Type-I 2HDM under Higgs and Electroweak Precision Measurement

Shuailong Li

U. of Arizona

Pheno-2019
7/May/2019

N. Cheng, T. Han, S. Su, W. Su, Y. Wu, S. Li, work in progress
N. Cheng, T. Han, S. Su, W. Su, Y. Wu, 1808.02037

2HDM: $\mathcal{L} = \sum_i |D_\mu \Phi_i|^2 - V(\Phi_1, \Phi_2) + \mathcal{L}_{\text{Yuk}}$

$V(\Phi_1, \Phi_2)$

Eight free parameters: $m_{11}^2, m_{22}^2, m_{12}^2, \lambda_{1-5}$

EWSB

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

Higgs Potential

Reparametrization

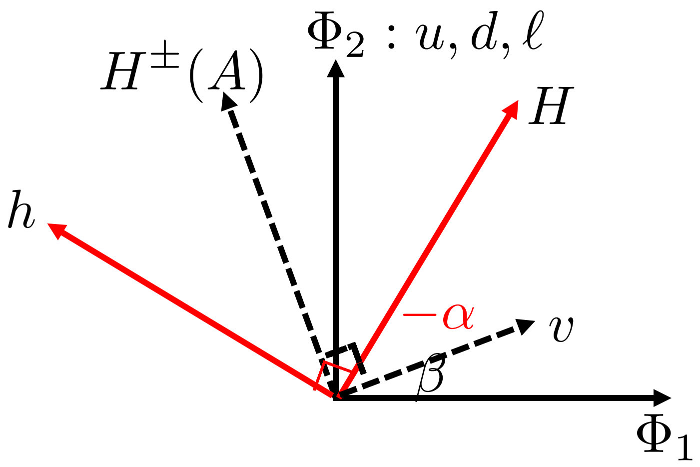
Rotate to Physical Space

$v, \tan\beta, \cos(\beta - \alpha), m_h, m_H, m_A, m_{H^\pm}, m_{12}^2$

- Convention: $\beta \in (0, \frac{\pi}{2}), \sin(\beta - \alpha) \geq 0$
- Alignment limit: $\cos(\beta - \alpha) = 0$
- Tree-level coupling depends on $\tan\beta, \cos(\beta - \alpha)$ solely

2HDM: Yukawa Couplings

Type-I



Normalized Higgs Couplings:

$$\kappa_\Phi^f = \propto \frac{\cos\langle \Phi, \Phi_f \rangle}{v_i} \quad i = 1, 2; \quad f = u, d, \ell \quad \Phi = h, H, A$$

κ_h^u	κ_h^d	κ_h^e	κ_H^u	κ_H^d	κ_H^e	κ_A^u	κ_A^d	κ_A^e
$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$

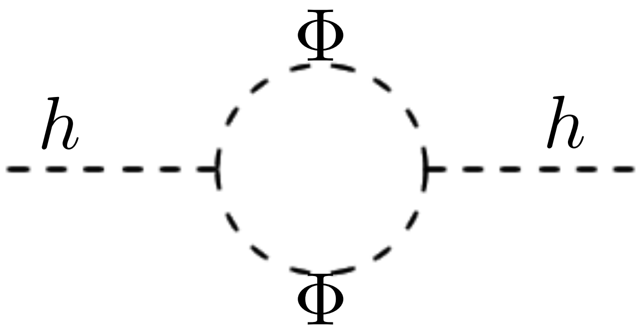
$$\kappa_h^f = \sin(\beta - \alpha) + \cos(\beta - \alpha)\cot\beta$$

$$\kappa_h^V = \sin(\beta - \alpha)$$

- At tree level, while type-II shows enhancement at both small and large $\tan\beta$, type-I only enhances at small $\tan\beta$.

Tri-higgs couplings play significant role in 2HDM

Proportional to
$\lambda v^2 \equiv M^2 - m_\Phi^2$
in alignment limit



Enhance at large
$\tan\beta / \cot\beta$.
Proportional to M ^{2}
in non-alignment case

$$\lambda_{H^+H^-h} = -\frac{1}{v}\left[(2M^2 - 2m_{H^\pm}^2 - m_h^2)s_{\beta-\alpha} + 2(M^2 - m_h^2)\cot 2\beta\, c_{\beta-\alpha}\right]$$

$$M^2 \equiv \frac{m_{12}^2}{\cos\beta \sin\beta}$$

1) Strong enhancement at tree-level when $\tan\beta$ is small
2) large $\tan\beta$ enhancement due to tri-higgs coupling at 1-loop level

are two main factors that define the behavior of type-I 2HDM.

Fitting strategy

σ_i's are the projected precision of CEPC

- **Higss Precision Measurement**

$$\chi^2_{\text{higgs}} = \sum_i \frac{(\mu_i^{\text{BSM}} - \mu_i^{\text{obs}})^2}{\sigma^2_{\mu_i}}$$

$$\mu^{\text{BSM}} = \frac{(\sigma \times \text{Br})_{\text{BSM}}}{(\sigma \times \text{Br})_{\text{SM}}}$$

