Learn from Higgs Physics at Future Higgs Factories

Shufang Su • U. of Arizona

Osaka University
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S. Su

J. Gu, H. Li, Z. Liu, W. Su, 1709.06103
N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037
H. Li, SS, W. Su, J. Yang, work in progress
Outline

- Higgs precision measurements
- Global fit framework
- Perturbative models
  - SM with a real singlet extension (skip in this talk)
  - 2HDM (tree + loop, Higgs + Zpole)
  - MSSM
- Strong dynamics models (skip in this talk)
- Complementarity with direct search @ 100 pp
- Conclusion
### ATLAS

**Individual analysis**

<table>
<thead>
<tr>
<th>Process</th>
<th>Input measurements</th>
<th>( m_H (\text{GeV}) )</th>
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<tbody>
<tr>
<td>( H \rightarrow \gamma \gamma )</td>
<td>Overall: ( \mu = 1.17^{+0.27}_{-0.27} )</td>
<td>125.4</td>
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<tr>
<td></td>
<td>ggF: ( \mu = 1.32^{+0.38}_{-0.38} )</td>
<td>125.4</td>
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<tr>
<td></td>
<td>VBF: ( \mu = 0.83^{+0.7}_{-0.7} )</td>
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</tr>
<tr>
<td></td>
<td>WH: ( \mu = 1.01^{+1.6}_{-1.4} )</td>
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<tr>
<td></td>
<td>ZH: ( \mu = 0.13^{+0.3}_{-0.1} )</td>
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<tr>
<td>( H \rightarrow ZZ^* )</td>
<td>Overall: ( \mu = 1.44^{+0.46}_{-0.46} )</td>
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<td>ggF+VH: ( \mu = 1.72^{+0.7}_{-0.4} )</td>
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<td>VBF+VH: ( \mu = 0.31^{+0.6}_{-0.4} )</td>
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<tr>
<td>( H \rightarrow WW^* )</td>
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<td>VBF: ( \mu = 1.28^{+0.35}_{-0.24} )</td>
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<td></td>
<td>VH: ( \mu = 3.0^{+1.6}_{-1.3} )</td>
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<td>( H \rightarrow \tau \tau )</td>
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<td>VBF+VH: ( \mu = 1.24^{+0.39}_{-0.24} )</td>
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<td>( VH \rightarrow Vb\bar{b} )</td>
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<tr>
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<td>WH: ( \mu = 1.11^{+0.35}_{-0.40} )</td>
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<td>( H \rightarrow \mu \mu )</td>
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<td>( ttH )</td>
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</table>

**Summary of the signal-strength measurements, as published, from individual analyses that are inputs to the combinations.**


**CERN-PH-EP-2013-037**
**Higgs Precision Measurements**

### ATLAS Simulation Preliminary

\[ \sqrt{s} = 14 \text{ TeV}: \int \mathcal{L} \mathit{dt} = 300 \text{ fb}^{-1}; \int \mathcal{L} \mathit{dt} = 3000 \text{ fb}^{-1} \]

### LHC: 14 TeV, 300 fb\(^{-1}\), 3000 fb\(^{-1}\)

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<th>No theory unc.</th>
<th>All unc.</th>
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<td>0.09</td>
<td>0.09</td>
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<tr>
<td>(0j)</td>
<td>0.19</td>
<td>0.12</td>
<td>0.16</td>
<td>0.05</td>
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<td>(1j)</td>
<td>0.27</td>
<td>0.14</td>
<td>0.23</td>
<td>0.05</td>
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<td>0.43</td>
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<td>0.33</td>
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<td>0.16</td>
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<tr>
<td>(ggF-like)</td>
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<td>0.07</td>
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<td>0.04</td>
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<tr>
<td>( H \to WW ) (comb.)</td>
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<tr>
<td>(0j)</td>
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<td>0.09</td>
<td>0.16</td>
<td>0.05</td>
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<tr>
<td>(1j)</td>
<td>0.30</td>
<td>0.18</td>
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<td>(VBF-like)</td>
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<td>0.56</td>
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<td>0.38</td>
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<td>(ttH-like)</td>
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**ATL-PHYS-PUB-2014-016**
Higgs Precision Measurements

