Precision Study of Type-II 2HDM at the lepton colliders

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Introduction

- The observed Higgs boson properties are close to the SM predictions, but this does not exclude the existence of additional scalars. The Type-II 2HDM provides a typical framework for studying an extended Higgs sector.

- Future Higgs factories and high-statistics Z-pole measurements can indirectly probe additional Higgs bosons through deviations in Higgs and electroweak observables. These indirect probes complement direct searches..

- In the Type-II 2HDM, we consider both tree-level deviations in Higgs couplings and one-loop corrections from heavy Higgs bosons. We perform a global fit to investigate deviations from the alignment limit and mass splittings among the heavy Higgs bosons.

The 2HDM

The 2HDM[G. C. Branco et al. 11'] is an extension of SM, with the following scalars:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \rho_i + i\eta_i)/\sqrt{2} \end{pmatrix}, \quad i = 1, 2, \tag{1}$$

Where Φ_1, Φ_2 are the $SU(2)_L$ doublets.

- The mass spectrum of the 2HDM includes two neutral CP-even Higgs (h and H), one neutral CP-odd Higgs (A), and one pair of charged Higgs $H^{\pm}$.
- Each obtains a vacuum expectation value after EWSB with $v_1^2 + v_2^2 = v^2 = (246\ \mathrm{GeV})^2$, and $v_2/v_1 = \tan\beta$.

The 2HDM in the mass eigenstate

The CP-even fields mix and generate two scalar Higgs

$$R\begin{pmatrix}\rho_1\\ \rho_2\end{pmatrix} = \begin{pmatrix}H\\ h\end{pmatrix}, \qquad RM^2R^T = \text{diag}\{m_H^2, m_h^2\}. \tag{2}$$

We fix the order of eigenvalues and the R matrix is given by the following configuration

$$R = \begin{pmatrix}c_\alpha & s_\alpha\\ -s_\alpha & c_\alpha\end{pmatrix} \tag{3}$$

The CP-odd fields mix and generate one goldstone boson and one pseudoscalar Higgs

$$R^A\begin{pmatrix}\eta_1\\ \eta_2\end{pmatrix} = \begin{pmatrix}G^0\\ A\end{pmatrix}, \qquad R^A = \begin{pmatrix}c_\beta & s_\beta\\ -s_\beta & c_\beta\end{pmatrix} \tag{4}$$

The Type-II 2HDM

The Type-II 2HDM Yukawa interactions are expressed as:

$$-\mathcal{L}_{\rm Yuk} = Y_d \overline{Q}_L \Phi_1 d_R + Y_e \overline{L}_L \Phi_1 e_R + Y_u \overline{Q}_L i\sigma_2 \Phi_2^* u_R + \text{h.c.}\,. \tag{5}$$

After EWSB, the effective Lagrangian for the light CP-even Higgs couplings to the SM particles can be parameterized as

$$\mathcal{L} = \kappa_Z \frac{m_Z^2}{v} h Z_\mu Z^\mu + \kappa_W \frac{2m_W^2}{v} h W_\mu^+ W^{\mu-} - \sum_{f=u,d,\ell} \kappa_f h \bar{f} f\,. \tag{6}$$

where

$$\kappa_i = \frac{g_{hii}^{\rm BSM}}{g_{hii}^{\rm SM}}\,, \tag{7}$$

for i indicates individual Higgs coupling. Their values at the tree level are

$$\kappa_Z = \kappa_W = \sin(\beta-\alpha)\,, \quad \kappa_u = \frac{\cos\alpha}{\sin\beta}\,, \quad \kappa_{d,e} = -\frac{\sin\alpha}{\cos\beta}\,. \tag{8}$$

Theoretical constraints

The general form of the Higgs potential

$$V_{\rm 2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left(\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right) . \tag{9}$$