- **EW Precision Measurement**

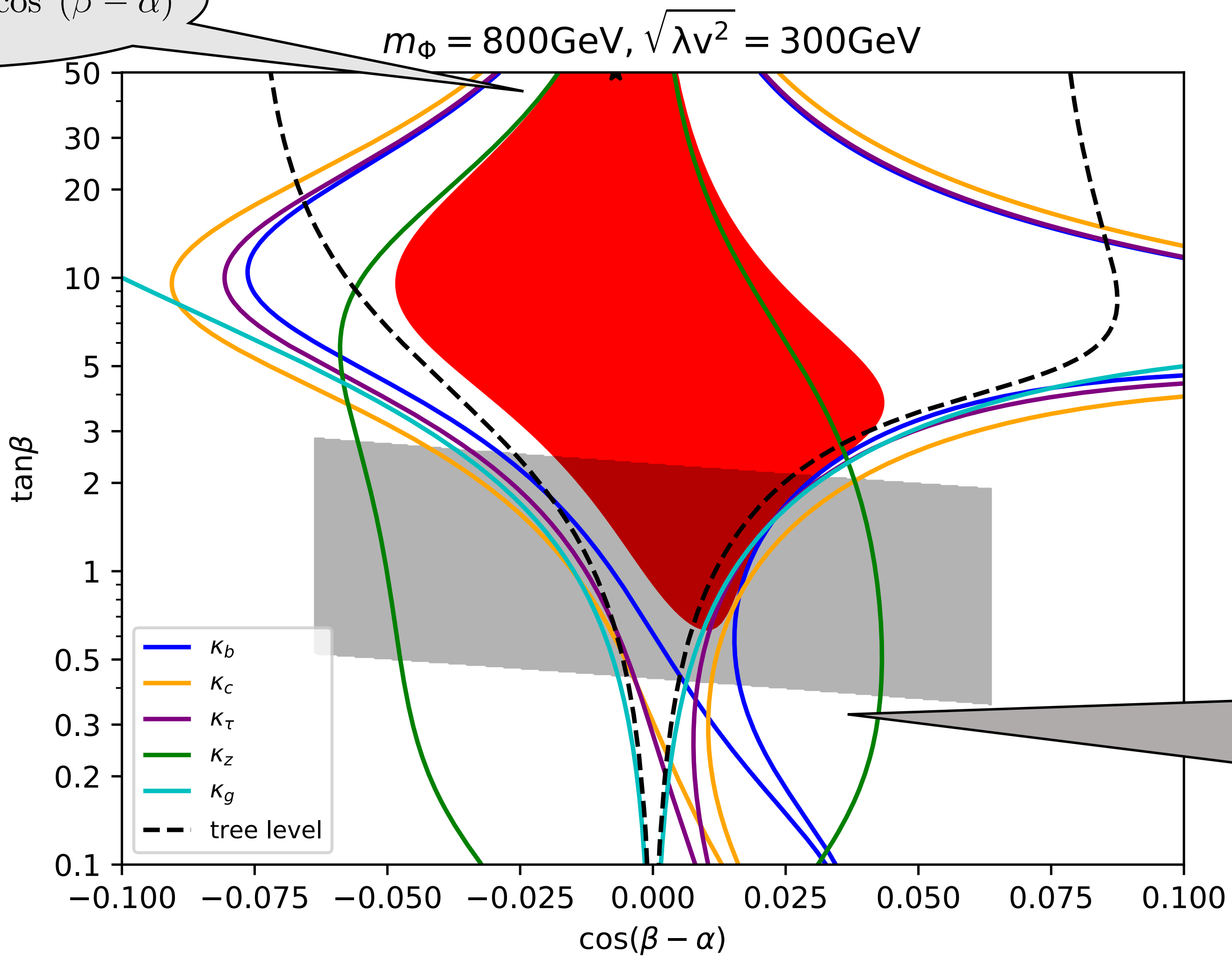
$$\chi^2_{\text{EW}} = \sum_{ij} (X_i - \hat{X}_i)(\sigma^2)^{-1}_{ij}(X_j - \hat{X}_j) \qquad X_i = \{S, T, U\}, \;\; \sigma^2_{ij} = \sigma_i \rho_{ij} \sigma_j$$

- **Total**

$$\chi^2 = \chi^2_{\text{higgs}} + \chi^2_{\text{EW}}$$

Type-I: mass degenerate $m_\Phi = m_H = m_A = m_{H^\pm}$

$$\Delta\kappa_Z \sim -\frac{m_\Phi^2 \tan^2\beta}{96\pi^2 v^2}\cos^2(\beta-\alpha)$$



