The precise measurement of the 2HDM at the future e^+e^- colliders

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We will (almost) have CEPC/ILC/Fcc-ee

http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf
http:
//cepc.ihep.ac.cn/CEPC_CDR_Vol2_Physics-Detector.pdf

What will CEPC buy us?

This talk: based on **1808.02037**, with T. Han, S. Su, W. Su, Y. Wu.

The estimated precisions for the Higgs measurements

collider	CEPC	FCC-ee	ILC
$\sqrt{s}$	240 GeV	240 GeV	250 GeV
$\int \mathcal{L}dt$	5 ab^{-1}	5 ab^{-1}	2 ab^{-1}
production	Zh	Zh	Zh
$\Delta\sigma/\sigma$	0.51%	0.57%	0.71%
$h \to b\bar{b}$	0.28%	0.28%	0.42%
$h \to c\bar{c}$	2.2%	1.7%	2.9%
$h \to gg$	1.6%	1.98%	2.5%
$h \to WW^*$	1.5%	1.27%	1.1%
$h \to \tau^+\tau^-$	1.2%	0.99%	2.3%
$h \to ZZ^*$	4.3%	4.4%	6.7%
$h \to \gamma\gamma$	9.0%	4.2%	12.0%
$h \to \mu^+\mu^-$	17%	18.4%	25.5%
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	3.7%

The model setup of 2HDM-II

- The 2HDM Lagrangian for the Higgs sector can be written as

$$
\begin{aligned}
\mathcal{L} &= \sum_i |D_\mu \Phi_i|^2 - V(\Phi_1, \Phi_2) + \mathcal{L}_{\rm Yuk} \,, \\
V(\Phi_1, \Phi_2) &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) \\
&\quad + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
&\quad + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2} \lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + h.c. \right] .
\end{aligned}
$$

- We shall focus on the type-II setup:

$$
-\mathcal{L}_{\rm Yuk} = Y_d \overline{Q}_L \Phi_1 d_R + Y_e \overline{L}_L \Phi_1 e_R + Y_u \overline{Q}_L \tilde{\Phi}_2 u_R + \text{h.c.}
$$

The model setup of 2HDM-II

- Relevant parameters in the *p*hysical basis:

$$\tan\beta\,,\quad \cos(\beta-\alpha)\,,\ \ \beta\in(0\,,\frac{\pi}{2})\,,\ \ \beta-\alpha\in(0\,,\pi)$$

$$m_{\Phi=H\,,A\,,H^\pm}\,,\quad \lambda v^2\equiv m_H^2-\frac{m_{12}^2}{\sin\beta\cos\beta}\,.$$

- Two limits in the 2HDM:
  1. The alignment limit of: $\cos(\beta-\alpha)=0$.
  2. The degenerate limit of: $m_H=m_A=m_\pm=m_\Phi$. For non-degenerate case, mass splittings are parametrized as $\Delta m_{A\,,C}\equiv m_{A\,,H^\pm}-m_H$.

The Higgs couplings in the 2HDM-II

- The effective couplings for the light CP-even Higgs boson to the SM particles in the κ frame:

$$\mathcal{L} = \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu h + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{\mu-} h$$
$$+\kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} h + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} h + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} h$$
$$-\left(\kappa_u \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_d \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_e \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f}\right) h$$

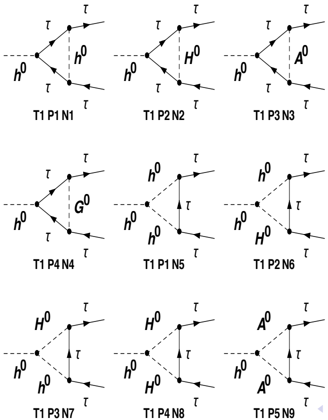
with the tree-level values of

$$\kappa_W = \kappa_Z = \sin(\beta - \alpha)\,, \quad \kappa_u = \frac{\cos\alpha}{\sin\beta}\,, \quad \kappa_{d\,,e} = -\frac{\cos\alpha}{\cos\beta}\,.$$

The one-loop corrected Higgs couplings in the 2HDM-II

- The SM-like Higgs boson couplings receive the one-loop corrections from the 2HDM sector:

$h^0 \rightarrow \tau\ \tau$



The one-loop corrected Higgs couplings in the 2HDM-II

- The effective Higgs couplings in the κ frame with loop effects included:

$$\kappa_{\text{loop}} \equiv \frac{g_{\text{tree}}^{\text{2HDM}} + g_{\text{loop}}^{\text{2HDM}}}{g_{\text{tree}}^{\text{SM}} + g_{\text{loop}}^{\text{SM}}}$$
$$\simeq \kappa_{\text{tree}} + \frac{g_{\text{loop}}^{\text{2HDM}}(\Phi)}{g_{\text{tree}}^{\text{SM}}} + \left[\frac{g_{\text{loop}}^{\text{2HDM}}(\text{SM})}{g_{\text{tree}}^{\text{SM}}} - \kappa_{\text{tree}}\frac{g_{\text{loop}}^{\text{SM}}}{g_{\text{tree}}^{\text{SM}}}\right]$$

  The alignment limit corresponds to $\kappa_{\text{tree}} = 1.0$.

- The general $h\bar{f}f$ and hVV vertices are

$$\hat{\Gamma}_{hff}^{R}(p_1^2, p_2^2, q^2) = \hat{\Gamma}_{hff}^{S} + \ldots ,$$
$$\hat{\Gamma}_{hVV}^{R,\mu\nu}(p_1^2, p_2^2, q^2) = \hat{\Gamma}_{hVV}^{1} g^{\mu\nu} + \ldots .$$

- The κ's with loop effects included:

$$\kappa_V = \frac{\hat{\Gamma}_{hVV}^{1}(m_V^2, m_h^2, q^2)_{\text{2HDM}}}{\hat{\Gamma}_{hVV}^{1}(m_V^2, m_h^2, q^2)_{\text{SM}}}, \quad \kappa_f = \frac{\hat{\Gamma}_{hff}^{S}(m_f^2, m_f^2, q^2)_{\text{2HDM}}}{\hat{\Gamma}_{hff}^{S}(m_f^2, m_f^2, q^2)_{\text{SM}}}.$$

The electroweak precision measurements

	Current (1.7×10^7 Z's)				CEPC (10^{10} Z's)				FCC-ee (7×10^{11} Z's)				ILC (10^9 Z's)			
	σ	correlation			σ	correlation			σ	correlation			σ	correlation		
		S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	2.46	1	0.862	-0.373	0.67	1	0.812	0.001	3.53	1	0.988	-0.879
T	0.09 ± 0.14	–	1	-0.87	2.55	–	1	-0.735	0.53	–	1	-0.097	4.89	–	1	-0.909
U	-0.02 ± 0.11	–	–	1	2.08	–	–	1	2.40	–	–	1	3.76	–	–	1

Table: Fit of the Peskin-Takeuchi S, T, U parameters performed by Gfitter.

Previous studies of electroweak S, T, U parameters made by **H. He, N. Polonsky, S. Su, hep-ph/0102144**:

$$\Delta S = \frac{1}{\pi m_Z^2}\left\{\left[\mathcal{B}_{22}(m_Z^2; m_H^2, m_A^2) - \mathcal{B}_{22}(m_Z^2; m_{H\pm}^2, m_{H\pm}^2)\right] + \left[...\right]\cos^2(\beta-\alpha)\right\},$$

$$\Delta T = \frac{1}{16\pi m_W^2 s_W^2}\left\{\left[F(m_{H\pm}^2, m_A^2) + \right] + \left[F(m_{H\pm}^2, m_h^2) - ...\right]\cos^2(\beta-\alpha)\right\},$$

$$\Delta U = -\Delta S + \frac{1}{\pi m_W^2}\left\{\left[\mathcal{B}_{22}(m_W^2, m_A^2, m_{H\pm}^2) - ...\right] + \left[\mathcal{B}_{22}(m_W^2, m_h^2, m_{H\pm}^2) - ...\right]\cos^2(\beta-\alpha)\right\}.$$