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<th>CEPC</th>
<th>FCC-ee</th>
<th>ILC</th>
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<td>240 GeV</td>
<td>250 GeV</td>
</tr>
<tr>
<td>$\int L dt$</td>
<td>5 ab$^{-1}$</td>
<td>5 ab$^{-1}$</td>
<td>2 ab$^{-1}$</td>
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<tr>
<td>production</td>
<td>$Zh$</td>
<td>$Zh$</td>
<td>$Zh$</td>
</tr>
<tr>
<td>$\Delta\sigma/\sigma$</td>
<td>0.51%</td>
<td>0.57%</td>
<td>0.71%</td>
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<tr>
<td>decay</td>
<td>$(\nu\bar{\nu})h \rightarrow bb$</td>
<td>0.28%</td>
<td>0.28%</td>
</tr>
<tr>
<td>$h \rightarrow bb$</td>
<td>0.28%</td>
<td>0.28%</td>
<td>0.42%</td>
</tr>
<tr>
<td>$h \rightarrow c\bar{c}$</td>
<td>2.2%</td>
<td>1.7%</td>
<td>2.9%</td>
</tr>
<tr>
<td>$h \rightarrow gg$</td>
<td>1.6%</td>
<td>1.98%</td>
<td>2.5%</td>
</tr>
<tr>
<td>$h \rightarrow WW^*$</td>
<td>1.5%</td>
<td>1.27%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$h \rightarrow \tau^+\tau^-$</td>
<td>1.2%</td>
<td>0.99%</td>
<td>2.3%</td>
</tr>
<tr>
<td>$h \rightarrow ZZ^*$</td>
<td>4.3%</td>
<td>4.4%</td>
<td>6.7%</td>
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<tr>
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<td>9.0%</td>
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<td>12.0%</td>
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<tr>
<td>$h \rightarrow \mu^+\mu^-$</td>
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<td>18.4%</td>
<td>25.5%</td>
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<tr>
<td>$(\nu\bar{\nu})h \rightarrow bb$</td>
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<td>3.1%</td>
<td>3.7%</td>
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</table>
### Higgs Precision Measurements

#### CEPC / FCC / ILC

<table>
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<tr>
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<th>ILC</th>
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<tr>
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<td>240 GeV</td>
<td>250 GeV</td>
</tr>
<tr>
<td>$\int \mathcal{L} dt$</td>
<td>5 ab$^{-1}$</td>
<td>2 ab$^{-1}$</td>
<td>200 fb$^{-1}$</td>
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<tr>
<td>production</td>
<td>$Zh$</td>
<td>$Zh$</td>
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</tr>
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<td>3.1%</td>
<td>3.7%</td>
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</tbody>
</table>

S. Su  CEPC-preCDR, TLEP Design Study Working Group, ILC Operating Scenarios.
Two model-independent approaches

**kappa framework**

\[ \kappa_f = \frac{g(hff)}{g(hff; SM)} , \kappa_V = \frac{g(hVV)}{g(hff; SM)} \]

**EFT framework**

\[ \delta c_Z, c_{ZZ}, c_{Z\Box}, c_{\gamma\gamma}, c_{Z\gamma}, c_{gg}, \delta y_u, \delta y_d, \delta y_e, \lambda_Z \]

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<tr>
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<td>( K_g )</td>
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<td>( K_Y )</td>
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Precision reach of the 12-parameter fit in Higgs basis

- LHC 300/3000 fb^{-1}
- CEPC 250 GeV at 5 ab^{-1} w/wo HL-LHC

Figure 2: Comparison between LHC and CEPC.
New Physics Implication

Experimental observables

Various $K_i$ (with correlation)

Coeff of EFT operators (with correlation)

parameters in New Physics Models
Kappa Framework and EFT Framework

limitations of model-independent approaches

• large level of degeneracy
  parameter space for specific model much smaller
• correlation matrix often not provided
  over conservative estimation when not include correlation
• assumptions and simplifications
  may not be valid for a particular model
New Physics Implication