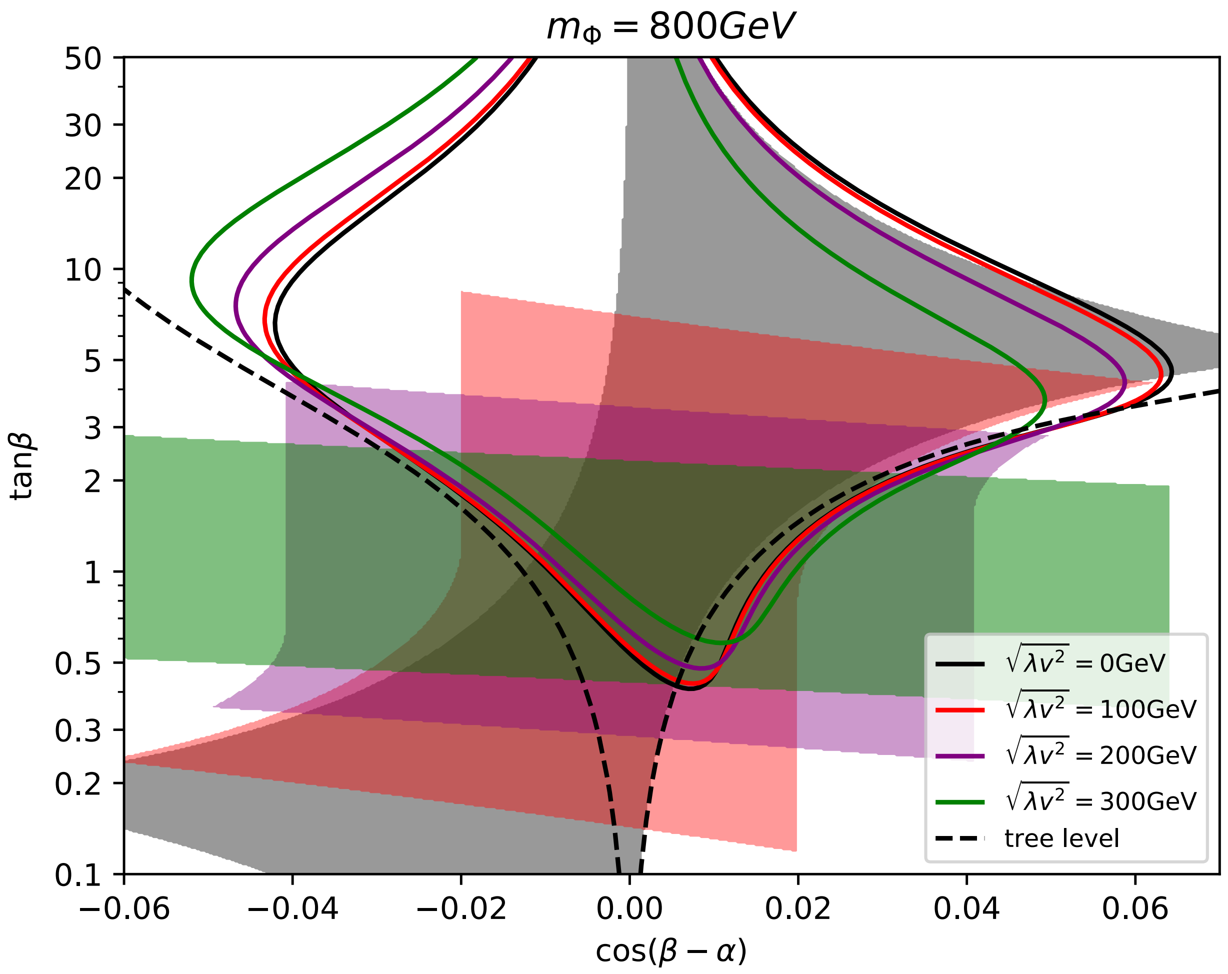
Theoretical Constraint

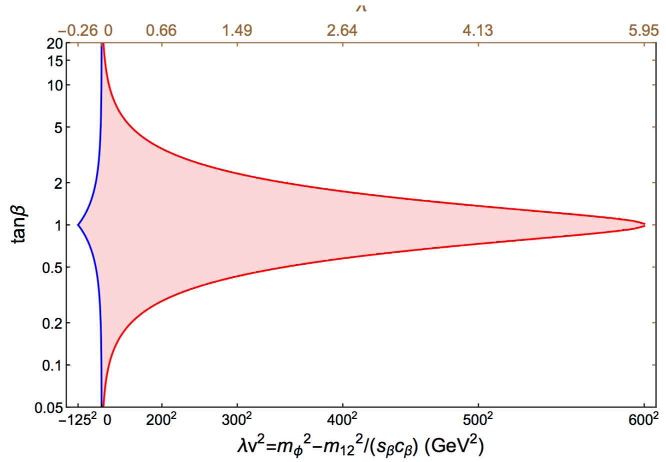
Unitarity + perturbtivity + stability

Tree level + 1-loop

Strong restriction due to κ_h^f enhancement at small $\tan\beta$ at tree level.

