Learning from Higgs Physics at Future Higgs Factories

Shufang Su • U. of Arizona

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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 (skip in this talk)
- **Strong dynamics models** (skip in this talk)
- **Complementarity with direct search @ 100 pp**
- **Conclusion**
**Higgs Precision Measurements**

**Input measurements**  
$m_H$ (GeV)  
$\pm 1\sigma$ on $\mu$

### ATLAS

**Individual analysis**

- **$H \rightarrow \gamma\gamma$**  
  Overall: $\mu = 1.17^{+0.27}_{-0.27}$  
  $ggF$: $\mu = 1.32^{+0.36}_{-0.36}$  
  VBF: $\mu = 0.83^{+0.21}_{-0.21}$  
  WH: $\mu = 1.07^{+1.4}_{-1.4}$  
  ZH: $\mu = 0.13^{+0.11}_{-0.11}$  
  $m_H = 125.4$

- **$H \rightarrow ZZ^*$**  
  Overall: $\mu = 1.44^{+0.48}_{-0.48}$  
  $ggF$: $\mu = 0.98^{+0.26}_{-0.26}$  
  VBF: $\mu = 1.72^{+0.44}_{-0.44}$  
  VBF+VH: $\mu = 0.3^{+0.14}_{-0.14}$  
  $m_H = 125.36$

- **$H \rightarrow WW^*$**  
  Overall: $\mu = 1.16^{+0.24}_{-0.24}$  
  $ggF$: $\mu = 0.96^{+0.26}_{-0.26}$  
  VBF: $\mu = 1.29^{+0.35}_{-0.35}$  
  VH: $\mu = 3.0^{+1.6}_{-1.6}$  
  $m_H = 125.36$

- **$H \rightarrow \tau\tau$**  
  Overall: $\mu = 1.43^{+0.37}_{-0.37}$  
  $ggF$: $\mu = 2.07^{+1.3}_{-1.3}$  
  VBF: $\mu = 1.24^{+0.36}_{-0.36}$  
  $m_H = 125.36$

- **$VH \rightarrow Vb\bar{b}$**  
  Overall: $\mu = 0.52^{+0.46}_{-0.46}$  
  WH: $\mu = 1.11^{+0.44}_{-0.44}$  
  ZH: $\mu = 0.05^{+0.16}_{-0.16}$  
  $m_H = 125.36$

- **$H \rightarrow \mu\mu$**  
  Overall: $\mu = -0.73^{+1.37}_{-1.37}$  
  $m_H = 125.5$

- **$H \rightarrow Z\gamma$**  
  Overall: $\mu = 2.7^{+4.5}_{-4.3}$  
  $m_H = 125.5$

- **ttH**  
  $b\bar{b}$: $\mu = 1.5^{+1.1}_{-1.1}$  
  Multilepton: $\mu = 2.1^{+1.5}_{-1.5}$  
  $\gamma\gamma$: $\mu = 1.3^{+1.3}_{-1.3}$  
  $m_H = 125.4$

### CMS

- **Combined**
  - $\mu = 1.00 \pm 0.14$
  - $H \rightarrow \gamma\gamma$ (untagged)
  - $H \rightarrow \gamma\gamma$ (VBF tag)
  - $H \rightarrow \gamma\gamma$ (VH tag)
  - $H \rightarrow \gamma\gamma$ (ttH tag)
  - $H \rightarrow ZZ$ (0/1-jet)
  - $H \rightarrow ZZ$ (2-jet)
  - $H \rightarrow WW$ (0/1-jet)
  - $H \rightarrow WW$ (VBF tag)
  - $H \rightarrow WW$ (VH tag)
  - $H \rightarrow WW$ (ttH tag)
  - $H \rightarrow \tau\tau$ (0/1-jet)
  - $H \rightarrow \tau\tau$ (VBF tag)
  - $H \rightarrow \tau\tau$ (VH tag)
  - $H \rightarrow \tau\tau$ (ttH tag)
  - $H \rightarrow bb$ (VH tag)
  - $H \rightarrow bb$ (ttH tag)

