Workshop on particle physics and cosmology 2021

# Probing EWPT in 2HDM with Future Lepton Colliders

**Wei Su**

KIAS

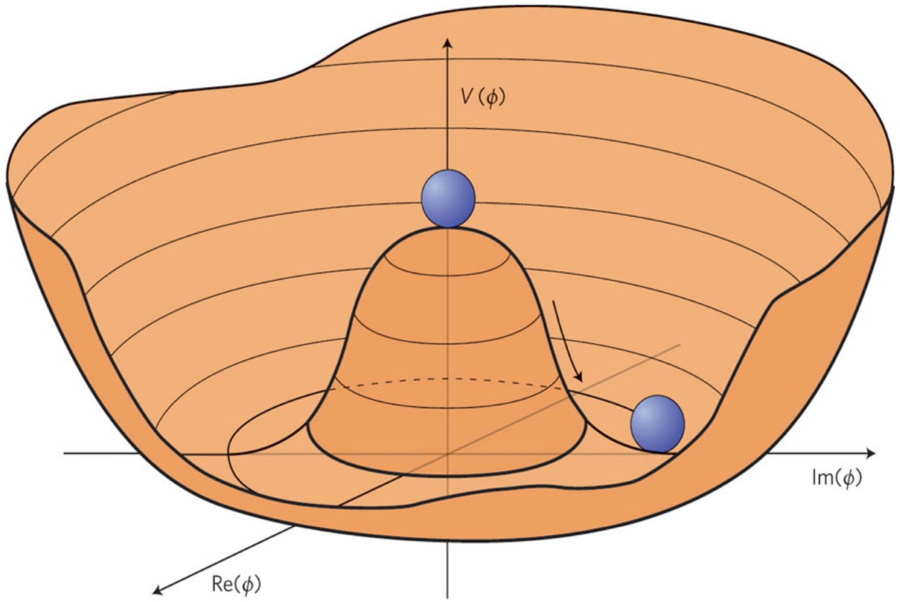
1808.02037 ( N. Chen, T. Han, S. Su, WS, Y. Wu )
1912.01431 ( N. Chen, T. Han, S. Li, S. Su, WS, Y. Wu )
2011.04540 ( WS, A G. Williams, M. Zhang)

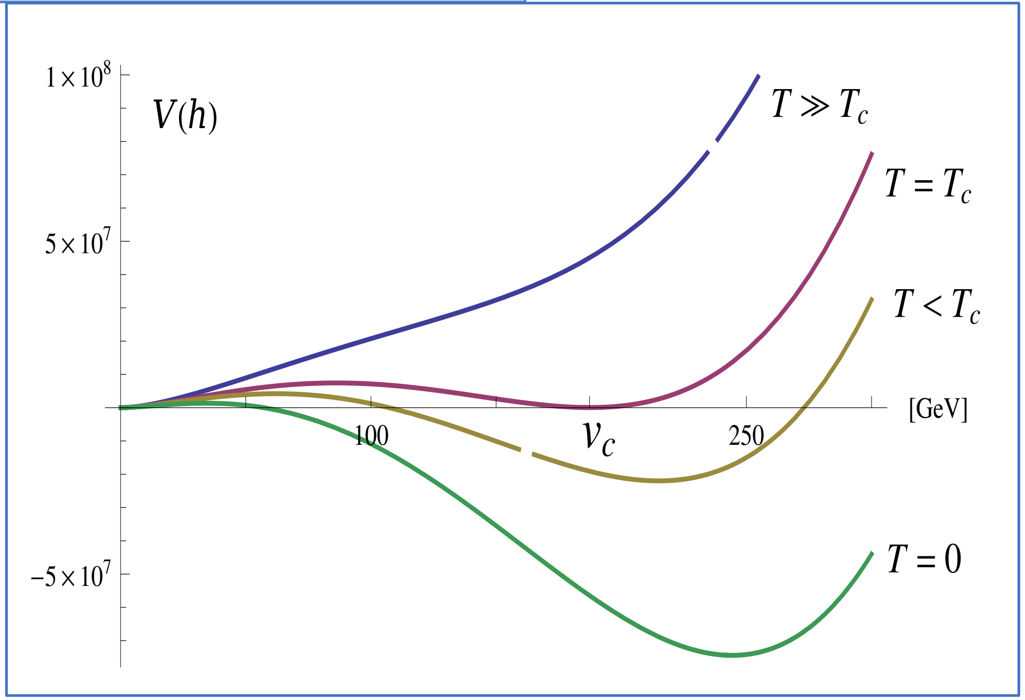
# Outline

- 2HDM and Phase Transition
- Higgs/Z-pole : Loop-level studies
- PT Results: cases and general scan
- Conclusion

# Electroweak Phase Transition

baryon asymmetry of the Universe (BAU)