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2} . \tag{10}$$

- Perturbativity

$$|\lambda_i| \leq 4\pi . \tag{11}$$

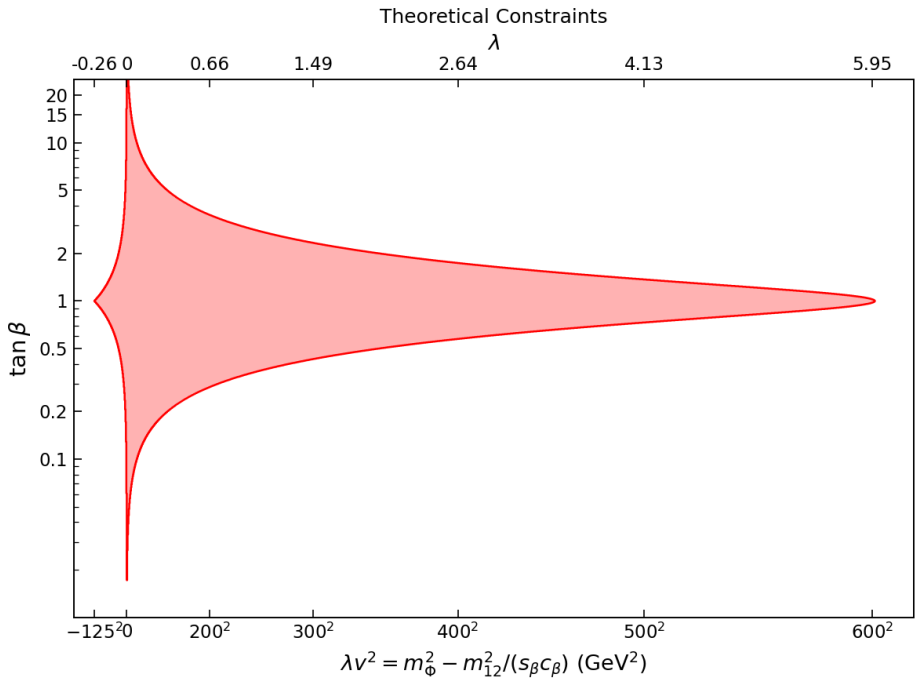
- Unitarity

$$|a^0_{i,\pm}| \leq \frac{1}{2} . \tag{12}$$

Theoretical constraints

In 2HDM with degenerate masses of $m_\Phi \equiv m_H = m_A = m_{H^\pm}$, we can introduce a new parameter λ defined as

$$\lambda v^2 \equiv m_\Phi^2 - \frac{m_{12}^2}{\sin\beta\cos\beta}\,, \tag{13}$$



- The shaded region indicates the surviving region of 2HDM parameter space of $\tan\beta$ vs. λv^2, after vacuum stability, unitarity and perturbativity are taken into account.
- Note that for $\lambda = 0$, $\tan\beta$ is unconstrained.
- The largest region on λv^2 occurs at $\tan\beta = 1$: $-m_h^2 \leq \lambda v^2 \leq (600\,GeV)^2$

Higgs precision measurements

collider	CEPC
$\sqrt{s}$	240 GeV
$\int \mathcal{L} dt$	20 ab^{-1}
production	Zh
$\Delta\sigma/\sigma$	0.26%
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$
$h \to b\bar{b}$	0.14%
$h \to c\bar{c}$	2.02%
$h \to gg$	0.81%
$h \to WW^*$	0.53%
$h \to \tau^+\tau^-$	0.42%
$h \to ZZ^*$	4.17%
$h \to \gamma\gamma$	3.02%
$h \to \mu^+\mu^-$	6.36%
$(\nu\bar{\nu})h \to b\bar{b}$	1.59%

Estimated statistical precisions for Higgs measurements obtained at the proposed CEPC program with 20 ab^{-1} integrated luminosity.

Golbal fit

To perform a χ^2-fit, we adopt the signal strength modifier (SSM) μ:

$$\mu = \frac{(\sigma \times Br)_{BSM}}{(\sigma \times Br)_{SM}} \tag{14}$$

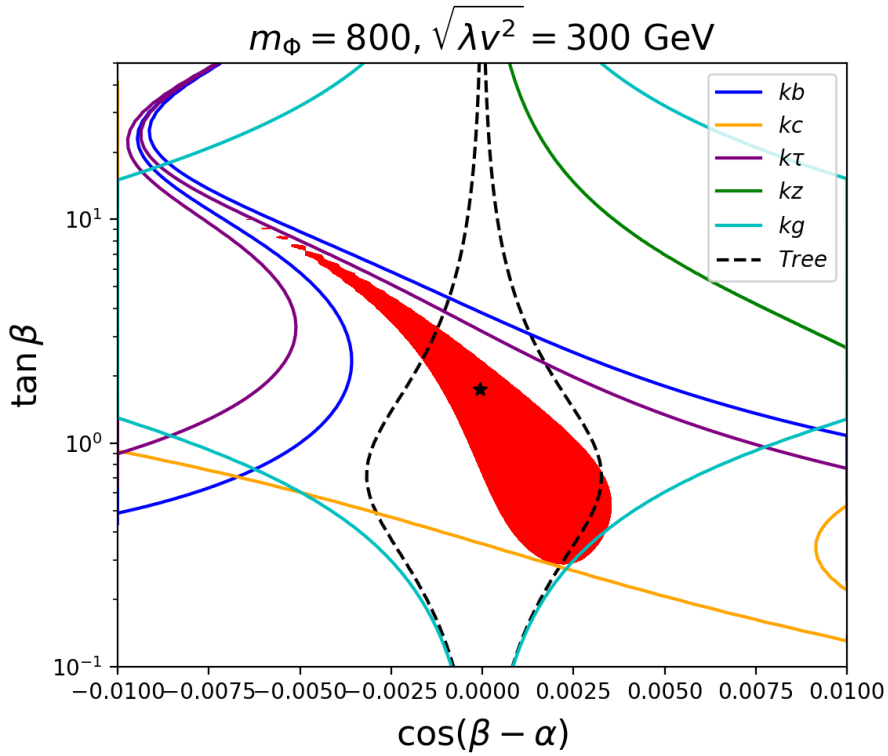
As a test statistic, the expression for χ^2 is as follows:

$$\chi^2 = \sum_i \frac{(\mu_i^0 - \mu_i^1)^2}{\sigma_{\mu_i}^2}, \tag{15}$$

For future colliders, μ_i^1 is taken to be the SM values 1.
For the one-, two- or three-parameter fit, the corresponding $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$ for 95% C.L. is 3.84, 5.99 or 7.82, respectively.

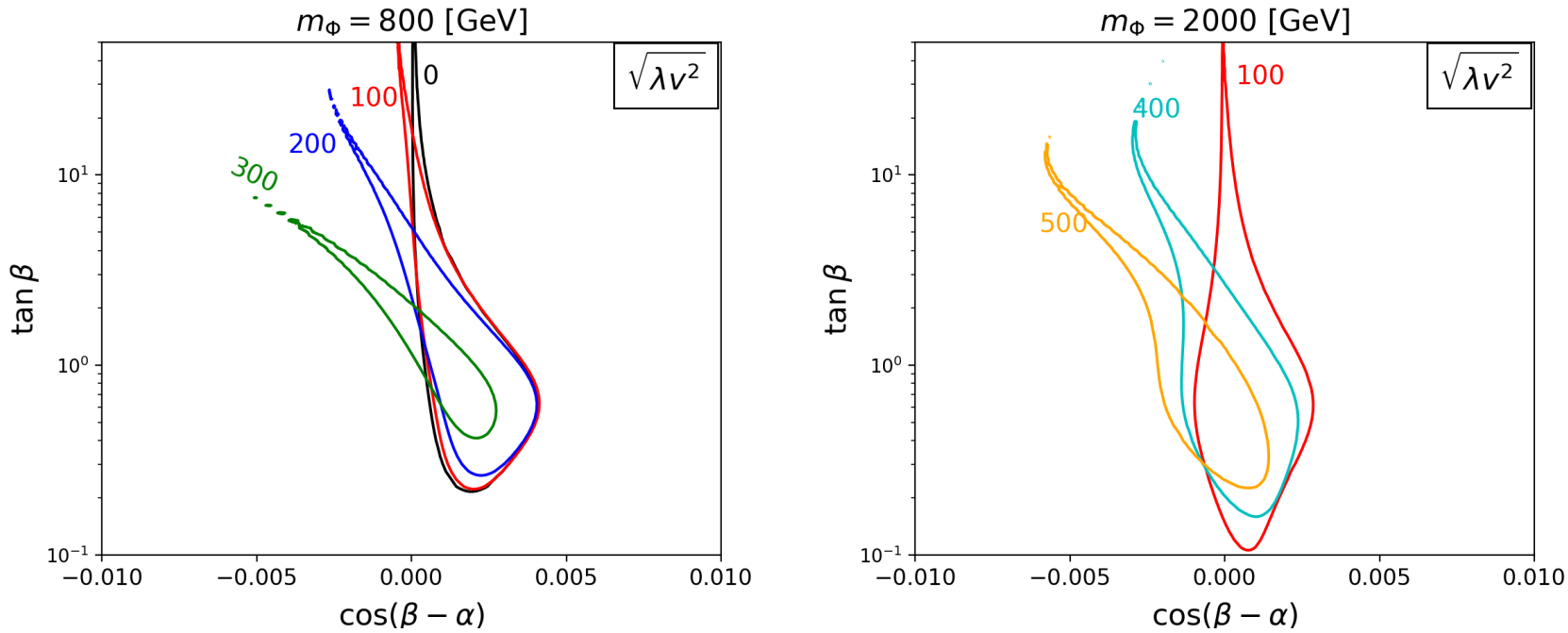
Degenerate heavy Higgs boson masses

Degenerate masses: $m_\Phi \equiv m_H = m_A = m_{H^\pm}$



- The central red region is the global fit result with the best-fit point indicated by the black star.
- 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.
- At large tan β, κ_b and κ_τ provide the strongest constraint since they are enhanced by tan β factor. Combining all the channels, the region for the global fit leads to $0.2 \leq \tan\beta \leq 20$, $-0.01 \leq c_{\beta-\alpha} \leq 0.0038$.