- **Best fit $\sigma/\sigma_{SM}$**
  - $m_H = 125$ GeV
  - $p_{SM} = 0.84$

**LHC: 7+8 TeV**

- $19.7$ fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)

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$\sqrt{s} = 7$ TeV, 4.5–4.7 fb$^{-1}$

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

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

**ATLAS Simulation Preliminary**
\[ \sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>H → γγ (comb.)</th>
<th>All unc.</th>
<th>No theory unc.</th>
<th>All unc.</th>
<th>No theory unc.</th>
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<tbody>
<tr>
<td>(0j)</td>
<td>0.13</td>
<td>0.09</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>(1j)</td>
<td>0.19</td>
<td>0.12</td>
<td>0.16</td>
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<tr>
<td>(VBF-like)</td>
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<td>0.47</td>
<td>0.43</td>
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<td>0.48</td>
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<tr>
<td>(VH-like)</td>
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<td>0.07</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>(ttH-like)</td>
<td>0.35</td>
<td>0.34</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>(VBF-like)</td>
<td>0.49</td>
<td>0.48</td>
<td>0.20</td>
<td>0.16</td>
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<tr>
<td>(ggF-like)</td>
<td>0.36</td>
<td>0.33</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td>H → WW (comb.)</td>
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<td>0.07</td>
<td>0.11</td>
<td>0.04</td>
</tr>
<tr>
<td>(0j)</td>
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<td>0.08</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>(1j)</td>
<td>0.18</td>
<td>0.09</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>(VBF-like)</td>
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<td>0.18</td>
<td>0.26</td>
<td>0.10</td>
</tr>
<tr>
<td>H → Zγ (incl.)</td>
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<td>0.15</td>
<td>0.09</td>
</tr>
<tr>
<td>H → b\bar{b} (comb.)</td>
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<td>0.44</td>
<td>0.30</td>
<td>0.27</td>
</tr>
<tr>
<td>(WH-like)</td>
<td>0.26</td>
<td>0.26</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>(ZH-like)</td>
<td>0.57</td>
<td>0.56</td>
<td>0.37</td>
<td>0.36</td>
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<tr>
<td>H → ττ (VBF-like)</td>
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<td>0.29</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>H → μμ (comb.)</td>
<td>0.21</td>
<td>0.18</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td>(incl.)</td>
<td>0.39</td>
<td>0.38</td>
<td>0.16</td>
<td>0.12</td>
</tr>
<tr>
<td>(ttH-like)</td>
<td>0.47</td>
<td>0.45</td>
<td>0.18</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**LHC: 14 TeV, 300 fb⁻¹, 3000 fb⁻¹**

\[ \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \]

\[ \Delta \mu/\mu \]

\[ 0 \quad 0.2 \quad 0.4 \]

ATL-PHYS-PUB-2014-016
The 2HDM Lagrangian for Higgs sector can be written as
\[ V = \frac{1}{2} \mu \Phi^\dagger \Phi + \frac{1}{4} \lambda \Phi^4 \]

where \( \lambda \) is the Higgs potential. As well as a pair of charged Higgs eigenstates are the two CP-even Higgses with the Higgs potential \( V \).

The CEPC-preCDR, TLEP Design Study Working Group, ILC Operating Scenarios.