Experimental observables

- Various $K_i$ (with correlation)
- Coeff of EFT operators (with correlation)

parameters in New Physics Models
New Physics Implication

Experimental observables

Various $K_i$ (with correlation)

Coeff of EFT operators (with correlation)

parameters in New Physics Models
New Physics Implication

- Experimental observables
- Various $K_i$ (with correlation)
- Coeff of EFT operators (with correlation)

parameters in New Physics Models

\[ \chi^2 = \sum_i \frac{(\mu_i^{\text{BSM}} - \mu_i^{\text{obs}})^2}{\sigma_{\mu_i}^2} \]

\[ \mu_i^{\text{BSM}} = \frac{(\sigma \times \text{Br})_{\text{BSM}}}{(\sigma \times \text{Br})_{\text{SM}}} \]
Perturbative Models

- SM with a real singlet extension (skip)
- 2HDM (Type I, II, L, F)
- MSSM
Two Higgs Doublet Model (CP-conserving)

\[ \Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix} \]

\[ v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2 \]
\[ \tan \beta = v_u/v_d \]

\[ \begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad A = -G_1 \sin \beta + G_2 \cos \beta \]
\[ H^\pm = -\phi_1^\pm \sin \beta + \phi_2^\pm \cos \beta \]

after EWSB, 5 physical Higgses

CP-even Higgses: \( h^0, H^0 \), CP-odd Higgs: \( A^0 \), Charged Higgses: \( H^\pm \)

h^0/H^0 VV coupling

\[ g_{H^0VV} = \frac{m_V^2}{v} \cos(\beta - \alpha), \quad g_{h^0VV} = \frac{m_V^2}{v} \sin(\beta - \alpha). \]

alignment limit: \( \cos(\beta - \alpha) = 0 \), \( h^0 \) is the SM Higgs with SM couplings.

S. Su
2HDM parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_V$</th>
<th>$\kappa_u$</th>
<th>$\kappa_d$</th>
<th>$\kappa_\ell$</th>
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<td>$\cos \alpha / \sin \beta$</td>
<td>$\cos \alpha / \sin \beta$</td>
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<td>$- \sin \alpha / \cos \beta$</td>
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<td>$\cos \alpha / \sin \beta$</td>
</tr>
</tbody>
</table>

(parameters (CP-conserving, flavor limit, $Z_2$ symmetry))

$\tan \beta$, $\cos(\beta-\alpha)$, control tree level $h^0$ couplings

$m_{11}^2$, $m_{22}^2$, $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$, $\lambda_5$

soft $Z_2$ breaking: $m_{12}^2$

246 GeV

125 GeV
2HDM: Loop in the Alignment Limit

- **theoretical constraints**

![Graph 1](image1)

\[ \lambda \]

- \[ \tan\beta = \frac{m_{H^\pm}}{m_H} = \frac{m_A}{m_\phi} \]

- \[ \lambda V^2 = m_\phi^2 - m_{12}^2 / (s_\beta c_\beta) \text{ (GeV}^2) \]

![Graph 2](image2)

- \[ \lambda \]

- \[ \tan\beta = \frac{m_H}{m_\phi} \]

- \[ \lambda V^2 = m_H^2 - m_{12}^2 / (s_\beta c_\beta) \text{ (GeV}^2) \]

- \[ \cos(\beta - \alpha) = 0.005 \]

- \[ \cos(\beta - \alpha) = 0.00 \]

- \[ \cos(\beta - \alpha) = -0.005 \]

- \[ m_\phi = 800 \text{ GeV} \]

- \[ \Delta m_A = \Delta m_C \]

- \[ m_H = 800 \text{ GeV} \]

S. Su

13
Tree-level 2HDM fit

2HDM, LHC/FCC fit

Figure 1.
The distorted shape of the global fit results, comparing to the tree-level only results, is due to the interplay between both the tree-level contribution and loop corrections. Note that while the overall range is slightly smaller than that obtained from the tree-level only result, shown by region enclosed by the dashed lines.