Degenerate heavy Higgs boson masses

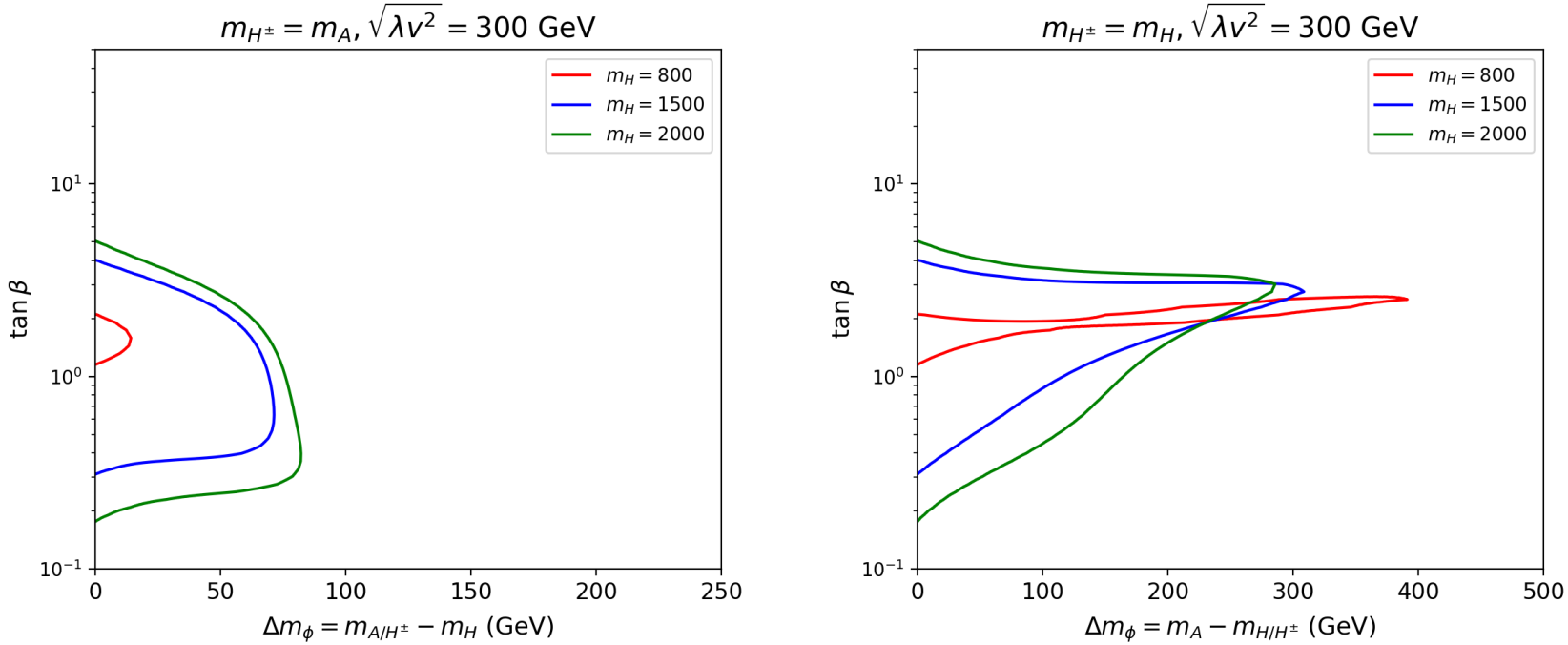


- The figure shows three-parameter fitting results in the $\cos(\beta-\alpha)$-$\tan\beta$ plane for various values of $\sqrt{\lambda v^2}$ with CEPC precision.
- In general, including loop corrections shrinks the allowed parameter space, especially for extreme values of $\tan\beta$, and for small m_Φ and large λv^2.
- For fixed m_Φ, larger $\sqrt{\lambda v^2}$ would lead to larger loop correction and thus larger shift from $\cos(\beta-\alpha)=0$ since λv^2 enters triple Higgs self-couplings.