### Table 3: Higgs Precision Measurements

<table>
<thead>
<tr>
<th>collider</th>
<th>CEPC</th>
<th>FCC-ee</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s} )</td>
<td>240 GeV</td>
<td>240 GeV</td>
<td>250 GeV</td>
</tr>
<tr>
<td>( \int \mathcal{L} dt )</td>
<td>5 ab(^{-1})</td>
<td>5 ab(^{-1})</td>
<td>2 ab(^{-1})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>production</th>
<th>Zh</th>
<th>Zh</th>
<th>Zh</th>
<th>Zh</th>
<th>( \nu \bar{\nu} h )</th>
<th>Zh</th>
<th>( \nu \bar{\nu} h )</th>
<th>( t \bar{t} h )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \sigma / \sigma )</td>
<td>0.51%</td>
<td>0.57%</td>
<td>0.71%</td>
<td>2.1%</td>
<td>-</td>
<td>1.06</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>decay</th>
<th>( h \to bb )</th>
<th>( h \to cc )</th>
<th>( h \to gg )</th>
<th>( h \to WW^* )</th>
<th>( h \to \tau^+ \tau^- )</th>
<th>( h \to ZZ^* )</th>
<th>( h \to \gamma \gamma )</th>
<th>( h \to \mu^+ \mu^- )</th>
<th>( (\nu \bar{\nu})h \to bb )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>0.28%</td>
<td>2.2%</td>
<td>1.6%</td>
<td>1.5%</td>
<td>1.2%</td>
<td>4.3%</td>
<td>9.0%</td>
<td>17%</td>
<td>2.8%</td>
</tr>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>0.28%</td>
<td>1.7%</td>
<td>1.98%</td>
<td>1.27%</td>
<td>0.99%</td>
<td>4.4%</td>
<td>4.2%</td>
<td>18.4%</td>
<td>3.1%</td>
</tr>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>0.42%</td>
<td>2.9%</td>
<td>2.5%</td>
<td>1.1%</td>
<td>2.3%</td>
<td>6.7%</td>
<td>12.0%</td>
<td>25.5%</td>
<td>3.7%</td>
</tr>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>1.67%</td>
<td>12.7%</td>
<td>9.4%</td>
<td>8.7%</td>
<td>4.5%</td>
<td>28.3%</td>
<td>43.7%</td>
<td>97.6%</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>1.67%</td>
<td>16.7%</td>
<td>11.0%</td>
<td>6.4%</td>
<td>24.4%</td>
<td>21.8%</td>
<td>50.1%</td>
<td>179.8%</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>0.64%</td>
<td>4.5%</td>
<td>3.9%</td>
<td>3.3%</td>
<td>1.9%</td>
<td>8.8%</td>
<td>12.0%</td>
<td>31.1%</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>0.25%</td>
<td>2.2%</td>
<td>1.5%</td>
<td>0.85%</td>
<td>3.2%</td>
<td>2.9%</td>
<td>6.7%</td>
<td>25.5%</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta (\sigma \cdot BR) / (\sigma \cdot BR) )</td>
<td>9.9%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>
Higgs Precision Measurements

<table>
<thead>
<tr>
<th>collider</th>
<th>CEPC</th>
<th>FCC-ee</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
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<td>5 ab$^{-1}$</td>
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<td>$Zh$</td>
<td>$Zh$</td>
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</tr>
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<td>0.51%</td>
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<td>0.71%</td>
</tr>
<tr>
<td>decay</td>
<td></td>
<td></td>
<td></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>$h \rightarrow τ^+τ^-$</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>
</tr>
<tr>
<td>$h \rightarrow γγ$</td>
<td>9.0%</td>
<td>4.2%</td>
<td>12.0%</td>
</tr>
<tr>
<td>$h \rightarrow μ^+μ^-$</td>
<td>17%</td>
<td>18.4%</td>
<td>25.5%</td>
</tr>
<tr>
<td>$(ν\bar{ν})h \rightarrow bb$</td>
<td>2.8%</td>
<td>3.1%</td>
<td>3.7%</td>
</tr>
</tbody>
</table>
In this 10 parameter list, the relation coupling from its SM value does enter two type of new decay channels will be distinguished: couplings and to the SM gauge bosons. For the discussion of coupling fits and their implications, CEPC will not be able to directly measure the Higgs coupling to top quarks. A deviation of this.

Furthermore, it is possible that the Higgs can decay directly into new physics particles. In this case, of the exotic decay or treating it as an independent parameter (essentially assuming it cannot be very distinct and can be measured very well. In another extreme, they can be in a form which cannot be measured directly but can be constrained by theory. This is the case for the SMEFT Higgs parameter fit in Higgs basis.