Strategies and results

- The one-loop Higgs coupling measurements: the Higgs Yukawa couplings ($\tan\beta$ and $\cos(\beta-\alpha)$), as well as the self couplings.
- The electroweak precision measurements: mass splitting in the heavy Higgs boson mass spectrum.
- Theoretical constraints of: tree-level vacuum stability, perturbativity, and unitarity are taken into account, as implemented by the `2HDMC`.
- The evaluations are made through the chain of packages: `FeynArts-FormCalc-LoopTools`. For more details: `https://github.com/ycwu1030/THDMNLO_FA`.
- The global fit:

$$\text{Higgs coupling} \quad : \quad \chi^2 = \sum_i \frac{(\mu_i^{\rm BSM} - \mu_i^{\rm obs})^2}{\sigma_{\mu_i}^2} \,,$$

$$\text{electroweak precision} \quad : \quad \chi^2 = \sum_{ij} (X_i - \hat{X}_i)(\sigma^2)_{ij}^{-1} (X_j - \hat{X}_j) \,.$$

with the μ-fit of $\mu_i = (\sigma \times {\rm Br})_{\rm 2HDM} / (\sigma \times {\rm Br})_{\rm SM}$ for various Higgs decay channels.

Higgs signal fit: degenerate heavy Higgs bosons

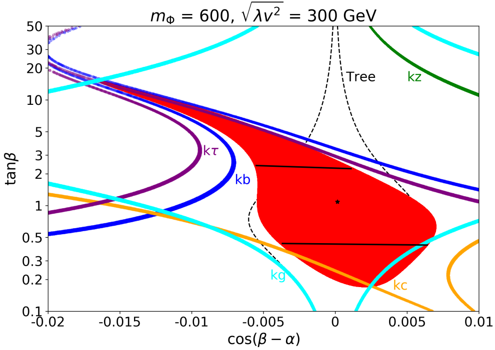


Figure: 95% C.L. allowed region in the $\cos(\beta-\alpha)$-$\tan\beta$ plane with CEPC Higgs precision measurements. Two solid horizontal black lines: theoretical constraints.

Higgs signal fit: degenerate heavy Higgs bosons

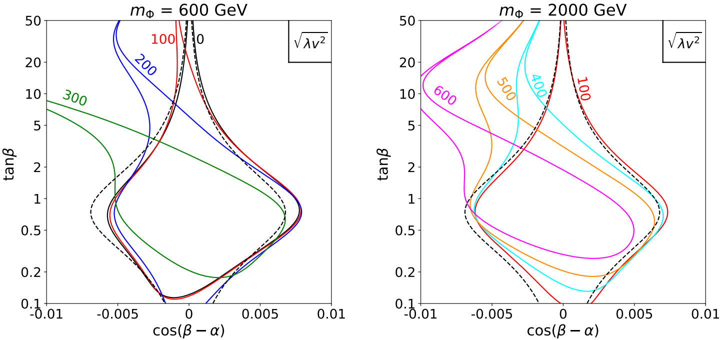


Figure: Three-parameter fitting results at 95% C.L. in the $\cos(\beta - \alpha)$-$\tan\beta$ plane for various values of $\sqrt{\lambda v^2}$ with CEPC precision.

Higgs signal fit: different machines

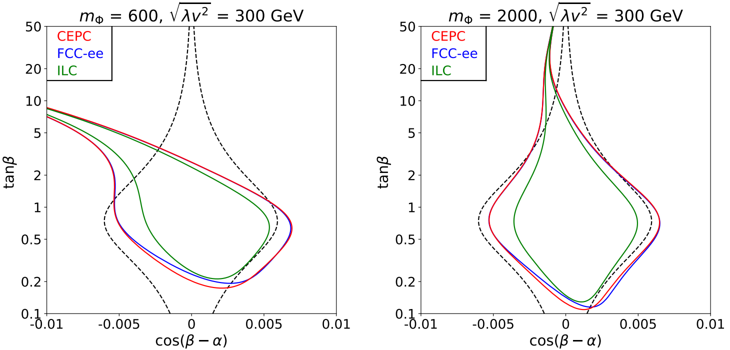


Figure: Two-parameter fitting results at 95% C.L. in the $\cos(\beta-\alpha)$-$\tan\beta$ plane with CEPC (red), Fcc-ee (blue) and ILC (green) precisions. The black dashed lines: the CEPC tree-level results.