Type-I: mass degenerate $m_\Phi = m_H = m_A = m_{H^\pm}$

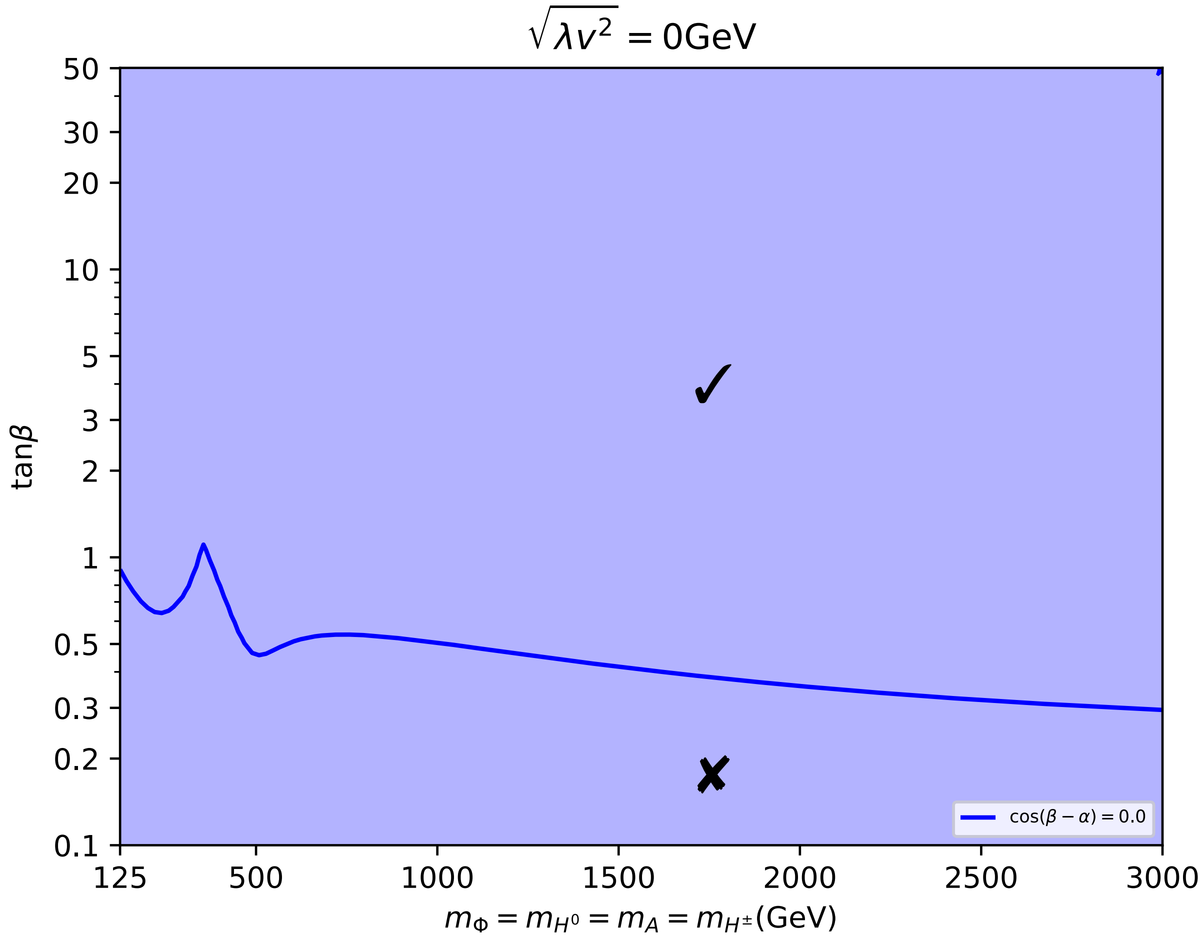




$\sqrt{\lambda v^2}$ dependence of theoretical constraint

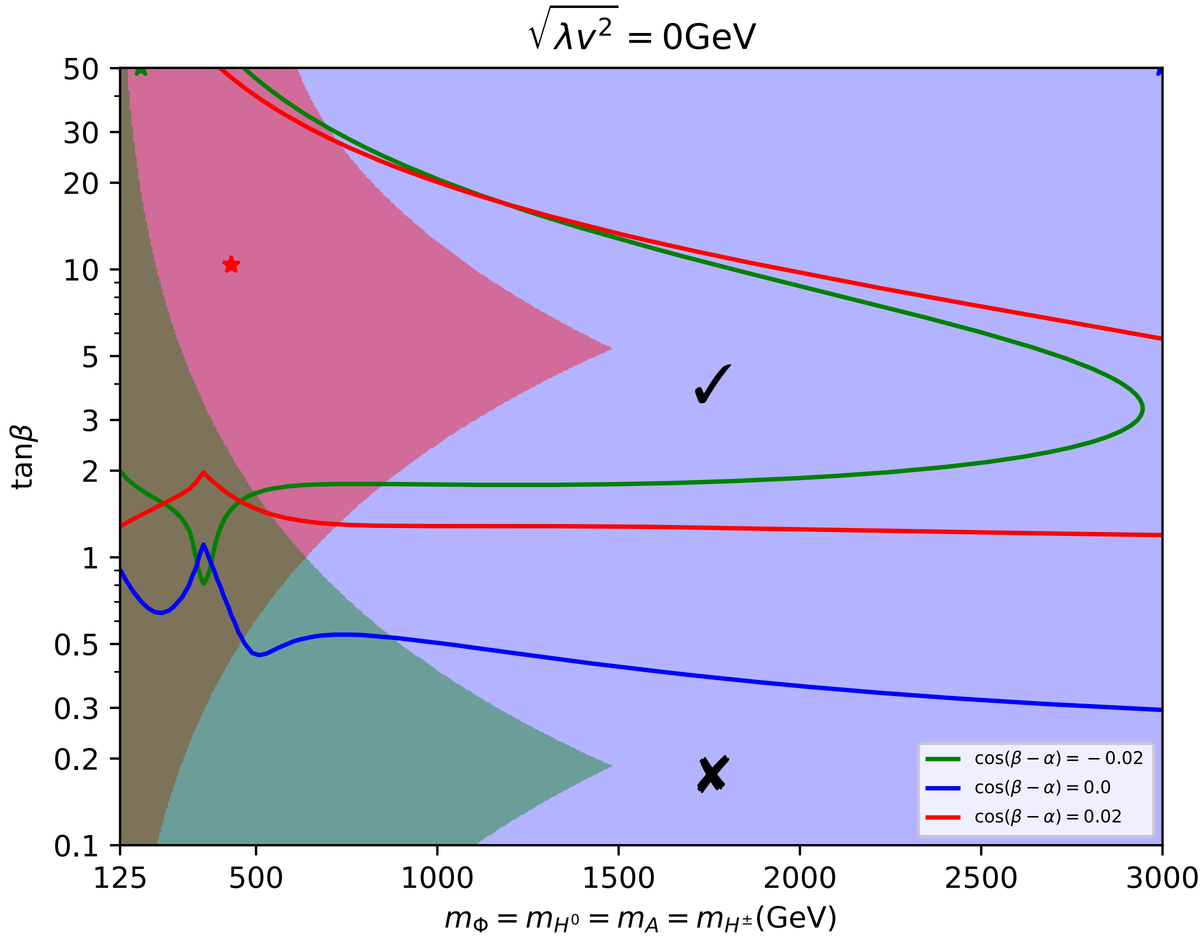
arXiv:1709.06103

Type-I: mass degenerate $m_\Phi = m_H = m_A = m_{H^\pm}$



- No large $\tan\beta$ dependence in alignment limit, so it's only bounded from below.
- Heavy higgs mass is bounded from above in non-alignment case.