The twelve-parameter GDPs for the combination of future lepton collider, LHC measurements however can resolve these flat directions. The horizontal blue lines on Fig. 2.19 in the top panel of Fig. 2.19 show the constraints on the SMEFT Higgs parameter fit in Higgs basis, which are then even substantially better than that set by the LEP measurements. LHC constraints also include measurements carried out at 300 fb⁻¹.

The precision reach of the 12–parameter fit in Higgs basis, which is compared with the HL-LHC projection with aggressive assumptions (Fig. 7). It is also much stronger in the (Z→ll) interval, one order of magnitude worst than that set by the GDPs in the (Z→ll) channel. Even with this set of restrictive assumptions, the advantage of the CEPC is shown in Table 2.38. Even with this set of restrictive assumptions, the advantage of the CEPC is shown in Table 2.38.

We emphasize that this is comparing with the HL-LHC projection with aggressive assumptions. A more complete comparison including several ILC upgrade options is shown in Fig. 2.35. Panel a shows the expected precision reach of the GDPs in the (Z→ll) channel when future lepton collider measurements are included. On the other hand, with GDPs in the (Z→ll) channel and the correlation matrix corresponding loop induced.
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
Therefore, fit to

Ultimately, fitting to either

are usually presented in most experimental papers. While using

fit, the corresponding

energies, we sum the contribution from each individual channel. For one or two parameter

CEPC, FCC-ee, ILC and Table

The corresponding

usually not provided, and are thus assumed to be zero in the fits.

It is also important to compare the reaches of the future Higgs factories to that of the

Precision corrections (improved by a

automatically satisfied.

To transfer the estimated error on the experimental measurements to the constraints on the

model parameter space (compared with SMEFT). Therefore, they are included in our global

analysis.

Various K_i
(with correlation)

Coeff of EFT operators
(with correlation)

parameters in New
Physics Models

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

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

S. Su
Perturbative Models

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

- 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>Type</th>
<th>ϕ₁</th>
<th>ϕ₂</th>
</tr>
</thead>
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</tr>
<tr>
<td>Type II</td>
<td>u</td>
<td>d,l</td>
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<tr>
<td>lepton-specific</td>
<td>u,d</td>
<td>l</td>
</tr>
<tr>
<td>flipped</td>
<td>u,l</td>
<td>d</td>
</tr>
</tbody>
</table>

- parameters (CP-conserving, flavor limit, Z₂ symmetry)

- 246 GeV
- 125 GeV

- soft Z2 breaking: m₁₂²

- m₁₁², m₂₂², λ₁, λ₂, λ₃, λ₄, λ₅

- ν, tan β, α, mₜ, m_H, m_A, m_H±

- tan β, cos(β-α),
  control tree level h⁰ couplings

S. Su
# 2HDM parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>$\phi_1$</th>
<th>$\phi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>u, d, l</td>
<td></td>
</tr>
<tr>
<td>Type II</td>
<td>u</td>
<td>d, l</td>
</tr>
<tr>
<td>lepton-specific</td>
<td>u, d</td>
<td>l</td>
</tr>
<tr>
<td>flipped</td>
<td>u, l</td>
<td>d</td>
</tr>
</tbody>
</table>

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

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

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

  - 246 GeV
  - 125 GeV

  - $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

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

---

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**theoretical constraints**

\[ \lambda \]

\[ \tan \beta = \frac{m_{H^+} - m_{H^-}}{m_H} = \frac{m_A}{m_{H^0}} = \frac{m_{H^0}}{m_{H^0}} \]

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

- \[ \cos(\beta-\alpha) = 0.005 \]
- \[ \cos(\beta-\alpha) = 0.00 \]
- \[ \cos(\beta-\alpha) = -0.005 \]
- \[ m_\phi = 800 \text{ GeV} \]

**Figure 2**

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

- \[ \cos(\beta-\alpha) = 0.0 \]
- \[ m_H = 800 \text{ GeV} \]
- \[ \Delta m_A = \Delta m_C \]
Tree-level 2HDM fit

2HDM, LHC/FCC fit

Figure 2. The allowed region in the plane of \( \tan \beta \) vs. \( \cos(\beta-\alpha) \) at 95% C.L. for the four types of 2HDM, given LHC and CEPC Higgs precision measurements. For future measurements, we assume that the measurements agree with SM predictions. The special “arm” regions for the Type-II, L and F are the wrong-sign Yukawa regions. See text for more details.