Higgs signal fit: non-degenerate heavy Higgs bosons

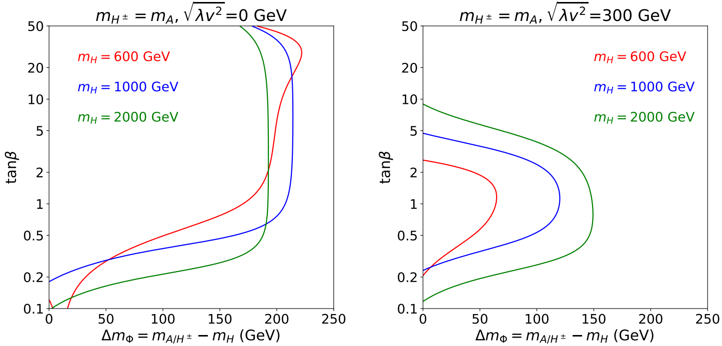


Figure: Three-parameter fitting results at 95% C.L. for $\Delta m_\Phi = m_{A/H^\pm} - m_H$, with varying m_H under the alignment limit $\cos(\beta - \alpha) = 0$ with CEPC Higgs precision.

Higgs signal fit: non-degenerate heavy Higgs bosons

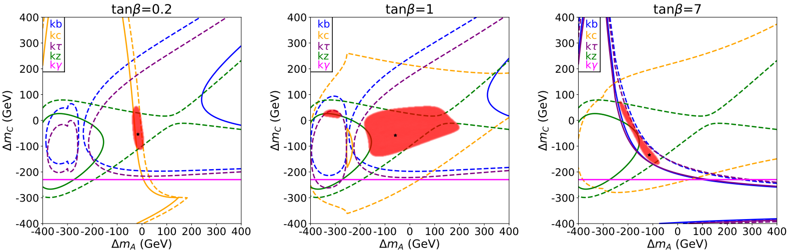


Figure: Constraints on the Δm_A-Δm_C plane from individual Higgs coupling measurement (color curves), and the 95% C.L. global fit results (red shaded region) under the alignment limit, with $m_H = 600$ GeV and $\sqrt{\lambda v^2} = 300$ GeV.

Higgs signal fit: different machines

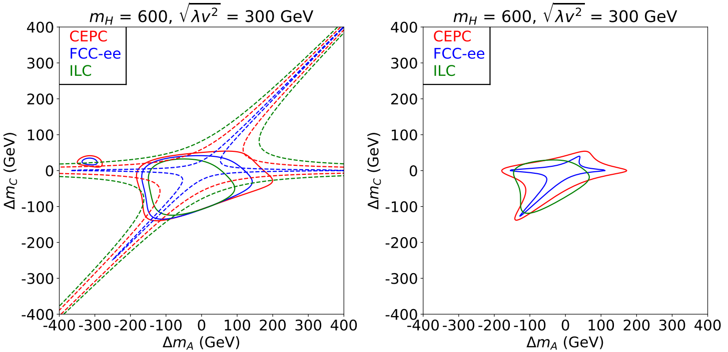
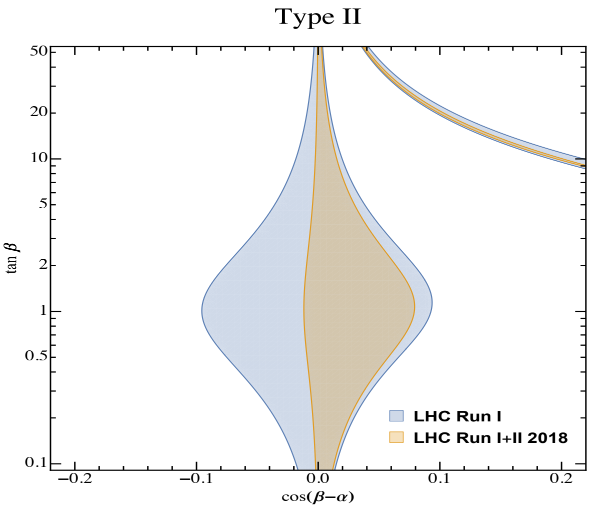


Figure: Two-parameter fitting results at 95% C.L. in the Δm_A-Δm_C plane with CEPC (red), Fcc-ee (blue) and ILC (green) precisions.