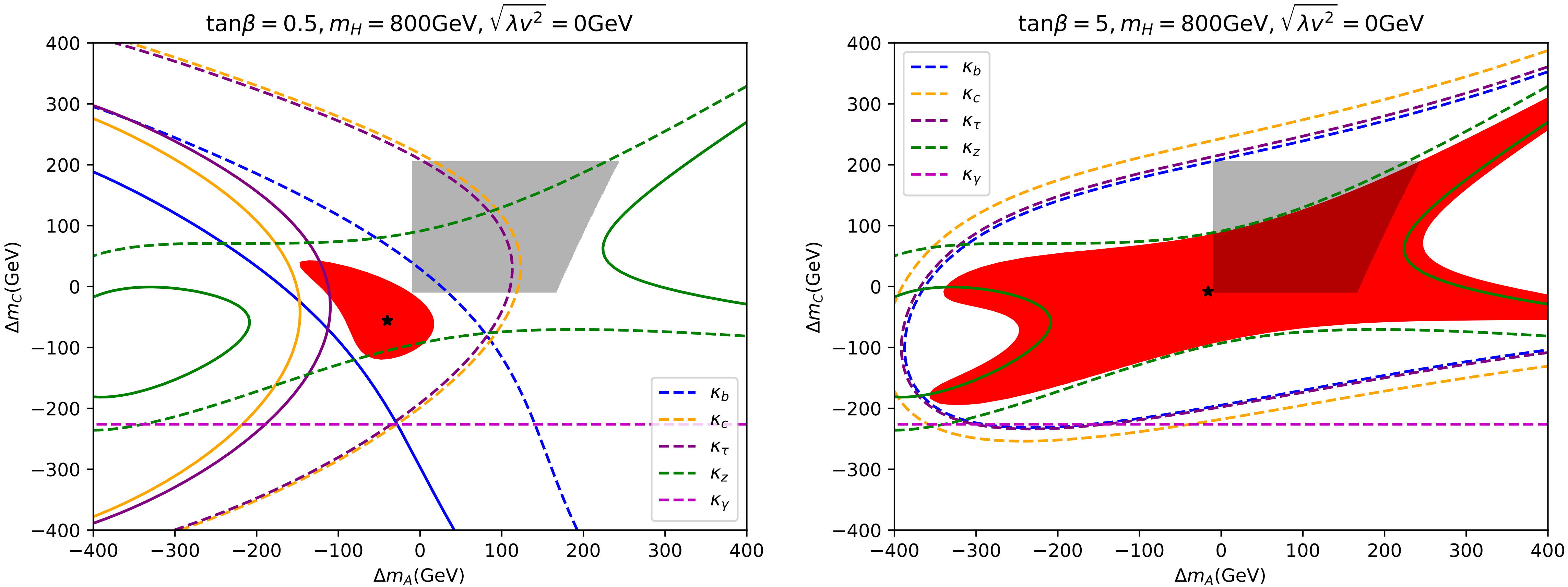
Type-I: mass degenerate $m_\Phi = m_H = m_A = m_{H^\pm}$



- No large $\tan\beta$ dependence in alignment limit, so it's only bounded from below.
- Heavy higgs mass is bounded from above in non-alignment case.

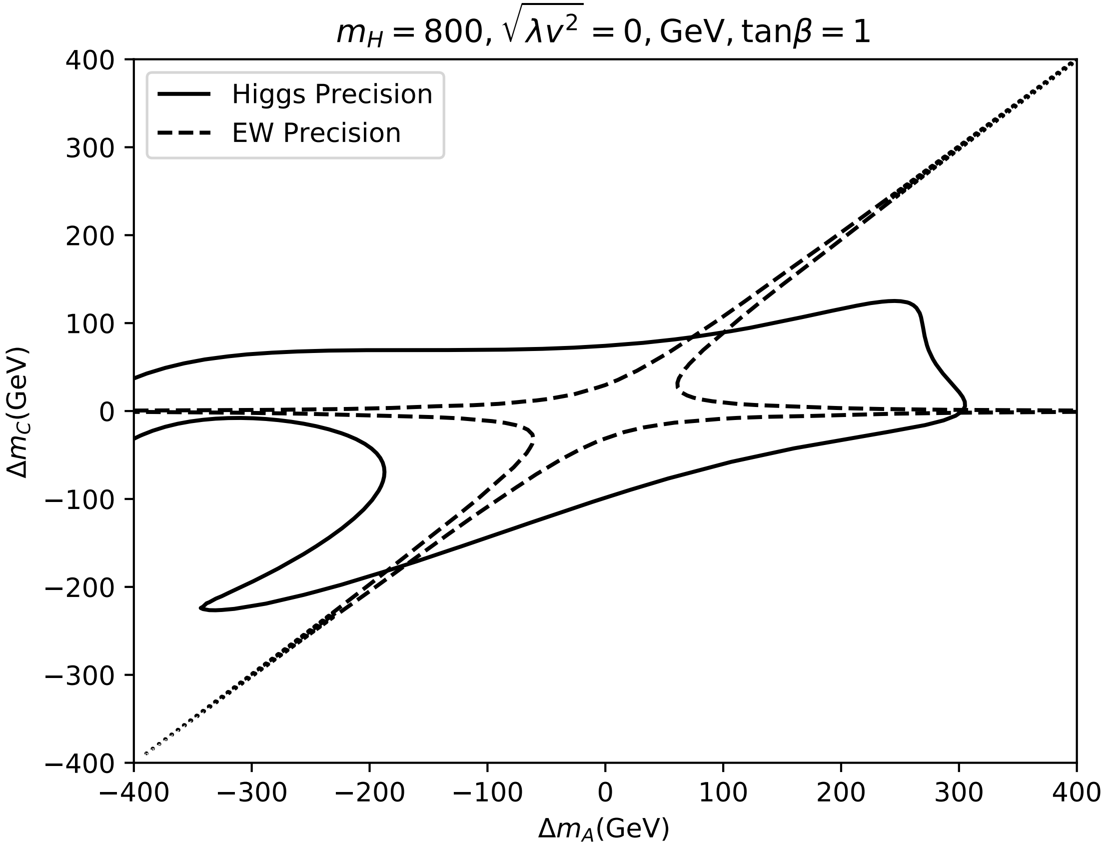
Type-I: alignment limit $\cos(\beta - \alpha) = 0$