Here \( x \) is \( d, e \) in the Type-II, \( e \) in the Type-L and \( d \) in the Type-F. Therefore, the survival parameter space at large \( \tan \beta \) is reduced significantly in all these three types.

For the Type-II at the upper right panel of Fig. 2, as a result of larger \( \tan \beta \) enhancement from \( d,e \) and small \( \tan \beta \) enhancement from \( u \), the region around \( \tan \beta = 1 \) accommodates...
TYPE II 2HDM: Tree + Loop

$m_\Phi = 800$ GeV, $\sqrt{\lambda v^2} = 300$ GeV

$\cos(\beta - \alpha)$ vs. $\tan\beta$

Figure 3

$\sqrt{\lambda v^2}$

$\cos(\beta - \alpha)$ vs. $\tan\beta$

Figure 4

$\sqrt{\lambda v^2} = 800$ GeV

Constraints from individual couplings are given with the color codes: blue (star), orange (400), purple (200), green (300), and cyan (500). The benchmark point of $m_\Phi = 800$ GeV, $\sqrt{\lambda v^2} = 300$ GeV is used here. The preferred region in the $\cos(\beta - \alpha)$ - $\tan\beta$ plane for various values of $m_\Phi$ and $\sqrt{\lambda v^2}$ is shown.

The distorted shape of the global fit results, comparing to the tree-level only results is due to contributions almost decoupling at small (large) $\tan\beta$. For fixed $m_\Phi = 2000$ GeV, large $\sqrt{\lambda v^2}$ can be accommodated. For $m_\Phi = 800$ GeV, no parameter space in the $\cos(\beta - \alpha)$ - $\tan\beta$ plane is excluded due to the deviation in mass of the heavy Higgs bosons running in the loop. In general, the final allowed region is close to the tree-level results. Comparing with the constraints from theoretical constraints. High precision on the Higgs coupling measurements can also be used to constrain the 2HDM parameter space at least an order of magnitude better in the allowed $\cos(\beta - \alpha)$ - $\tan\beta$ plane via LHC searches with CEPC precision.

N. Chen, T. Han, SS, W. Su, Y. Wu, 1808.02037

S. Su
**2HDM: Loop in the Alignment Limit**

- **Type II**

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

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

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

- Red: 95%CL, Sqrt(\lambda v^2) = 0 GeV
- Blue: 95%CL, Sqrt(\lambda v^2) = 100 GeV
- Green: 95%CL, Sqrt(\lambda v^2) = 300 GeV
- Orange: 95%CL, Sqrt(\lambda v^2) = 500 GeV

\[
\text{Sqrt}(\lambda v^2) = \text{Sqrt}(m_\phi^2 - \frac{m_{12}^2}{s\beta c\beta})
\]

**CEPC 5 ab⁻¹**

\[m_\phi = m_{H^0} = m_A = m_{H^\pm} \text{ (GeV)}\]
For negative cos(\(\beta - \alpha\)) precision. Once cos(\(\beta - \alpha\)) deviates from zero, tree-level contributions become sizable. Even as small as 0.005, tan(\(\beta\)) and tan(\(\beta - \alpha\)) are allowed in the alignment limit of cos(\(\beta - \alpha\)). While all ranges of cos(\(\beta - \alpha\)) = 0, once cos(\(\beta - \alpha\)) = 0, tan(\(\beta\)) further shrinks, the allowed region further shrinks, the allowed region in \(m_{\Phi} = m_{H^0} = m_A = m_{H^\pm}\) varies from 0 to 0.35 when cos(\(\beta - \alpha\)) = 300 GeV, larger loop corrections further modify the allowed region in \(m_{\Phi} = m_{H^0} = m_A = m_{H^\pm}\), as well as small and large tan(\(\beta\)). Three-parameter fitting results at 95% C.L. in the \(m_{\Phi} = m_{H^0} = m_A = m_{H^\pm}\) plane under theoretical considerations.

