0.016 \]
(for \( \Lambda = 1 \text{ TeV} \))

\[ e^+ + e^- \rightarrow Z h \rightarrow f \bar{f} h \]

CP sensitive observable (\( \Delta \Phi \)):
angle between Zh production plane & Z decay plane

[Ogawa, Fujii, JT, 1712.09772]
Higgs total width $\Gamma_H$ (4 MeV in SM)

- too small to be determined directly through line-shape ($\sigma_D \sim O(500)$ MeV)
- unique method enabled by meas. of inclusive $\sigma_{ZH}$ @ e+e-
  1. extraction of absolute HZZ coupling (given a theory formalism)
  2. computation of partial width $\Gamma(H \rightarrow ZZ^*)$
  3. with meas. of $BR(H \rightarrow ZZ^*)$, total width is determined as

\[
\Gamma_H = \frac{\Gamma(H \rightarrow ZZ^*)}{BR(H \rightarrow ZZ^*)}
\]

(similar for $H \rightarrow WW^*$)

\[\delta \Gamma_H \sim 1 - 2\%\]

tricky due to Step 1

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<table>
<thead>
<tr>
<th>Collider</th>
<th>$\delta \Gamma_H$ [%] from Ref.</th>
<th>Extraction technique standalone result</th>
<th>$\delta \Gamma_H$ [%] kappa-3 fit</th>
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<tbody>
<tr>
<td>ILC250</td>
<td>2.3</td>
<td>EFT fit [3,4]</td>
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<td>ILC500</td>
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<td>EFT fit [3,4,14]</td>
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<td>CLIC380</td>
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<td>$\kappa$-framework [98]</td>
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<td>FCC-ee365</td>
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<td>1.1</td>
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</table>
From observables to couplings — Global Fit

- **kappa formalism**
  - useful to quantify the sensitivity to new physics effect from single measurement; but may miss important relations
  
  \[ \mathcal{L} = (1 + \eta_Z) \frac{m_Z^2}{v} H Z^\mu Z_\mu + \zeta_Z \frac{H}{2v} Z^{\mu\nu} Z_{\mu\nu} \]  
  (new Lorentz structure)

  \[ \delta\sigma(e^+e^- \to ZH) = 2\eta_Z + 5.5\zeta_Z \]

  \[ \delta\Gamma(H \to ZZ^*) = 2\eta_Z - 0.5\zeta_Z \]

  can’t be both represented by a single \( \kappa_Z \)

- **SM Effective Field Theory formalism**

  \[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i^{(d_i)} \]

  17 D-6 ops related to Higgs can be determined simultaneously at e+e-

  represent most general BSM effects

  respect SM gauges symmetries

[Barklow et al, 1708.09079;1708.08912]
expected Higgs coupling precisions @ future e+e-
global perspective for Higgs meas. @ future e+e-

- The same new physics that modifies Higgs properties may show somewhere else as well
  - Combined probe with EWPO, e+e- → WW / 2-fermion

- Great synergies with (HL-)LHC measurements
  - Higgs rare decays; Top-quark EW couplings; TGC / QGC; etc

- CEPC / FCC-ee: important role by Z-pole run, ~x2 better δg_{HVV}

- ILC/ CLIC: important role by beam polarizations, made up ∫L

\[ \begin{array}{c|cccc}
  & \text{ILC250} & \text{CLIC380} & \text{CEPC} & \text{FCC-ee240} \\
  \hline
  \int L \cdot ab & 2 & 1 & 5.6 & 5 \\
  \delta g_{HZZ} & 0.39\% & 0.5\% & 0.45\% & 0.47\% \\
  \delta g_{Hbb} & 0.78\% & 0.99\% & 0.63\% & 0.71\% \\
  \delta g_{H\tau\tau} & 0.81\% & 1.3\% & 0.66\% & 0.69 \\
\end{array} \]

[de Blas et al, arXiv:1907.04311]
Higgs self-coupling $\delta \lambda_{HHH}$

Through double Higgs ($ZHH \sim 500\text{GeV}; \nu\nu HH \geq 1\text{TeV}$)

Through single Higgs (need multiple $Q^2$ to identify $\lambda_{HHH}$ effects)


[FCC-ee 240+365] 44% 27% (4IP)

[ILC 250+500] 58%

(HL-LHC excluded)
**summary**

- future e+e- Higgs factories will add great opportunities on precision determination of Higgs properties, which will help reveal the nature of BSM physics
- recoil mass analysis is the key to model-independent meas. of absolute Higgs couplings & total width
- need a global perspective on Higgs physics (+EW/Top/BSM)
- all proposed e+e- are capable of reaching $\lesssim 1\%$ precision for many of the Higgs couplings
- when will any of them be realized?