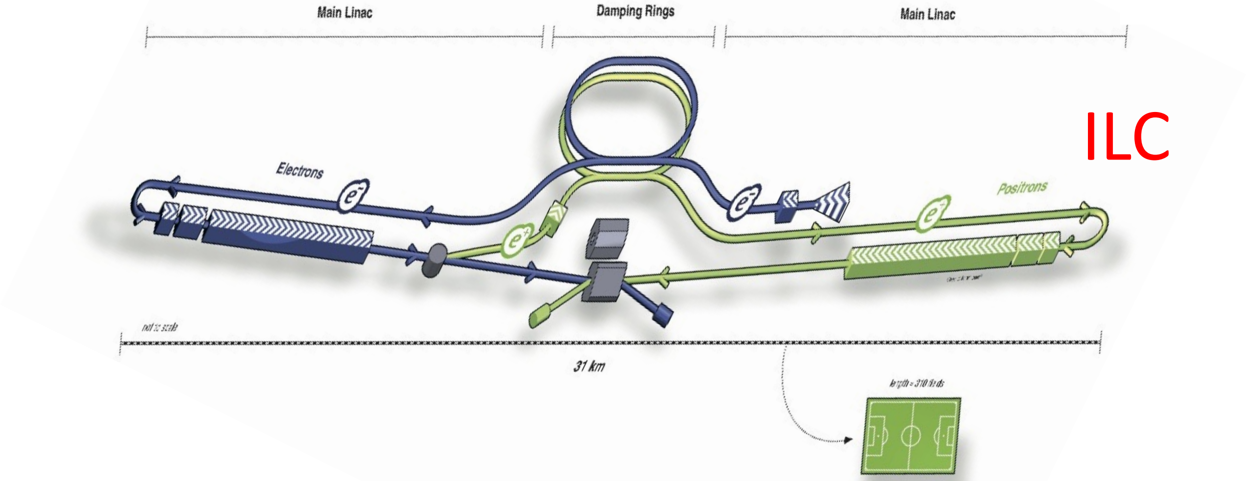




SM: Cross-over around T=100 GeV

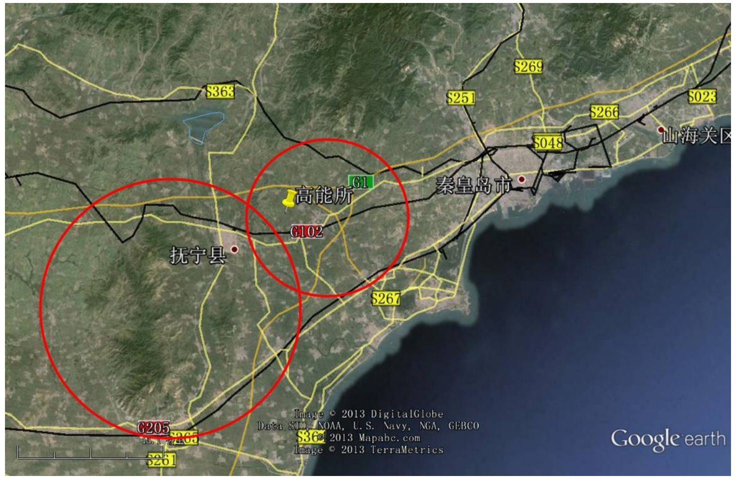
BSM: bubble formation → asymmetry

# Electroweak Phase Transition

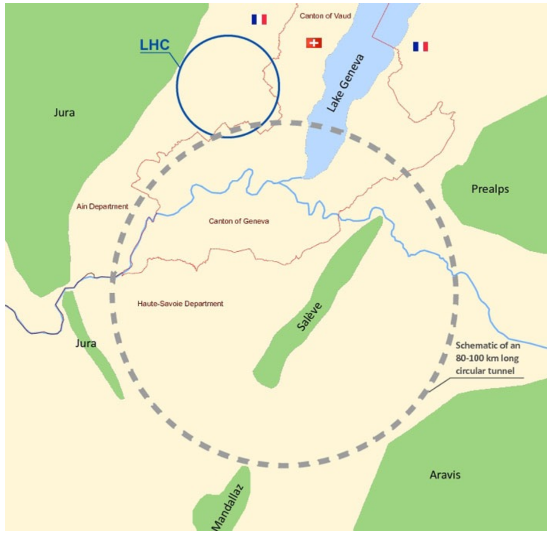
| Collider | $\Delta\mu$ (hbb) |
|---|---|
| LHC Run-I | 50% (wh) |
| LHC 14 TeV $300fb^{-1}$ | 26% |
| LHC 14 TeV $3000fb^{-1}$ | 12% |
| CEPC 240 GeV $5ab^{-1}$ (zh) | 0.28% |
| FCC-ee 240 GeV $10ab^{-1}$ (zh) | 0.2% |
| ILC 240 GeV $2ab^{-1}$ (zh) | 0.42% |
| ILC 350 GeV $0.2ab^{-1}$ (zh) | 1.6% |
| ILC 500 GeV $4ab^{-1}$ (vvh) | 0.24% |




ILC




CEPC




LHC
HL-LHC
FCC

# 2HDM: Brief Introduction

- Two Higgs Doublet Model

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

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \end{aligned}$$

| | $\Phi_1$ | $\Phi_2$ |
|---|---|---|
| Type I | u,d,l | |
| Type II | u | d,l |
| lepton-specific | u,d | l |
| flipped | u,l | d |

- Parameters (CP-conserving, Flavor Limit, $Z_2$ Symmetry)