Theoretical considerations under the same color codes. Best-fit point. Also shown are the allowed regions under theoretical considerations under the same precision. We set cos(\(\beta - \alpha\)) = -0.005, tan(\(\beta\)) = 0, and tan(\(\beta - \alpha\)) = 0.005, while tan(\(\beta\)) = 0.005, tan(\(\beta - \alpha\)) = 0, and tan(\(\beta\)) = 0.005 respectively. The colored stars show the corresponding regions are ruled out by theoretical considerations.

\[\sqrt{\lambda v^2} = 0\text{ GeV}\]

\[\sqrt{\lambda v^2} = 300\text{ GeV}\]

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
Each obtains a VEV introduced in 2HDM. Two SU(2)

### Table 3

<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>$\Delta \alpha_{\text{had}}^{(5)}(M_Z^2)$</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>$\pm 0.005$</td>
<td>$\pm 0.0021$</td>
<td>$\pm 0.0001_{\text{exp}}$</td>
</tr>
<tr>
<td>$m_t$ [GeV] (pole)</td>
<td>$0.6_{\text{exp}} \pm 0.25_{\text{th}}$</td>
<td>$&lt; \pm 0.1$</td>
<td>$0.6_{\text{exp}} \pm 0.25_{\text{th}}$</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>$\sin^2 \theta^\ell_{\text{eff}}$</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>$0.001$</td>
<td>$(\pm 1_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-4}$</td>
</tr>
</tbody>
</table>
\[ \Delta m_a = m_A - m_H, \quad \Delta m_c = m_{H^±} - m_H \]

\[ m_H = 800 \text{ GeV}, \quad \sqrt{\lambda v^2} = 0 \text{ GeV} \]

- \cos(\beta - \alpha) = 0.007
- \cos(\beta - \alpha) = 0.0
- \cos(\beta - \alpha) = -0.007

Complementary to Zpole precision
Different Higgs Factories

In this paper, we examined the impacts of the precision measurements of the SM parameters on the extended Higgs sector. We first summarized the general formulation, theoretical considerations and the existing constraints to the model. Previous works focused on either just the tree-level deviations, or loop corrections under the alignment limit, and with the assumption of 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.

Section 2: Different Higgs Factories

The main results of the paper were presented in a two-parameter fitting framework. We then illustrated the simple case with degenerate heavy Higgs masses. In our analyses, we extended the existing results by including the tree-level and one-loop level effects.

Fig. 1: $m_A = 800$ GeV, $\sqrt{\lambda v^2} = 300$ GeV

Fig. 2: $m_H = 800$ GeV, $\sqrt{\lambda v^2} = 300$ GeV

Fig. 3: Higgs factories at the proposed CEPC, CLIC, FCC-ee and ILC luminosities. The black dashed line indicates the CEPC tree-level precision measurements alone constrain the deviation from the SM Higgs boson. As shown in Fig. 3, two-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$ plane is complementary to direct non-SM Higgs search limits at the LHC and the other colliders, especially in the intermediate $\tan\beta$ region when the direct search limits are relaxed.

Fig. 4: The reach seen in Fig. 3 shows the allowed region when the direct search limits are relaxed.

Fig. 5: The limits on the heavy Higgs masses also depend on $\tan\beta$. The largest 95% C.L. range of $\tan\beta$ achieved for $\tan\beta \sim 1$, with smaller and larger values of $\tan\beta$ leading to much tighter constraints, especially for allowed range of $\tan\beta$.