Non-degenerate heavy Higgs boson masses

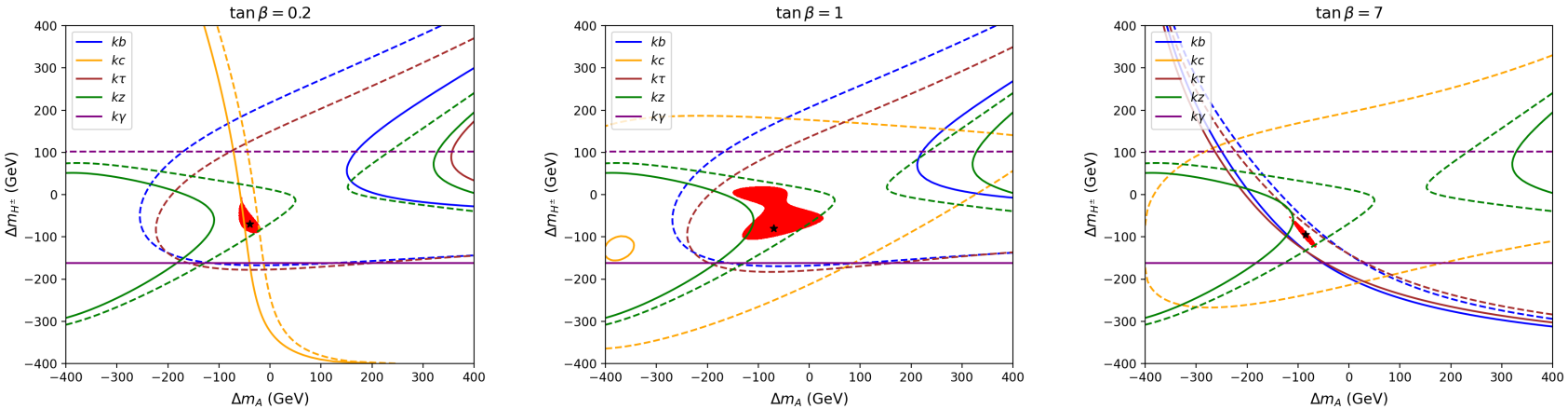
For convenience, we define the following mass splittings:

$$\Delta m_A \equiv m_A - m_H, \quad \Delta m_{H^\pm} \equiv m_{H^\pm} - m_H \tag{16}$$



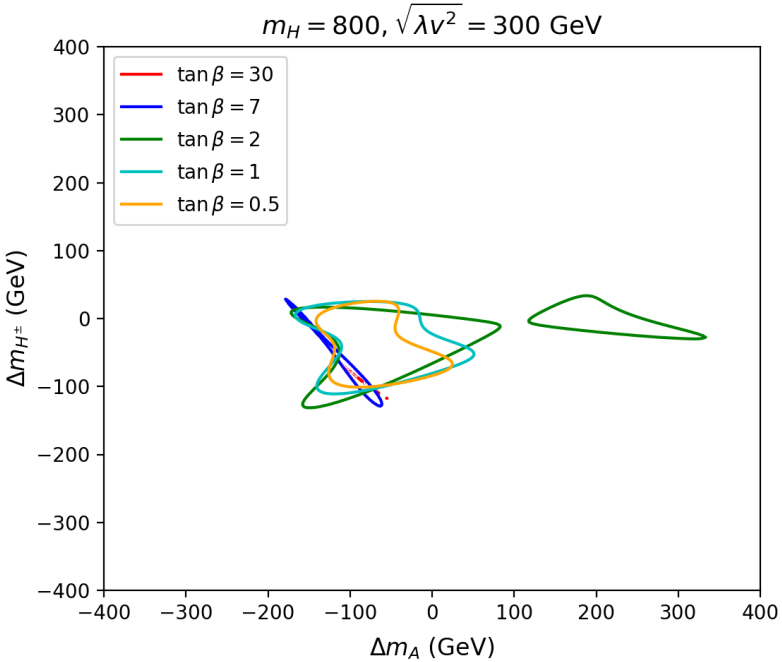
- For the case of $m_A = m_{H^\pm}$ (left panel), Δm_Φ can be as large as 80 GeV for $\sqrt{\lambda v^2} = 300$ GeV.
- For the case of $m_H = m_{H^\pm}$ (right panel), the allowed range of Δm_Φ is larger, up to about 400 GeV for $\sqrt{\lambda v^2} = 300$ GeV.