$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

$v$ → 246 GeV

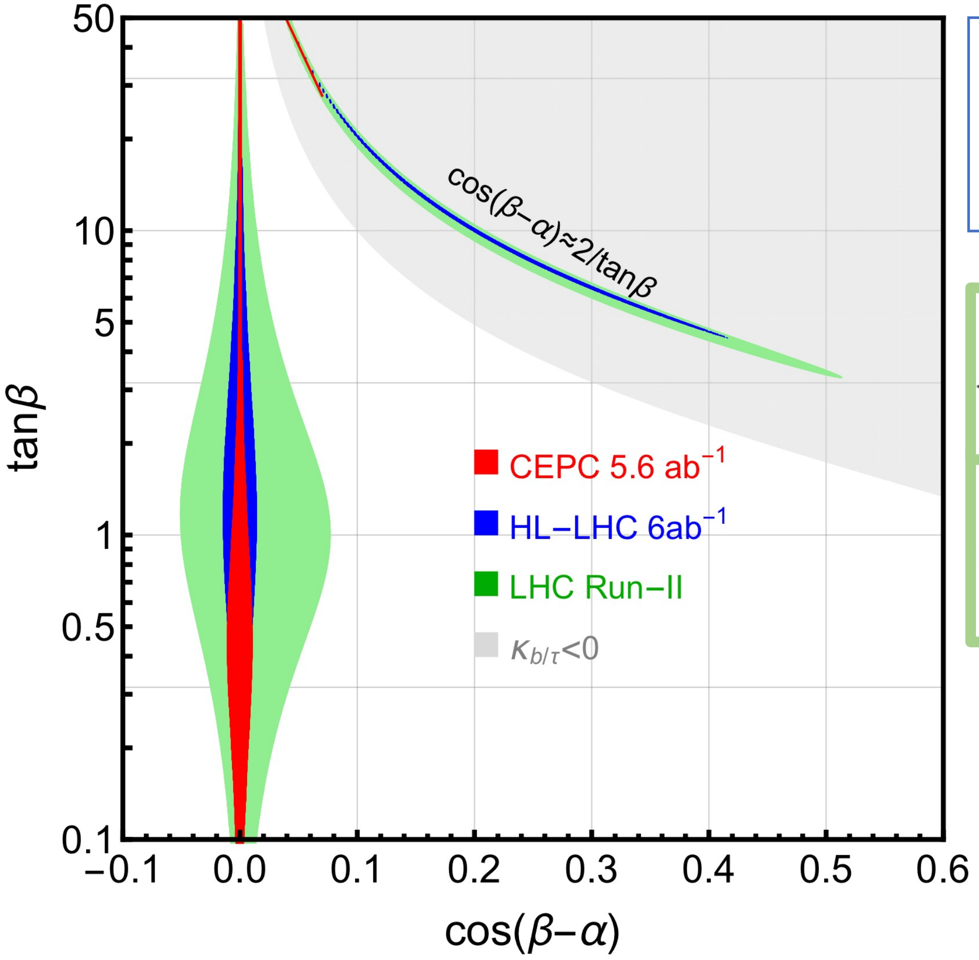
$m_h$ → 125. GeV

Soft $Z_2$ symmetry breaking: $m_{12}^2$

# 2HDM: Tree Level

| Model | $\kappa_V$ | $\kappa_u$ | $\kappa_d$ | $\kappa_\ell$ |
|---|---|---|---|---|
| 2HDM-I | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| 2HDM-II | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $-\sin\alpha/\cos\beta$ |
| 2HDM-L | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| 2HDM-F | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |

2HDM Type-II




Alignment limit :
$\cos(\beta-\alpha)=0$
$g(2HDM)=g(SM)$

1910.06269
WS

$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

# 2HDM: Tree Level

| Model | $\kappa_V$ | $\kappa_u$ | $\kappa_d$ | $\kappa_\ell$ |
|---|---|---|---|---|
| 2HDM-I | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
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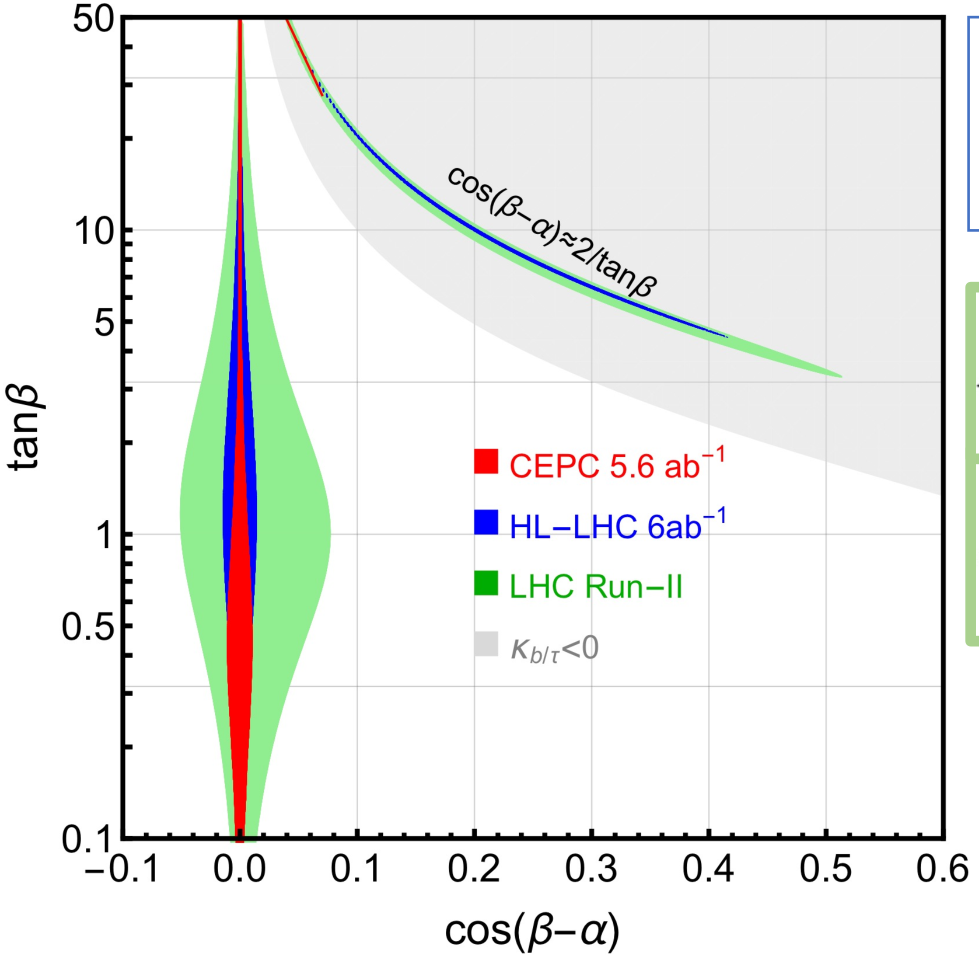
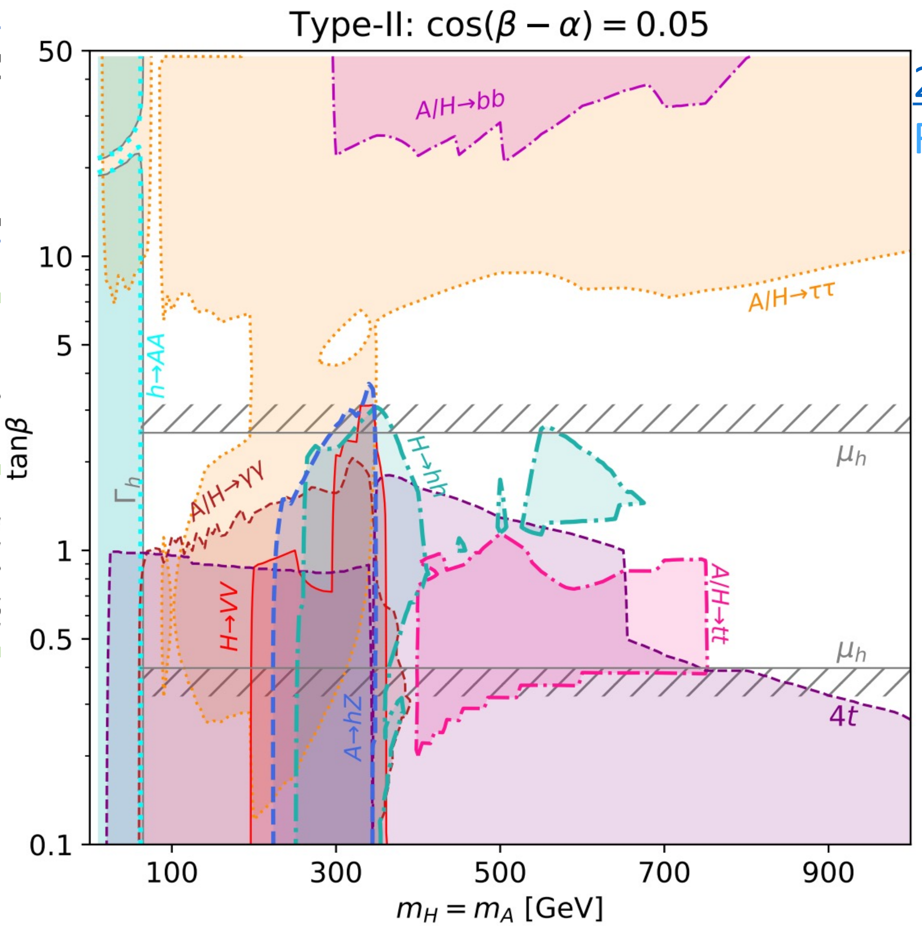
| 2HDM-L | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| 2HDM-F | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |

2HDM Type-II




2004.04172
F. Kling, S. Su, WS

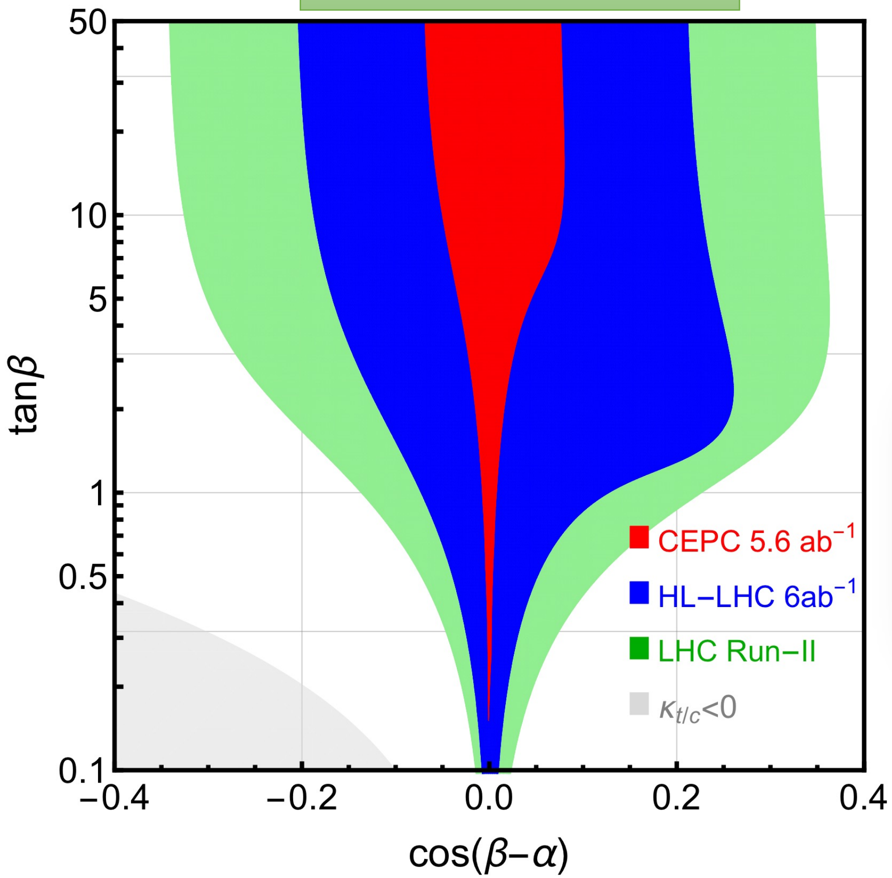
$\alpha) \times \tan\beta$

$\alpha)$

# 2HDM: Tree Level

| Model | $\kappa_V$ | $\kappa_u$ | $\kappa_d$ | $\kappa_\ell$ |
|---|---|---|---|---|
| 2HDM-I | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| 2HDM-II | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $-\sin\alpha/\cos\beta$ |
| 2HDM-L | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| 2HDM-F | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |

2HDM Type-I




Alignment limit :