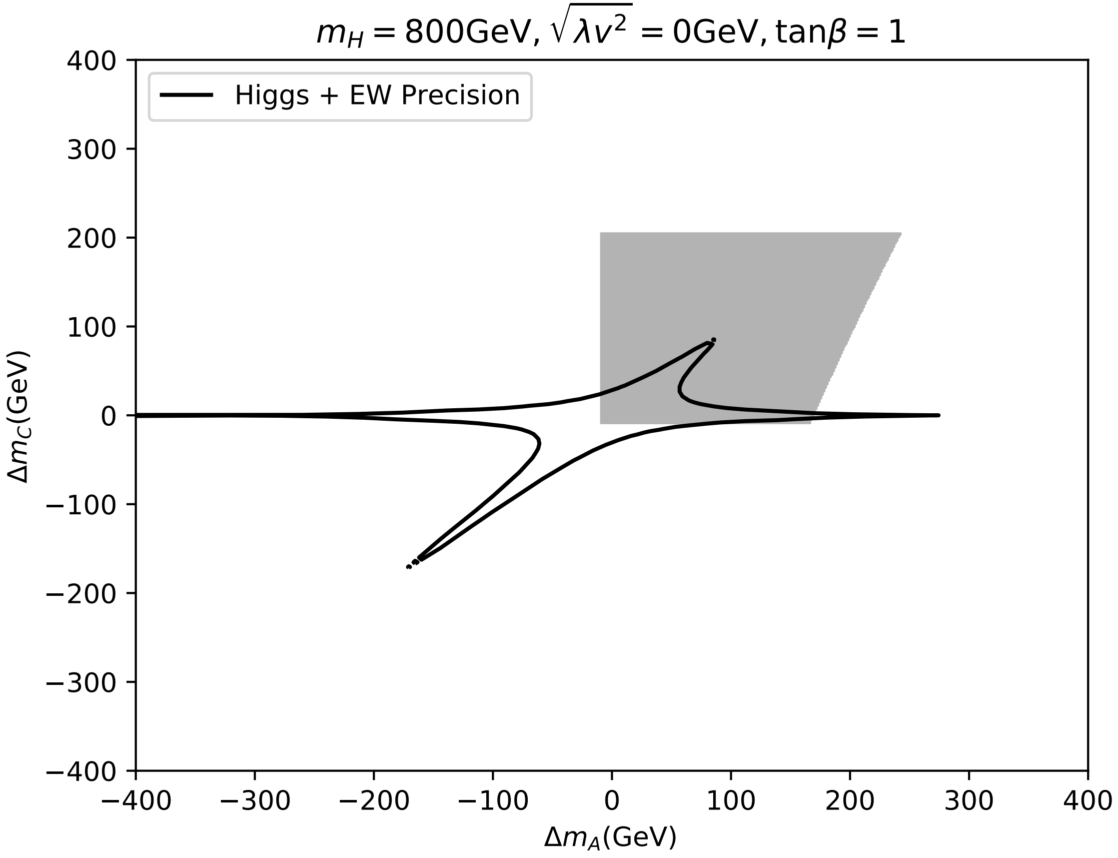
$\Delta m_A = m_A - m_H$
$\Delta m_C = m_C - m_H$



- Theoretical constraint forces $\lambda v^2 \approx 0$.
- A correlation between Δm_A and Δm_C manifests for $\tan\beta \gtrsim 1$.

