LHC/ILC Synergy for Exploring Extended Higgs Sectors

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Collaboration with
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BSM must exist, because of unsolved phenomena such as Neutrino masses, DM and Baryon asymmetry of Universe.

New paradigm for the EWSB is necessary, such as Supersymmetry, Composite Higgs and Gauge Higgs Unification.

Exploring the Higgs sector is a key to probe these BSM/NP!

How can we clarify the property of the Higgs sector?

Direct searches for additional Higgs bosons and indirect searches via Higgs precise measurements can probe the Higgs sector.
Keywords: Alignment/Decoupling

Direct search at LHC may cover

Alignment

SM-limit

Decoupling
Synergy b/w LHC and ILC searches is important!
2 Higgs doublet models

- Simple extension of the Higgs sector:
  \( \Phi_{SM} \rightarrow \Phi_1, \Phi_2 \)
  \( h_{SM} \rightarrow h, H, A, H^\pm \)

- Variations of the 2HDM

  - CP-conserving 2HDM
  - CP-violating 2HDM
    (See, talk by M. Kubota)
  - Hardly-broken (General 2HDM)
  - Softly-broken (Type-I, Type-II, Type-X, Type-Y)
  - Unbroken (Inert doublet model)

\[ V = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 (\Phi_1^\dagger \Phi_2 + h.c.) \]
\[ + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 \]
\[ + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + h.c.] \]

- 8 parameters: \( v, m_h, m_H, m_A, m_{H^\pm}, \sin(\beta-\alpha), \tan\beta, \) and \( M^2 \)
Alignment/Decoupling in the 2HDM

- **Higgs basis**  
  \( \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix} \)  
  \( \tan \beta = \frac{v_2}{v_1} \)

- **NG boson**
  \( \Phi = \begin{bmatrix} \frac{1}{\sqrt{2}} (h'_1 + v + iG^0) \end{bmatrix} \)

- **Charged Higgs**
  \( \Psi = \begin{bmatrix} \frac{1}{\sqrt{2}} (h'_2 + iA) \end{bmatrix} \)

- **Masses of the Higgs boson at** \( \sin(\beta-\alpha) \sim 1 \)
  \( m_h^2 \sim \lambda v^2, \quad m_\Phi^2 \sim M^2 + \lambda'v^2 \)  
  (\( \Phi = H^\pm, A, H \))

- **Decoupling limit:**  
  \( M^2 \rightarrow \infty \)  
  - Masses of \( H, A, H^\pm \) become infinity.

- **Alignment limit:**  
  \( \sin(\beta - \alpha) \rightarrow 1 \)  
  - \( h \) plays a role of the Higgs boson.  
  - \( H, A, H^\pm \) behave fermio-philic scalars.
(Non) alignment in the 2HDM

Type-I 2HDM with $m_H = m_A = m_{H^+} = M = 400$ GeV, $\tan \beta = 10$

Higgs to Higgs decays become important for the non-alignment case.

Computed by H-COUP v3-β, Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

NLO EW corr. to $H \rightarrow hh$:
Krause, Muhlleitner, Santos, Ziesche (2016)
Decoupling without alignment?

Q. Can we take $M \rightarrow \infty$ with $\sin(\beta-\alpha) \neq 1$?

A. No.

$$m_h^2 = \lambda v^2 + \cos^2(\beta - \alpha) M^2 = (125 \text{ GeV})^2$$

This term becomes huge when $M \gg v$ and $\sin(\beta-\alpha) \neq 1$

This term should also be huge to keep $125 \text{ GeV} \rightarrow$ unitarity violation

The upper limit on $M$ ($\sim 2^{\text{nd}}$ Higgs scale) appears when $\sin(\beta-\alpha) \neq 1$.