Fig. 6: For the combined fit, FCC-ee shows the best constraint, dominated by the tree-level effects.

Fig. 7: The main results of the paper were presented in a two-parameter fitting framework. We then illustrated the simple case with degenerate heavy Higgs masses.

Fig. 8: Two-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$ plane with CEPC (red), FCC-ee (blue) and ILC (green) precisions, similar to Fig. 3. The left and right panels are for Higgs/$Z^0$-pole. For the combined fit, FCC-ee shows the best constraint, dominated by the tree-level effects.

Fig. 9: Two-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$ plane with CEPC (red), FCC-ee (blue) and ILC (green) precisions, similar to Fig. 3. The main results of the paper were presented in a two-parameter fitting framework. We then illustrated the simple case with degenerate heavy Higgs masses.

Fig. 10: Two-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$ plane with CEPC (red), FCC-ee (blue) and ILC (green) precisions, similar to Fig. 3. The main results of the paper were presented in a two-parameter fitting framework. We then illustrated the simple case with degenerate heavy Higgs masses.

Fig. 11: Two-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$ plane with CEPC (red), FCC-ee (blue) and ILC (green) precisions, similar to Fig. 3. The main results of the paper were presented in a two-parameter fitting framework. We then illustrated the simple case with degenerate heavy Higgs masses.

Fig. 12: Two-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$ plane with CEPC (red), FCC-ee (blue) and ILC (green) precisions, similar to Fig. 3. The main results of the paper were presented in a two-parameter fitting framework. We then illustrated the simple case with degenerate heavy Higgs masses.

Fig. 13: Two-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$ plane with CEPC (red), FCC-ee (blue) and ILC (green) precisions, similar to Fig. 3. The main results of the paper were presented in a two-parameter fitting framework. We then illustrated the simple case with degenerate heavy Higgs masses.
The global fit to the expected precision measurements in the full model-parameter space. We first set up the general formulation, theoretical considerations and the existing constraints to the model tree-level deviations, or loop corrections under the alignment limit, and with the assumption of the well-motivated theory, the Type-II 2HDM. Previous works focused on either just the mass spectrum or other parameters. In this paper, we examined the impacts of the precision measurements of the SM parameters on the Higgs parameter space.

### Summary and Conclusions

The main results of the paper were presented in Sections 2-4. Those expectations serve as the general guidances and inputs for future investigations.

**Different Higgs Factories**

- **CEPC**: Highest precision on the Higgs parameter space.
- **FCC-ee**: Sensitive to deviations away from the tree-level predictions.
- **ILC**: Best for small values of $\tan\beta$.

- **Higgs Factories**
  - **CEPC**: High precision on the Higgs parameter space.
  - **FCC-ee**: Sensitive to deviations away from the tree-level predictions.
  - **ILC**: Best for small values of $\tan\beta$.

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**Figures**

- **Fig. 12**: Comparison of the reach obtained under the alignment limit with the expected CEPC precision. We found that in the parameter space of $\cos(\beta - \alpha)$, the smallest 95% C.L. range of $m_A$ is achieved for $\tan\beta < 1$, with smaller and larger values of $\tan\beta$.

- **Fig. 13**: Two-parameter fitting results at 95% C.L. in the $\Delta m_c - \Delta m_A$ plane with CEPC (red), FCC-ee (blue) and ILC (green) precisions, similar to the expected CEPC precision. While the most relaxed limits can be obtained under the alignment limit with small $\cos(\beta - \alpha)$, the largest 95% C.L. range of $m_A$ is achieved for $\tan\beta > 10$, leading to much tighter constraints, especially for allowed range of $\tan\beta$. The reach seen in the $\Delta m_c$ axis is complementary to direct non-SM Higgs search limits at the LHC and FCC-ee has the best performance because of the higher proposed luminosity at the proposed colliders, especially in the intermediate $\tan\beta$ region when the direct search limits are relaxed.
Conclusion

- 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

An exciting journey ahead of us!

LHC

Lepton Collider

100 TeV pp

S. Su