The benchmark point of $\tan \beta = 300$ GeV can be measured with less than 0.2% precision, it is less constraining comparing to other constraints from individual couplings are given with the color codes: blue ($\kappa_t$), cyan ($\kappa_b$), orange ($\kappa_c$), purple ($\kappa_g$), green ($\kappa_z$), and red ($m_\Phi = 800$ GeV, $\sqrt{\lambda v^2} = 300$ GeV). The region enclosed by the dashed black lines shows the tree-level two-loop corrections only (blue curve) provides the most relaxed bounds for the parameter space. As a comparison we also show the tree-level only global fit results, represented by the dashed black lines.

The overall range is slightly smaller than the constraints from theoretical predictions.
2HDM: Loop in the Alignment Limit

- **Type II**

\[ \kappa_{\text{loop}}^{2\text{HDM}} \equiv \frac{g_{\text{tree}}^{2\text{HDM}} + g_{\text{loop}}^{2\text{HDM}}}{g_{\text{tree}}^{\text{SM}} + g_{\text{loop}}^{\text{SM}}} \]

\[ \kappa_{1-\text{loop}}^{2\text{HDM}}|_{\text{alignment}} = 1 + \Delta \kappa_{1-\text{loop}}^{2\text{HDM}} \]

Alignment limit 2HDM one-loop correction, type-II

\[ \text{CEPC 5 ab}^{-1} \]

\[ m_{\phi} = m_{H^0} = m_A = m_{H^\pm} \text{ (GeV)} \]

S. Su
2HDM: Tree + Loop

N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037
Direct Search of Heavy Higgses @ 100 pp

Conventional search

Exotic Decay

S. Su  Craig et. al., 1605.08744
3.1 Model Setup

Type-II Two Higgs doublet model

In addition to the rate measurements alone, the Higgsstrahlung as well as the Higgs production grow with c.m. energy logarithmically. While the rate is still rather small, the Higgsstrahlung process can be improved by more than one order of magnitude at the future lepton collider of the Higgs factory with the center-of-mass (c.m.) energy.

Table 2: S. Su

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CEPC</th>
<th>ILC</th>
<th>TLEP-W/TLEP-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_s(M_Z^2)$</td>
<td>$\pm 1.0 \times 10^{-4}$</td>
<td>$\pm 1.0 \times 10^{-4}$</td>
<td>$\pm 1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta \alpha^{(5)}_{\text{had}}(M_Z^2)$</td>
<td>$\pm 4.7 \times 10^{-5}$</td>
<td>$\pm 4.7 \times 10^{-5}$</td>
<td>$\pm 4.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$\pm 0.0005$</td>
<td>$\pm 0.0021$</td>
<td>$\pm 0.0001$</td>
</tr>
<tr>
<td>$m_t$ [GeV] (pole)</td>
<td>$\pm 0.6_{\text{exp}} \pm 0.25_{\text{th}}$</td>
<td>$\pm 0.03_{\text{exp}} \pm 0.1_{\text{th}}$</td>
<td>$\pm 0.6_{\text{exp}} \pm 0.25_{\text{th}}$</td>
</tr>
<tr>
<td>$m_h$ [GeV]</td>
<td>$&lt; \pm 0.1$</td>
<td>$&lt; \pm 0.1$</td>
<td>$&lt; \pm 0.1$</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$(\pm 3_{\text{exp}} \pm 1_{\text{th}}) \times 10^{-3}$</td>
<td>$(\pm 5_{\text{exp}} \pm 1_{\text{th}}) \times 10^{-3}$</td>
<td>$(\pm 8_{\text{exp}} \pm 1_{\text{th}}) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}$</td>
<td>$(\pm 4.6_{\text{exp}} \pm 1.5_{\text{th}}) \times 10^{-5}$</td>
<td>$(\pm 1.3_{\text{exp}} \pm 1.5_{\text{th}}) \times 10^{-5}$</td>
<td>$(\pm 0.3_{\text{exp}} \pm 1.5_{\text{th}}) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$(\pm 5_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-4}$</td>
<td>$\pm 0.001$</td>
<td>$(\pm 1_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table: Z-pole precision