$\cos(\beta-\alpha)=0$

$g(2HDM)=g(SM)$

$$\Delta\kappa_{u,d,e}=\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

# 2HDM: Tree Level

| Model | $\kappa_V$ | $\kappa_u$ | $\kappa_d$ | $\kappa_\ell$ |
|---|---|---|---|---|
| 2HDM-I | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
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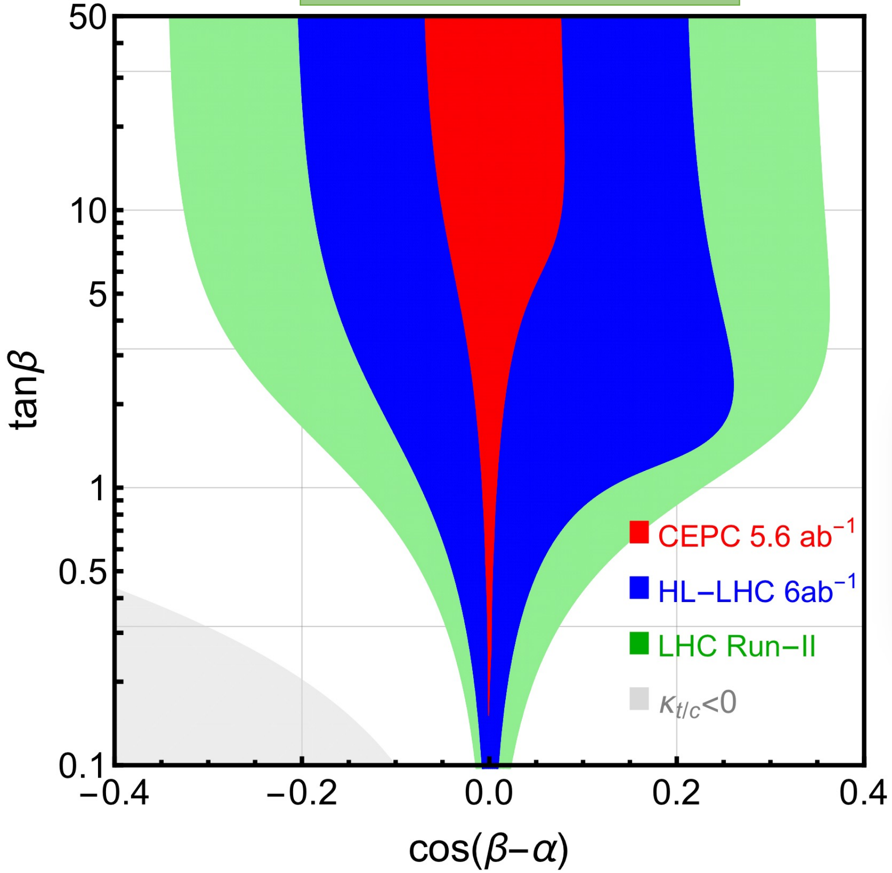
| 2HDM-F | $\sin(\beta-\alpha)$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |

2HDM Type-I

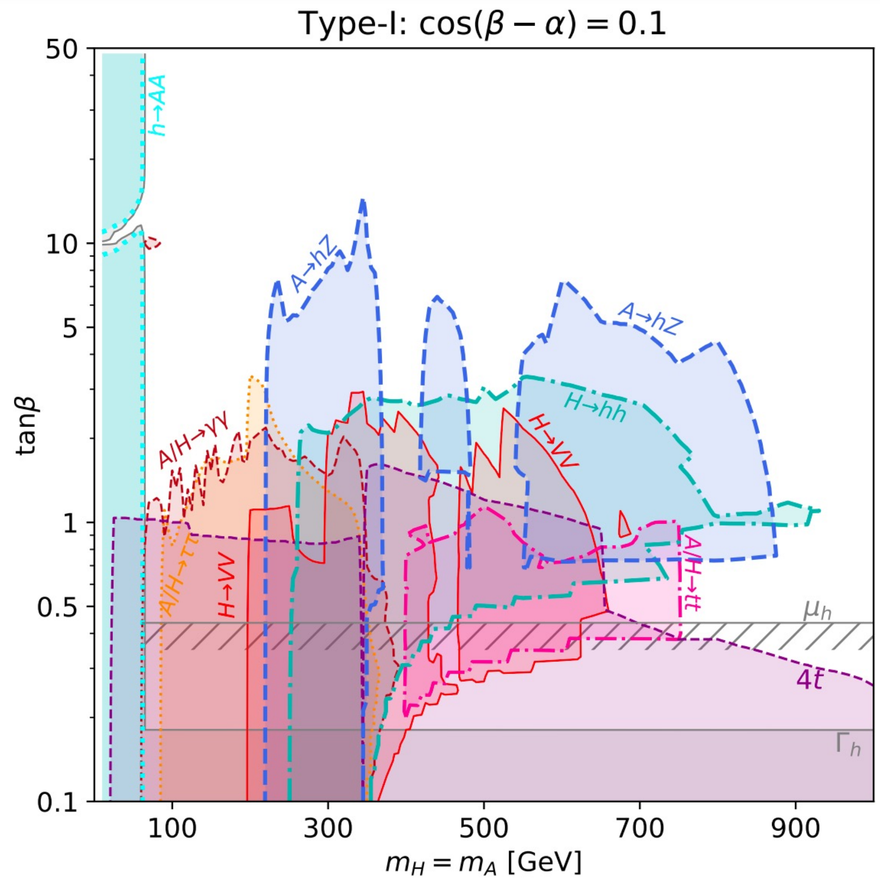



Alignme

cos (β

g(2HD

$\Delta\kappa_u,$




2004.04172

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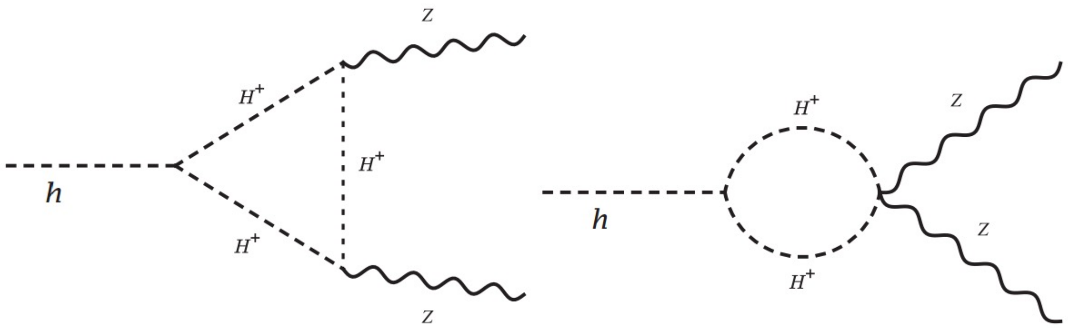
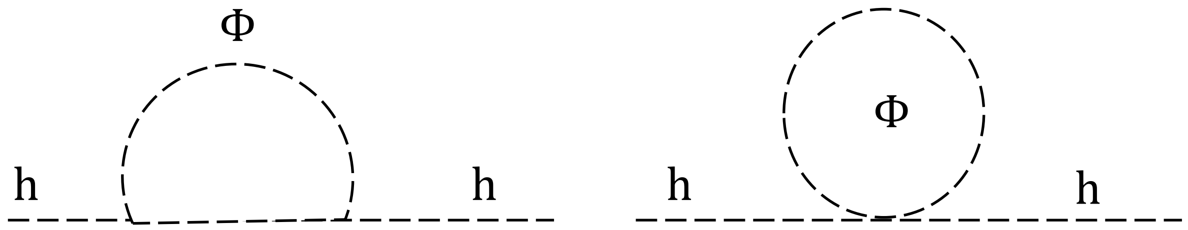
$\frac{\cos(\beta-\alpha)}{\tan\beta}$

# 2HDM: One-Loop Level




Main contribution

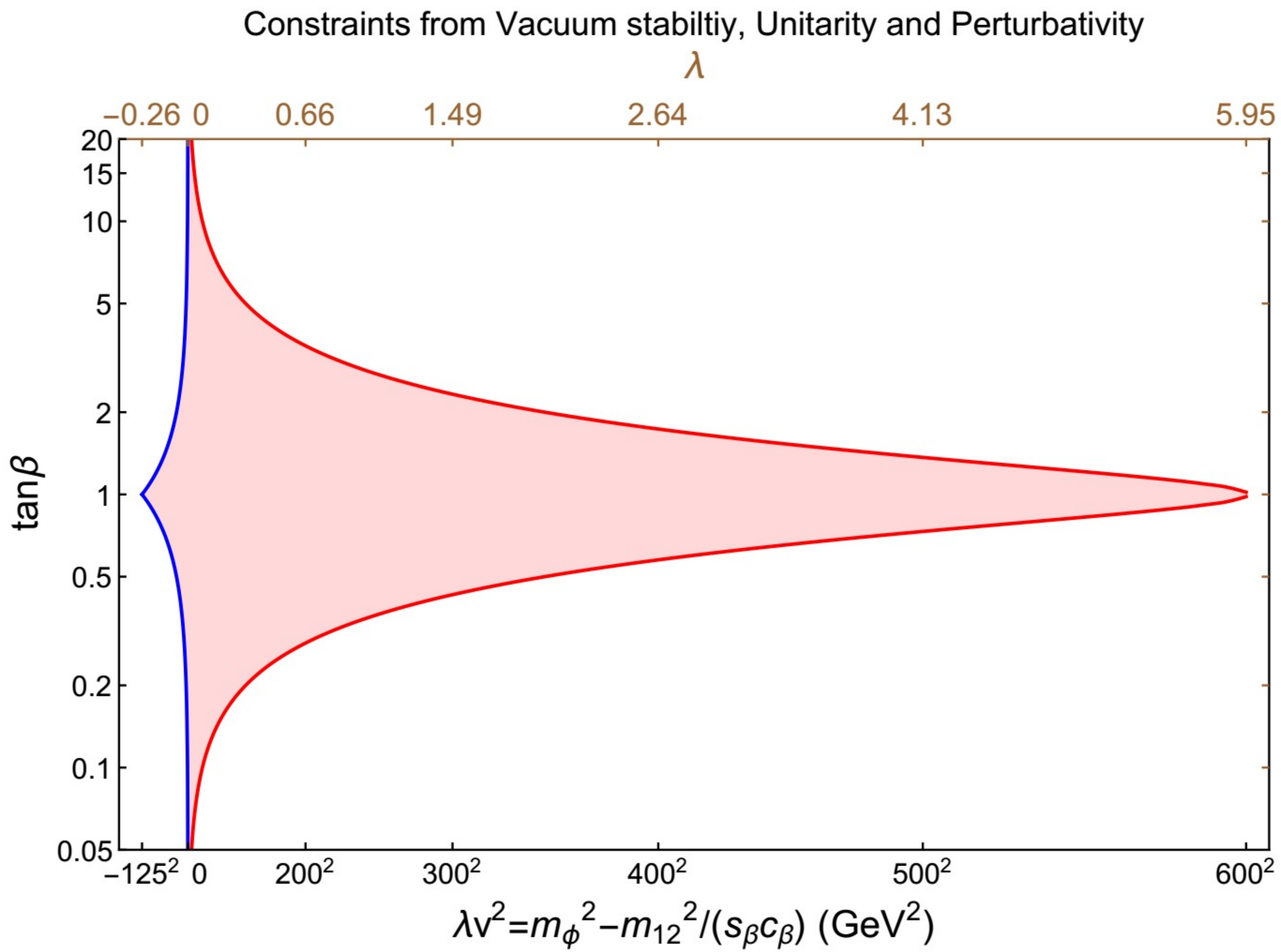
**Parameter : $\cos(\beta - \alpha), \tan\beta, m_H, m_A, m_{H^\pm}, m_{12}^2$**