ILC can extract it from precise measurements of $h$ couplings

ILC can set the upper limit on the second Higgs mass scale.
Current Exclusion Limits @ LHC Run-II

Aiko, Kanemura, Mawatari, Yagyu (in preparation)

Current [Type-II; $s_{\beta-\alpha} = 0.995$, $c_{\beta-\alpha} > 0$]

Cross section: SusHi v1-7-0
Harlander, Liebler, Mantler

BR: H-COUPO v3-β
Aiko, Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu
Expected Exclusion Limits @ HL-LHC

Aiko, Kanemura, Mawatari, Yagyu (in preparation)

Cross section: SusHi v1-7-0
Harlander, Liebler, Mantler

BR:H-COUP v3-β
Aiko, Kanemura, Kikuchi, Mawatari,
Sakurai, Yagyu
Combined Limits from LHC/ILC

Aiko, Kanemura, Mawatari, Yagyu (in preparation)

Cross section: SusHi v1-7-0
Harlander, Liebler, Mantler

BR:H-COUP v3-β
Aiko, Kanemura, Kikuchi, Mawatari,
Sakurai, Yagyu

Indirect:H-COUP v3-β
Aiko, Kanemura, Kikuchi, Mawatari,
Sakurai, Yagyu

$$\kappa_V = 0.995 \pm 0.0038$$
\[ \sin(\beta - \alpha) = 1 \]

\[ \sin(\beta - \alpha) = 0.995 \]

\[ \sin(\beta - \alpha) = 0.99 \]

\[ \sin(\beta - \alpha) = 0.98 \]
- Higgs physics is the window of New Physics.

- Scenario of extended Higgs sectors can be classified by alignment and decoupling.

- Wide region of the parameter space can be excluded by the synergy of LHC direct and ILC indirect searches.

- Alignment without decoupling region can be survived, which can be explored by measuring other observables e.g., the triple h coupling.
### Parameter (a) no BSM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$\kappa_Z$</td>
<td>$1.07 \pm 0.10$</td>
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<tr>
<td>$\kappa_W$</td>
<td>$1.07 \pm 0.11$</td>
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<tr>
<td>$\kappa_b$</td>
<td>$0.97^{+0.24}_{-0.22}$</td>
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<tr>
<td>$\kappa_t$</td>
<td>$1.09^{+0.15}_{-0.14}$</td>
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<tr>
<td>$\kappa_\tau$</td>
<td>$1.02^{+0.17}_{-0.16}$</td>
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<td>$\kappa_\gamma$</td>
<td>$1.02^{+0.09}_{-0.12}$</td>
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<tr>
<td>$\kappa_g$</td>
<td>$1.00^{+0.12}_{-0.11}$</td>
</tr>
<tr>
<td>$B_{BSM}$</td>
<td>-</td>
</tr>
</tbody>
</table>

\[
\kappa_X = \frac{g_{hX}^{\text{Exp}}}{g_{hX}^{\text{SM}}}
\]
Fujii et al, 1710.07621 [hep-ph]
NEW!!  H-COUP version 2.3 was released (30 Apr. 2020)

H-COUP version 2 (1 Sep. 2019) is a calculation tool composed of a set of Fortran codes to compute the Higgs boson decay rates and the branching ratios with radiative corrections (NNLO for QCD and NLO for EW) in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. H-COUP ver. 2 contains all the functions in H-COUP ver. 1.

Authors:
Shinya Kanemura, Mariko Kikuchi, Kentarou Mawatari, Kodai Sakurai and Kei Yagyu

Current Exclusion Limits @ LHC Run-II

Cross section: SusHi
Harlander, Liebler, Mantler

BR:H-COUP v2
Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu
Expected Exclusion Limits @ HL-LHC

Cross section: SusHi
Harlander, Liebler, Mantler
BR:H-COUP v2
Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

\[ A \rightarrow Zh \]

\[ H \rightarrow hh \]
Combined Limits from LHC/ILC

Expected [Type-I; $s_{\beta-\alpha} = 0.995$, $c_{\beta-\alpha} > 0$]

$A \rightarrow Zh$

$H^\pm \rightarrow \tau \nu$

$A \rightarrow \tau\tau$

$H \rightarrow hh$

Cross section: SusHi
Harlander, Liebler, Mantler

BR:H-COUP v2
Kanemura, Kikuchi, Mawatari,
Sakurai, Yagyu

Indirect:H-COUP v2
Kanemura, Kikuchi, Mawatari,
Sakurai, Yagyu

$\kappa_V = 0.995 \pm 0.0038$
Allowed by vacuum stab.

Allowed by unitarity
Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu, arXiv: 1803.01456 (PLB)
• LHCWG (H+: NLO)
• SusHi (A, H: N3LO)