<table>
<thead>
<tr>
<th>$\sigma$</th>
<th>Current</th>
<th>CEPC</th>
<th>FCC-ee</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>$0.04 \pm 0.11$</td>
<td>$1 \ 0.92 \ -0.68$</td>
<td>$2.46 \ 1 \ 0.862 \ -0.373$</td>
<td>$0.67 \ 1 \ 0.812 \ 0.001$</td>
</tr>
<tr>
<td>$T$</td>
<td>$0.09 \pm 0.14$</td>
<td>$- \ 1 \ -0.87$</td>
<td>$2.55 \ - \ 1 \ -0.735$</td>
<td>$0.53 \ - \ 1 \ -0.097$</td>
</tr>
<tr>
<td>$U$</td>
<td>$-0.02 \pm 0.11$</td>
<td>$- \ - \ 1$</td>
<td>$2.08 \ - \ - \ 1$</td>
<td>$2.40 \ - \ - \ 1$</td>
</tr>
</tbody>
</table>
2HDM: non-degenerate

\[ \Delta m_a = m_A - m_H, \quad \Delta m_c = m_{H^\pm} - m_H \]
2HDM: non-degenerate

$$\Delta m_a = m_A - m_H, \Delta m_c = m_{H^\pm} - m_H$$

- For $$\tan\beta = 0.2$$
- For $$\tan\beta = 1$$
- For $$\tan\beta = 7$$

The plots show the allowed regions in the plane of $$\Delta m_A$$ vs $$\Delta m_c$$ for different values of $$\tan\beta$$. The regions are defined by the conditions on the mass differences, with the solid line representing the positive limit and the dashed line the negative limit. The allowed regions shrink for smaller $$\tan\beta$$.

S. Su
$2\text{HDM: non-degenerate}$

\[
\Delta m_a = m_A - m_H, \quad \Delta m_c = m_{H^\pm} - m_H
\]

\begin{align*}
\text{Complementary to Zpole precision}
\end{align*}
Different Higgs Factories

![Diagrams showing different Higgs factories](Image)

**Figure 12**

- **m_\Phi = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 13**

- **m_H = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 11**

- **m_\Phi = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 10**

- **m_H = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 9**

- **m_\Phi = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 8**

- **m_H = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 7**

- **m_\Phi = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 6**

- **m_H = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 5**

- **m_\Phi = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 4**

- **m_H = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 3**

- **m_\Phi = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 2**

- **m_H = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

**Figure 1**

- **m_\Phi = 800 GeV, \sqrt{\lambda v^2} = 300 GeV**
- **CEPC**
- **FCC-ee**
- **ILC**

S. Su
Different Higgs Factories

For the left panel, $m_\Phi = 800$ GeV, $\sqrt{\lambda v^2} = 300$ GeV, and $m_H = 800$ GeV, $\sqrt{\lambda v^2} = 300$ GeV. The reach seen in Fig. 6 showed the allowed regions of the parameter space at 95% C.L. for the Higgs factories on the extended Higgs sector. We first summarized the anticipated accuracies on determining the EW observables at the Higgs factories in great detail.

It is important to explore the extent to which the parametric deviations from the degenerate masses of the heavy Higgs bosons. In our analyses, we extended the existing results by including the tree-level and one-loop level effects. We illustrated this by studying in great detail the following studies for BSM Higgs sector. We showed the allowed regions of the parameter space at 95% C.L. for the Higgs factories on the extended Higgs sector. We first summarized the anticipated accuracies on determining the EW observables at the Higgs factories in great detail.

In this paper, we examined the impacts of the precision measurements of the SM parameters by the lumi

...continued on the next page...