① Loop + degenerate: $\cos(\beta - \alpha) = 0,\ m_\Phi \equiv m_H = m_A = m_{H^\pm}$

② Tree + Loop + degenerate: $\cos(\beta - \alpha) \neq 0\ ,\ m_\Phi \equiv m_H = m_A = m_{H^\pm}$

③ Tree + Loop + non-degenerate: $\Delta m_a = m_A - m_H,\ \Delta m_c = m_{H^\pm} - m_H$

# 2HDM: theoretical consideration




$\cos(\beta - \alpha) = 0,$

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

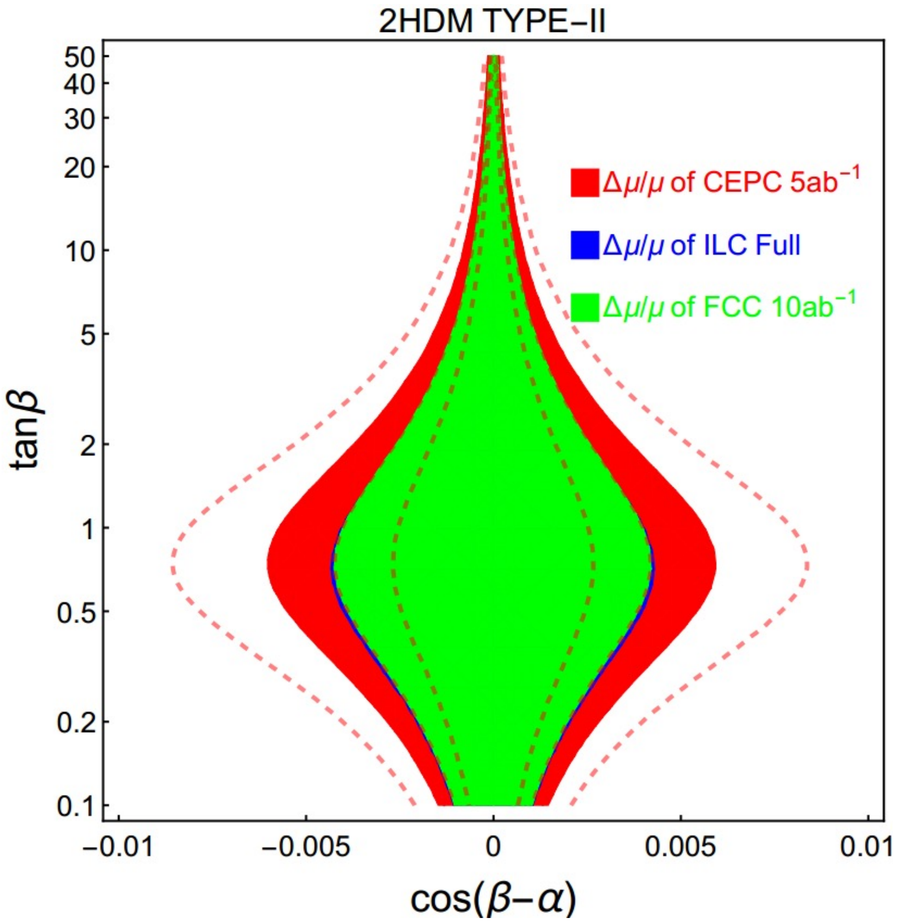
Theoretical constraints