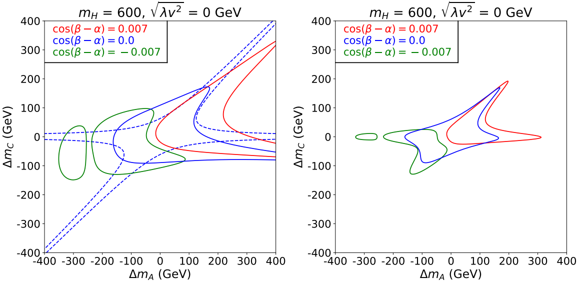
Summary

- The previous studies focus on either tree-level deviations, or loop effects under the alignment/degenerate limits.
- The BSM NP sector can lead to corrections to the Higgs couplings to the SM particles. We show that the Higgs self couplings ($\sim \lambda v^2$ or $\Delta m_{A,C}$) play a role at the one-loop level.
- The generally allowed parameter ranges are: $\tan\beta \sim 0.2 - 5$, $|\cos(\beta - \alpha)| \lesssim 0.008$, $|\Delta m_\Phi| < 200$ GeV for 2HDM-II.
- We focus on the CEPC measurements, while the ILC and Fcc-ee show better reaches in the Higgs precision or Z-pole precision, respectively.
- More BSM NP models are being tested, to appear. More improvements can be made: theoretical constraints and productions at loop level, and the bridges to other BSM issues.

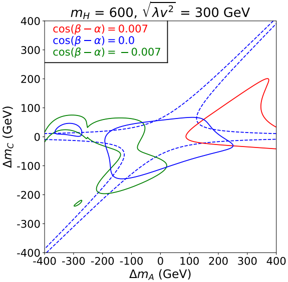
Backups: Higgs signal fit by LHC data (tree-level)



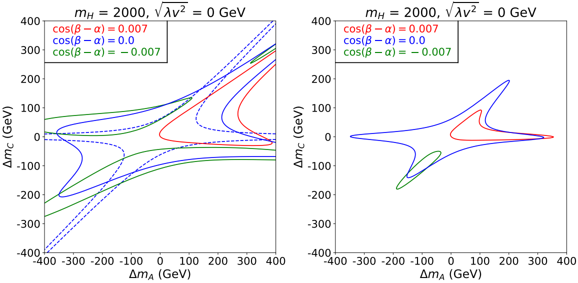
Backups


m_H = 600, $\sqrt{\lambda v^2}$ = 0 GeV
$\cos(\beta-\alpha) = 0.007$
$\cos(\beta-\alpha) = 0.0$
$\cos(\beta-\alpha) = -0.007$
Δm_C (GeV)
Δm_A (GeV)
400
300
200
100
0
-100
-200
-300
-400
m_H = 600, $\sqrt{\lambda v^2}$ = 0 GeV
$\cos(\beta-\alpha) = 0.007$
$\cos(\beta-\alpha) = 0.0$
$\cos(\beta-\alpha) = -0.007$
Δm_C (GeV)
Δm_A (GeV)

Backups


m_H = 600, $\sqrt{\lambda v^2}$ = 300 GeV
cos(β − α) = 0.007
cos(β − α) = 0.0
cos(β − α) = −0.007
Δm_C (GeV)
Δm_A (GeV)
400
300
200
100
0
-100
-200
-300
-400
m_H = 600, $\sqrt{\lambda v^2}$ = 300 GeV
cos(β − α) = 0.007
cos(β − α) = 0.0
cos(β − α) = −0.007
Δm_C (GeV)
Δm_A (GeV)

Backups


m_H = 2000, $\sqrt{\lambda v^2}$ = 0 GeV
cos(β − α) = 0.007
cos(β − α) = 0.0
cos(β − α) = −0.007
Δm_C (GeV)
Δm_A (GeV)
400
300
200
100
0
-100
-200
-300
-400
m_H = 2000, $\sqrt{\lambda v^2}$ = 0 GeV
cos(β − α) = 0.007
cos(β − α) = 0.0
cos(β − α) = −0.007
Δm_C (GeV)
Δm_A (GeV)