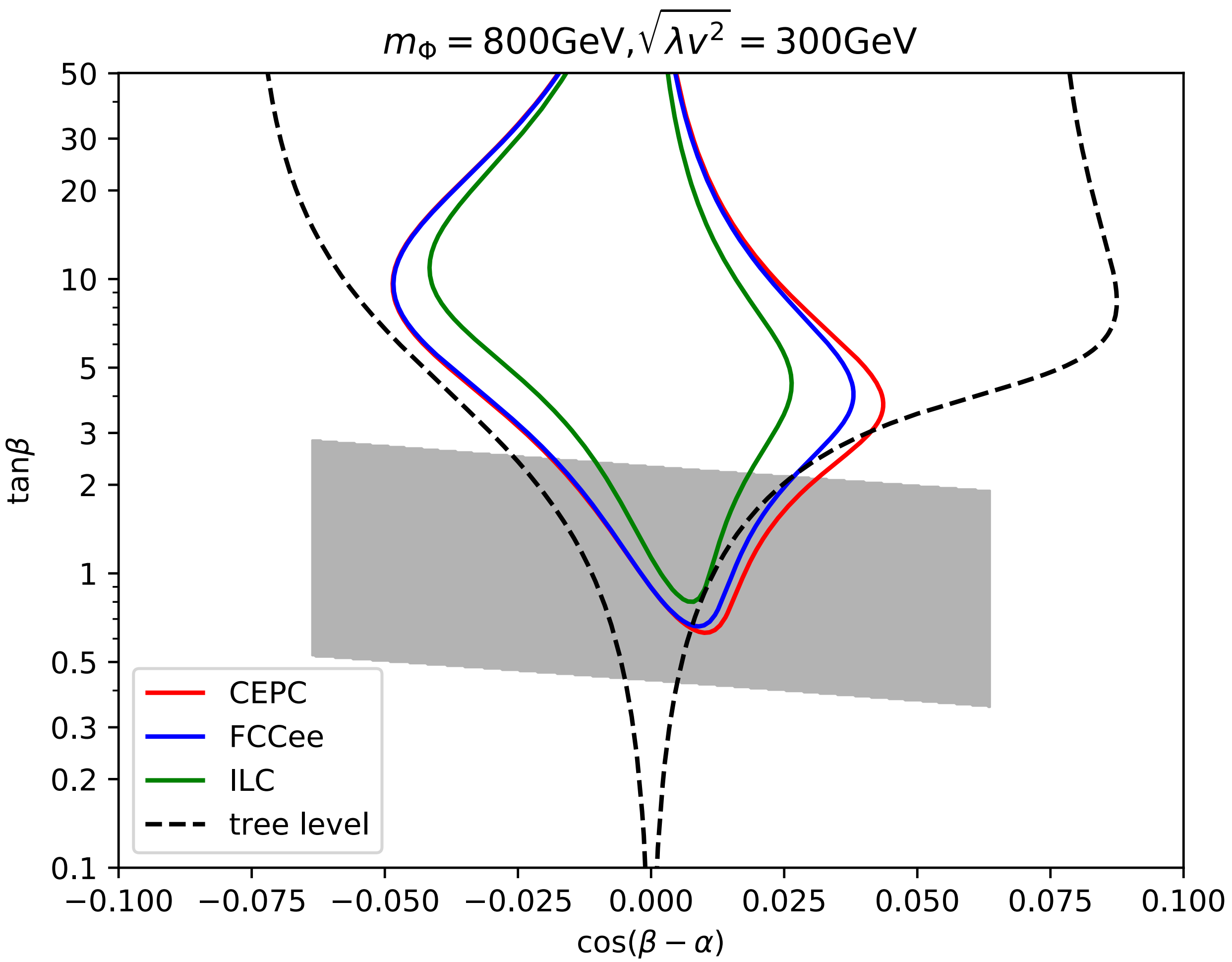
Type-I: alignment limit $\cos(\beta - \alpha) = 0$