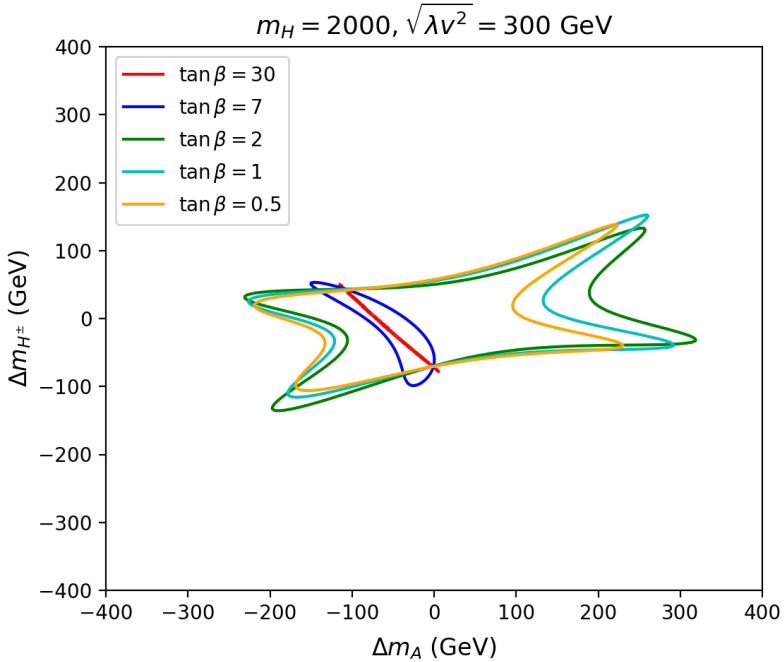
Non-degenerate heavy Higgs boson masses



- Under the alignment limit, κ_Z is independent of $\tan\beta$ as apparent in the figure.
- For small $\tan\beta$, the main constraint on the mass splitting comes from κ_c and leads to a small overlapping red region with κ_Z.
- For large $\tan\beta$, it is due to $\kappa_{b,\tau}$, resulting in $\Delta m_A \sim -120$ GeV to -60 GeV (right panel).
- For $\tan\beta \sim 1$, constraints from both $\kappa_{b,\tau}$ and κ_c are relatively relaxed, leading to a larger allowed region in the mass splittings mostly due to κ_Z.