S. Su
Perturbative Models

- SM with a real singlet extension
- 2HDM (Type I, II, L, F)
- MSSM
**MSSM**

- **Higgs mass**

\[ M_h^2 = m_h^2, \text{tree} + \frac{3 G_F \sqrt{2}}{2 \pi^2} m_t \left\{ -\ln \left( \frac{m_t^2}{M_Z^2} \right) + \frac{X_t^2}{M_S^2} \left( 1 - \frac{1}{12} \frac{X_t^2}{M_S^2} \right) \right\} \]

\[ \sim 3 \text{ GeV uncertainties (higher loops, } m_t, \ldots) \]

- **gauge and Yukawa couplings**

\[
\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos \alpha_{eff} & \sin \alpha_{eff} \\ -\sin \alpha_{eff} & \cos \alpha_{eff} \end{pmatrix} \begin{pmatrix} H^d \\ H^u \end{pmatrix}
\]

- **hgg and hγγ**

**MSSM parameters:**
- \( m_A, \tan \beta, M_S, X_t, \)
- \( \mu=500 \text{ GeV, other irrelevant} \)
mA vs. X_t

\[ \tan \beta = 30, \ \mu = 500 \text{ GeV}, \ mA = 2000 \text{ GeV} \]

H. Li, SS, W. Su, J. Yang, work in progress
mA vs. tanβ

Figure 9.

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H. Li, SS, W. Su, J. Yang, work in progress
Figure 9.

- mA vs. tanβ

Complementary to LHC direct search

S. Su

H. Li, SS, W. Su, J. Yang, work in progress
Figure 9.

- $X_t = 0$ (no mixing)

- $X_t = 2M_{SUSY}$ (maximal mixing)

H. Li, SS, W. Su, J. Yang, work in progress
Higgs factory reach impressive precision
Kappa-scheme/EFT scheme/model specific fit
indirect constraints on new physics models
complementary to Zpole precision program
complementary to direct search @ 100 TeV pp
Conclusion

MSSM

Complementary to pp direct search

Figure 9.

Figure 8.

\[ X_t = 2M_{\text{SUSY}} \text{(maximal mixing)} \]
Conclusion

An exciting journey ahead of us!
Backup Slides
Tree-level 2HDM fit

2HDM TYPE-II

- $\kappa$-fit of CEPC 5ab$^{-1}$
- $\Delta\mu/\mu$ of CEPC 5ab$^{-1}$
- $\Delta\mu/\mu$ of ILC Full
- $\Delta\mu/\mu$ of FCC 10ab$^{-1}$

$\kappa$-fit vs $\Delta\mu/\mu$ fit

CEPC/FCC/ILC luminosity

Figure 3. The comparison between the CEPC (red region), ILC (blue region) and FCC-ee (green region) reach in the plane $\cos(\beta - \alpha)$ vs. $\tan\beta$. A tiny arm region for Type-L is omitted for clarity. We also show the global fitting results to $\kappa$ effective couplings from the 7 parameter fit of CEPC, instead of fitting to $\Delta\mu/\mu$, in red solid line. Scaled CEPC results with 2.5 ab$^{-1}$, 10 ab$^{-1}$, 25 ab$^{-1}$ are shown in dashed lines, from outer to inner region.
Strong Dynamics

- Minimum composite Higgs Model (MCHM)
- General EFT patterns of strong interacting models with a light Higgs
Composite Higgs in one slide

- Higgs is the PNGB of the spontaneous breaking of \( G \Rightarrow H \)
- EWSB is induced by vacuum misalignment, parametrized by \( \xi = v^2/f^2 \)
- mass of SM fermion generated by mixing with composite states
- light top partners can be searched at the LHC
- minimal composite Higgs Model (MCHM): SO(5)/SO(4)
  - \( hVV \)
    \[ \kappa_V \equiv \frac{g_{hVV}^{\text{CH}}}{g_{hVV}^{\text{SM}}} = \sqrt{1 - \xi} \]
  - \( hff \): depends on the fermion representation
    \[ F_1 \equiv \frac{1 - 2\xi}{\sqrt{1 - \xi}}, \quad F_2 \equiv \sqrt{1 - \xi} \]
Fermion representation

MCHM:

\[ \xi = \frac{v^2}{f^2} < 10^{-3}, \quad f > 4 \text{ TeV} \]