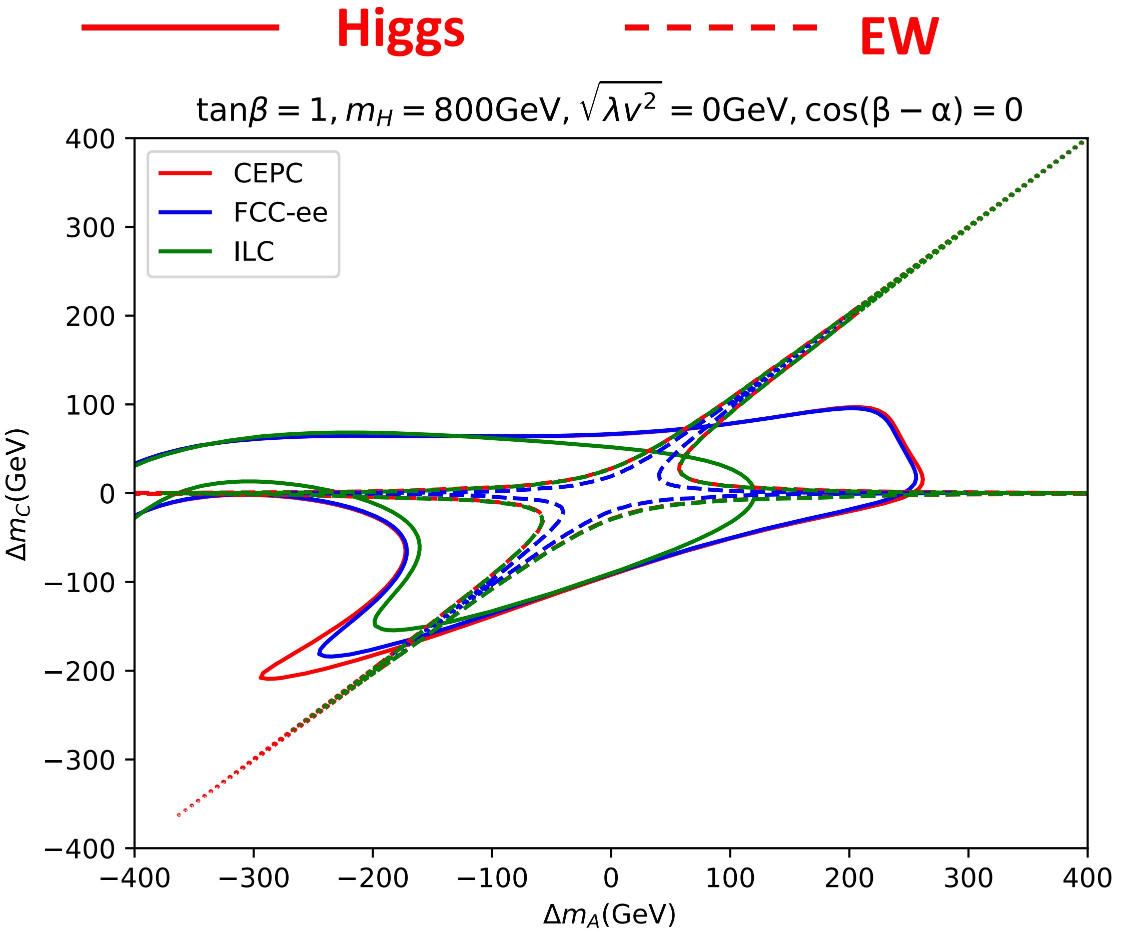


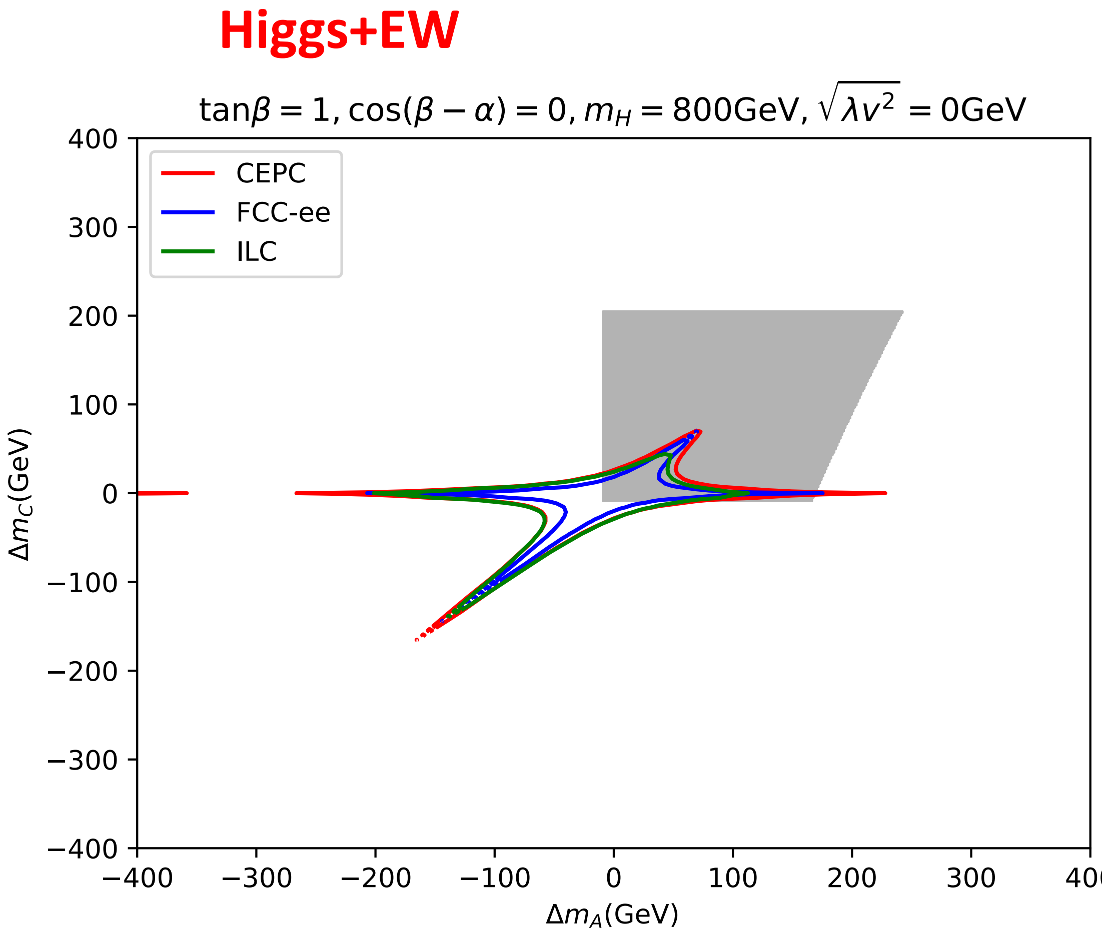
- EW precision requires $m_{H^\pm} \approx m_H$ or $m_{H^\pm} \approx m_A$.
- Higgs precision measurement sets a bound on heavy higgs mass splitting, which is complementary to EW precision.

Comparison Among Different Colliders



Comparison Among Different Colliders





Summary

- At tree level, Type-I higgs coupling to fermions manifests strong enhancement at small $\tan\beta$.
- Tri-higgs coupling imposes a strong cosntraint at large $\tan\beta$.
- Due to tri-higgs coupling, heavy higgs mass is bounded from above *in non-alignment case*.
- Complementary to EW precision measurement, higgs precision measurement sets a bound on heavy higgs mass splitting.