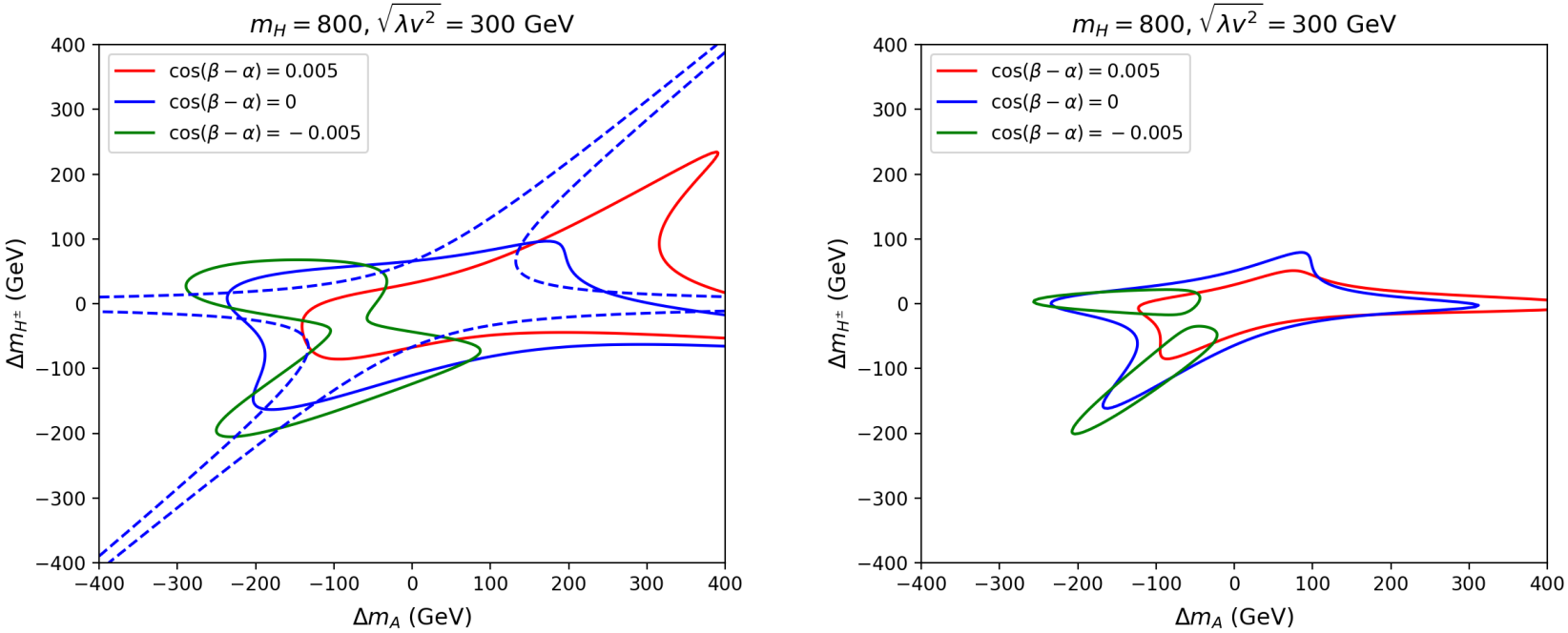
Non-degenerate heavy Higgs boson masses





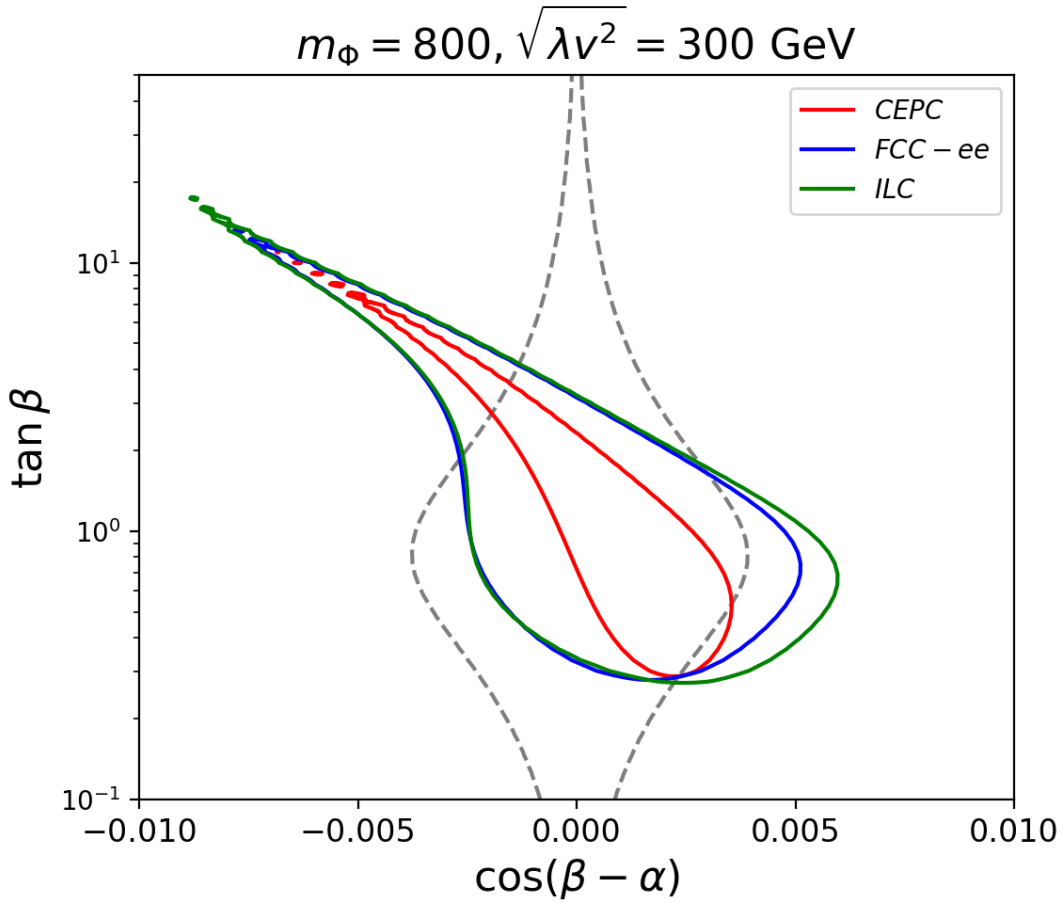
- The largest ranges for $\Delta m_{H^\pm,A}$ could be achieved for $\tan\beta \sim 2$, for both benchmark choices of m_Φ, due to the constraints from individual couplings.
- For $m_H = 2000$ GeV, the allowed ranges of the mass difference varies little with $0.5 < \tan\beta < 2$, but shrink quickly for larger $\tan\beta$.