<table>
<thead>
<tr>
<th>MCHM Reps.</th>
<th>5, 10</th>
<th>10-5-10</th>
<th>5-5-10</th>
<th>5-10-10</th>
<th>14-14-10</th>
<th>14-5-10</th>
<th>5-14-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_t, \kappa_g )</td>
<td>( F_1 )</td>
<td>( F_2 )</td>
<td>( F_1 )</td>
<td>( F_2 )</td>
<td>( F_3 )</td>
<td>( F_4 )</td>
<td>( F_5 )</td>
</tr>
<tr>
<td>( \kappa_b )</td>
<td>( F_1 )</td>
<td>( F_1 )</td>
<td>( F_2 )</td>
<td>( F_2 )</td>
<td>( F_1 )</td>
<td>( F_1 )</td>
<td>( F_1 )</td>
</tr>
</tbody>
</table>

**CEPC**

| \( \xi \times 10^3 \) | 2.56 | 2.36 | 4.19 | 3.87 | 2.78 – 2.56 | 2.71 – 2.36 | 2.36 – 2.04 |
| \( f \) [TeV] | 4.86 | 5.06 | 3.80 | 3.95 | 4.67 – 4.86 | 4.72 – 5.07 | 5.07 – 5.45 |

**ILC**

| \( \xi \times 10^3 \) | 2.19 | 2.02 | 3.44 | 3.20 | 2.31 – 2.19 | 2.06 – 2.01 | 1.87 – 1.72 |
| \( f \) [TeV] | 5.26 | 5.48 | 4.19 | 4.35 | 5.12 – 5.26 | 5.42 – 5.48 | 5.69 – 5.93 |

**FCC-ee**

| \( \xi \times 10^3 \) | 1.80 | 1.66 | 3.06 | 2.74 | 1.85 – 1.80 | 1.70 – 1.66 | 1.66 – 1.41 |
| \( f \) [TeV] | 5.79 | 6.04 | 4.45 | 4.70 | 5.72 – 5.80 | 5.97 – 6.05 | 6.05 – 6.56 |
Once deviations of the Higgs couplings are observed at future colliders, different embeddings, as a function of $\kappa_V$, $\kappa_t$, $\kappa_c$, and $\kappa_b$, vary in a certain range, given the extra parameter dependence. The left panel shows the constraints for CEPC, FCC-ee and ILC, while the right panel shows the constrained fit with $\kappa_V$, $\kappa_t$, $\kappa_c$, and $\kappa_b$. The 68% C.L. (solid lines) and 95% C.L. (dashed lines) constraints in the $(\Delta \kappa_V, \Delta \kappa_t)$ plane at various future Higgs factories from a four-parameter fit with $\kappa_V$, $\kappa_t$, $\kappa_c$, and $\kappa_b$. Also shown are the predicted deviation of $\Delta \kappa_V$, $\Delta \kappa_t$, $\Delta \kappa_c$, and $\Delta \kappa_b$ for different fermion embeddings, as a function of $\xi$. For different fermion representations, the parameter space is further constrained, implying certain comparisons with the lepton colliders.
Strong Dynamics

- **Minimum composite Higgs Model (MCHM)**
- **General EFT patterns of strong interacting models with a light Higgs**
Strong Dynamics in EFT Language

- **EFT operators**

\[
\mathcal{L}_6 = \frac{1}{m^2_*} \sum_i c_i \mathcal{O}_i
\]