Non-degenerate heavy Higgs boson masses



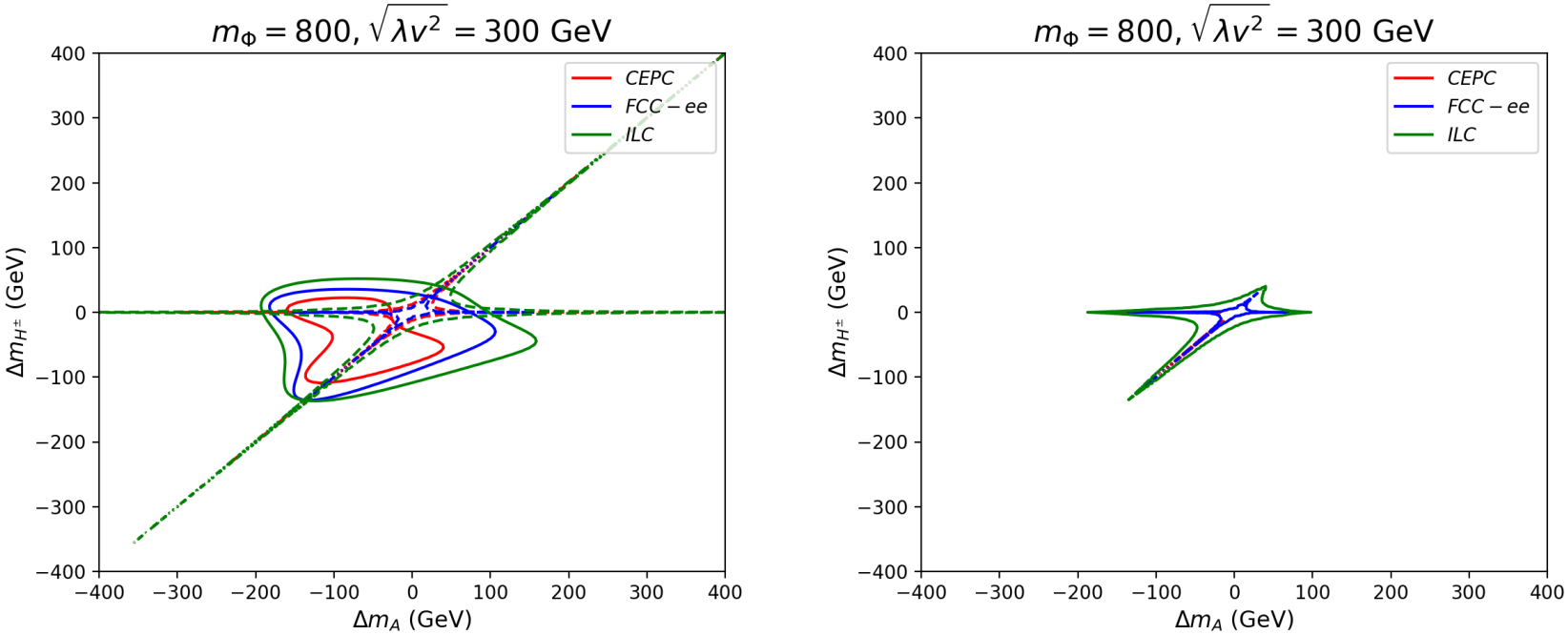
- The figure shows the individual constraints from Higgs (solid curves) and Z-pole precision measurements (dashed curves) in the Δm_A vs. $\Delta m_{H^\pm}$ plane (left panel), as well as their combined constraints (right panel).
- For the Higgs precision fit, the alignment limit $\cos(\beta - \alpha) = 0$ (blue curve) typically gives the largest allowed ranges.
- Z-pole measurements constrain the deviation from $m_{H^\pm} \sim m_{A,H}$.
- The Higgs and Z-pole precision measurements at future lepton colliders provide complementary information.

Comparison between different lepton colliders



- The figure show the constraints in the $\cos(\beta - \alpha)$-tan β plane for CEPC, FCC-ee, and ILC including both tree-level and loop effects, for benchmark points of $m_\Phi = 800$ GeV, and $\sqrt{\lambda v^2} = 300$ GeV.
- Dashed curves show the tree-level only results with FCC-ee precision as a comparison. The reach with Higgs precision is similar for ILC and FCC-ee, while slightly better for CEPC.

Comparison between different lepton colliders



- The figure show the comparison among three machines for Higgs and Z-pole precision constraints individually (left panel) and combined fitting results (right panel) in the Δm_A-$\Delta m_{H^\pm}$ plane.
- CEPC provides a better sensitivity to Higgs precision measurements. In contrast, FCC-ee has a better sensitivity to Z-pole precision measurements. CEPC yields the strictest constraints.

Summary

Conclusions

- We found that in the parameter space of $\cos(\beta-\alpha)$ and $\tan\beta$, the largest 95% C.L. range of $|\cos(\beta-\alpha)| \lesssim 0.0038$ could be achieved for $\tan\beta$ around 1, with smaller and larger values of $\tan\beta$ tightly constrained by $\kappa_{g,c}$ and $\kappa_{b,\tau}$, respectively.
- Smaller heavy Higgs masses and larger λv^2 lead to larger loop corrections.
- The Higgs precision measurements alone constrain $\Delta m_{A,H^\pm}$ to be less than about a few hundred GeV, with tighter constraints achieved for small m_H, large λv^2 and small/large values of $\tan\beta$.
- Z-pole measurements constrain the deviation from $m_{H^\pm} \sim m_{A,H}$.
- Combining both Higgs and Z-pole precision measurements, the mass splittings are constrained even further.
- A comparison of the CEPC, FCC-ee, and ILC shows that the CEPC has slightly better sensitivity in Higgs precision fits.

Thank you!