<table>
<thead>
<tr>
<th>( \mathcal{O}_H )</th>
<th>( \mathcal{O}_W )</th>
<th>( \mathcal{O}_B )</th>
<th>( \mathcal{O}_{HW} )</th>
<th>( \mathcal{O}_{HB} )</th>
<th>( \mathcal{O}_{BB} )</th>
<th>( \mathcal{O}_{GG} )</th>
<th>( \mathcal{O}_{yu} )</th>
<th>( \mathcal{O}_{yd} )</th>
<th>( \mathcal{O}_{ye} )</th>
<th>( \mathcal{O}_{3W} )</th>
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<tr>
<td>ALH</td>
<td>( g_*^2 )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>( g_*^2 )</td>
<td>( g_*^2 )</td>
<td>( g_*^2 )</td>
</tr>
<tr>
<td>GSILH</td>
<td>( g_*^2 )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>( \frac{y_f^2}{16\pi^2} )</td>
<td>( \frac{y_f^2}{16\pi^2} )</td>
<td>( g_*^2 )</td>
<td>( g_*^2 )</td>
<td>( g_*^2 )</td>
</tr>
<tr>
<td>SILH</td>
<td>( g_*^2 )</td>
<td>1</td>
<td>1</td>
<td>( \frac{g_*^2}{16\pi^2} )</td>
<td>( \frac{g_*^2}{16\pi^2} )</td>
<td>( \frac{y_f^2}{16\pi^2} )</td>
<td>( \frac{y_f^2}{16\pi^2} )</td>
<td>( g_*^2 )</td>
<td>( g_*^2 )</td>
<td>( g_*^2 )</td>
</tr>
</tbody>
</table>
Strong Dynamics in EFT Language

Figure 12. The 95% C.L. constraints on the overall coefficient of $O_i$ from Ref. [38], which are translated into the SILH basis and presented in the form $m_\nu^*/p_i$. Estimated Higgs measurement precision from CEPC, ILC, and FCC-ee are used with the inclusion of HL-LHC Higgs precision.

Figure 13. The 95% C.L. limit on the new physics scale for the three cases of ALH (dotted lines), GSILH (dashed lines) and SILH (solid lines) as a function of $g^*_{\nu}$ with CEPC (red), ILC (blue) and FCC-ee (green) precision. The left plot is the results obtained using fit on individual operators, and the right plot is the results obtained using global fit of all 12 operators. The operator that is most sensitive (therefore determines the best reach) is labelled alongside the curves.

Fig. 12 shows the results from individual constraints on operators obtained by switching on one of them at a time (light shade) and the other from a 12-parameter global fit (solid shade). The single operator fit results are typically factors of a few better for operators involving electroweak gauge bosons, due to their correlation in Higgs physics. We also note here the typical scale from a global fit on these operators are around $1_{-3}^{+3}$ TeV with $c_i \ll 1$, with the exception of $m_\nu^*/p_{BB}$ and $m_\nu^*/p_{GG}$, which could reach around 10 TeV. This is because the leading order contribution from the SM to $h! g g$ appears at one-loop level.

95%CL bound of the 12-parameter fit in SILH' basis

- CEPC: 240GeV (5/ab) + 350GeV (200/fb) + HL-LHC
- FCC-ee: 240GeV (10/ab) + 350GeV (2.6/ab) + HL-LHC

translated from the results in arXiv:1704.02333

light shade: individual fit (one operator at a time)
solid shade: global fit

$m_\nu^*/|c_i|$ [TeV]
Strong Dynamics in EFT Language

**Figure 12.** The 95% C.L. constraints on the overall coefficient of $O_i$ from Ref. [38], which are translated into the SILH basis and presented in the form $m^*/p_i$. Estimated Higgs measurement precision from CEPC, ILC, and FCC-ee are used with the inclusion of HL-LHC Higgs precision.

<table>
<thead>
<tr>
<th>$g^*$</th>
<th>$m^*$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
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<td>6</td>
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<tr>
<td>8</td>
<td>20</td>
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<tr>
<td>10</td>
<td>50</td>
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</tbody>
</table>

**Figure 13.** The 95% C.L. limit on the new physics scale for the three cases of ALH (dotted lines), GSILH (dashed lines) and SILH (solid lines) as a function of $g^*$ with CEPC (red), ILC (blue) and FCC-ee (green) precision. The left plot is the results obtained using fit on individual operators, and the right plot is the results obtained using global fit of all 12 operators. The operator that is most sensitive (therefore determines the best reach) is labelled alongside the curves.

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Conclusion

**strong dynamics models**
- **MCHM**: $\xi = v^2/f^2 < 10^{-3}$, $f > 4$ TeV
- **ALH/GSILH/SILH**

**individual fit**

**global fit**

95% CL bound on $m_\star$, individual fit

95% CL bound on $m_\star$, global fit

S. Su