$-125^2\text{GeV}^2 < \lambda v^2 < 600^2\text{GeV}^2$

$\lambda \in (-0.26, 5.95)$

$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$

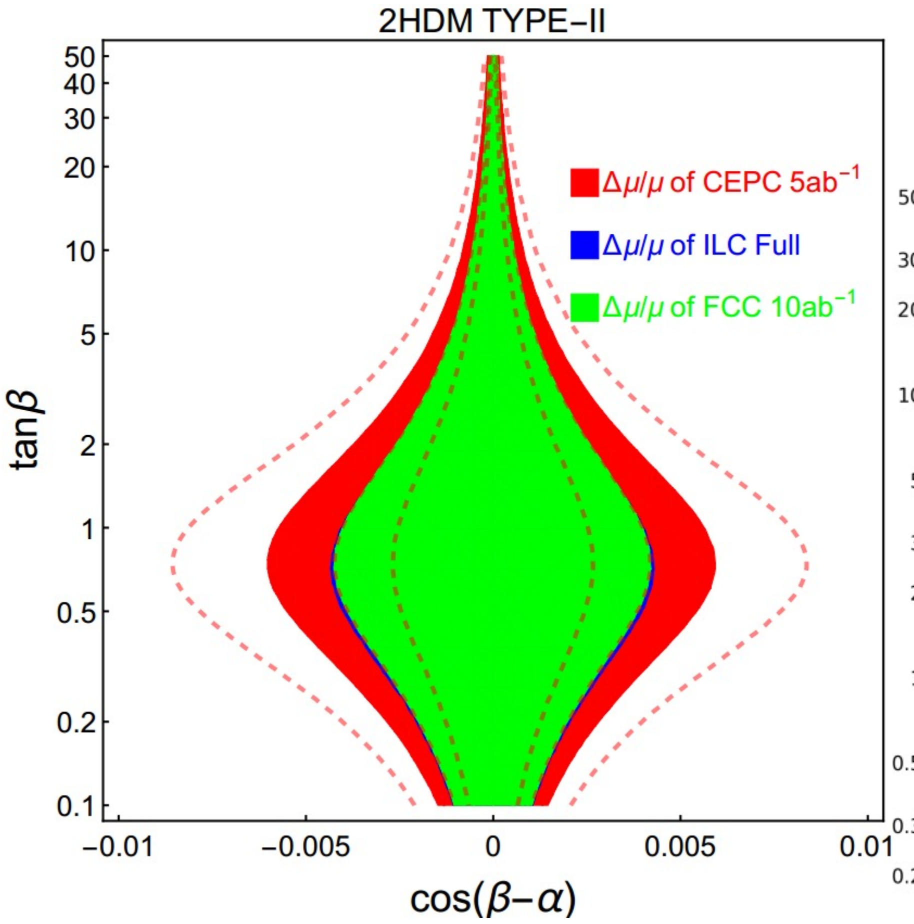
# 2HDM: $Tree + Loop + degenerate$




Tree-level

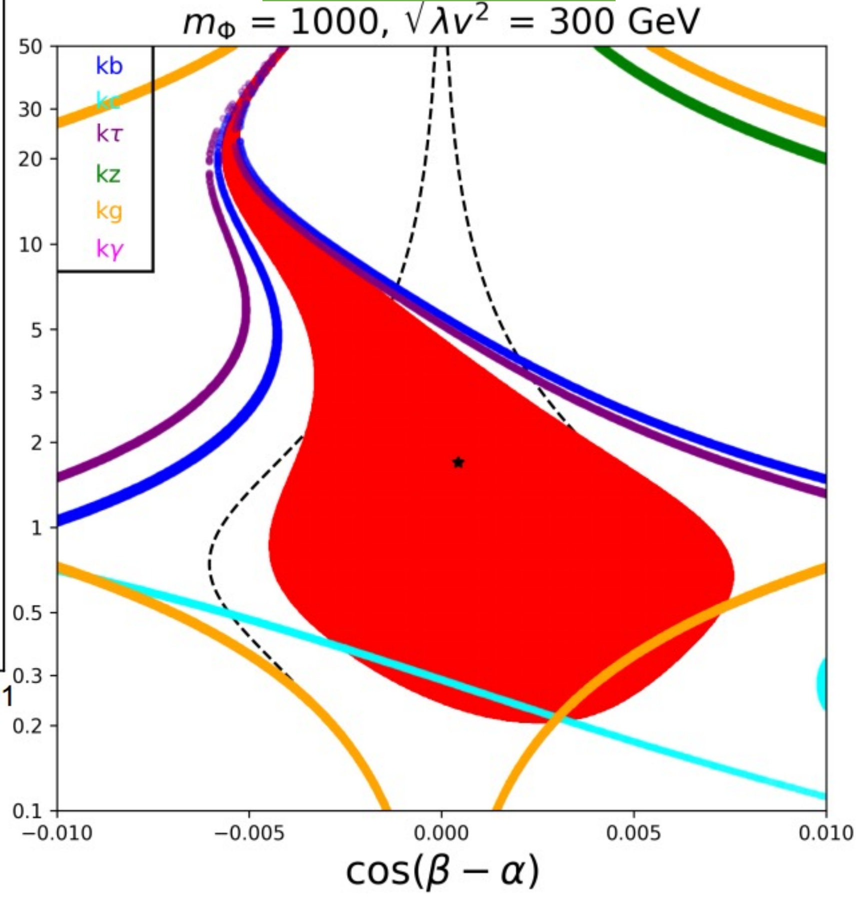
$\cos(\beta - \alpha) \neq 0,$
$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

# 2HDM: $Tree + Loop\ +\ degenerate$

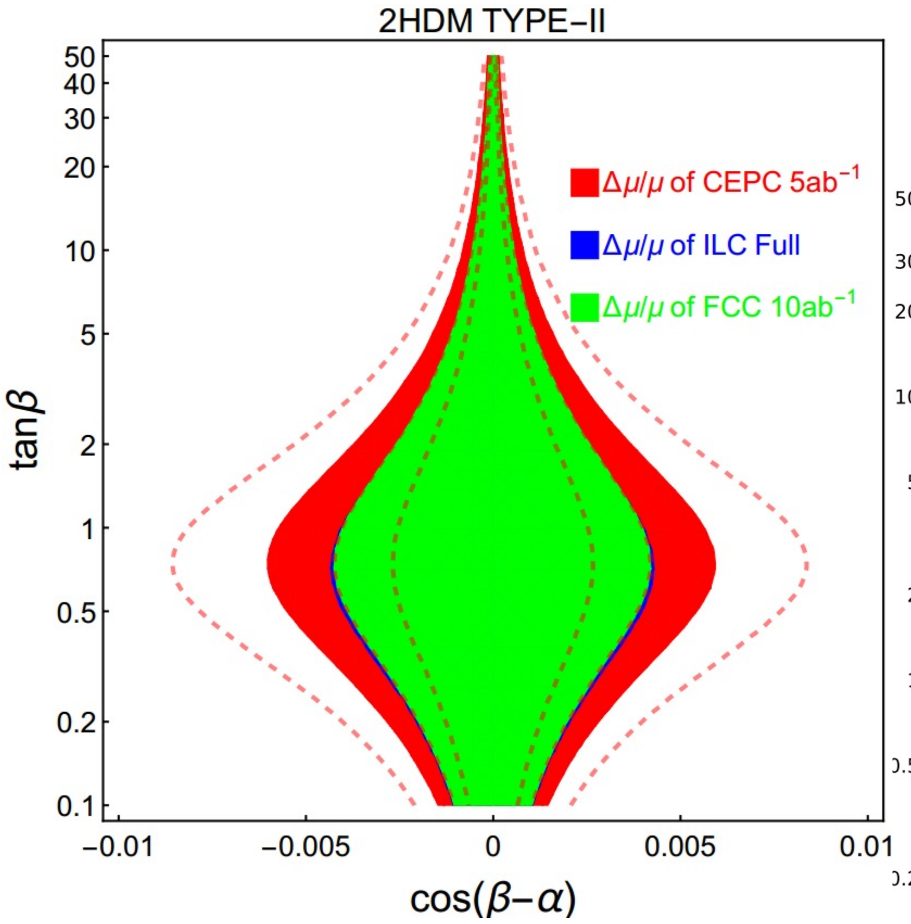



Tree-level

Loop-level

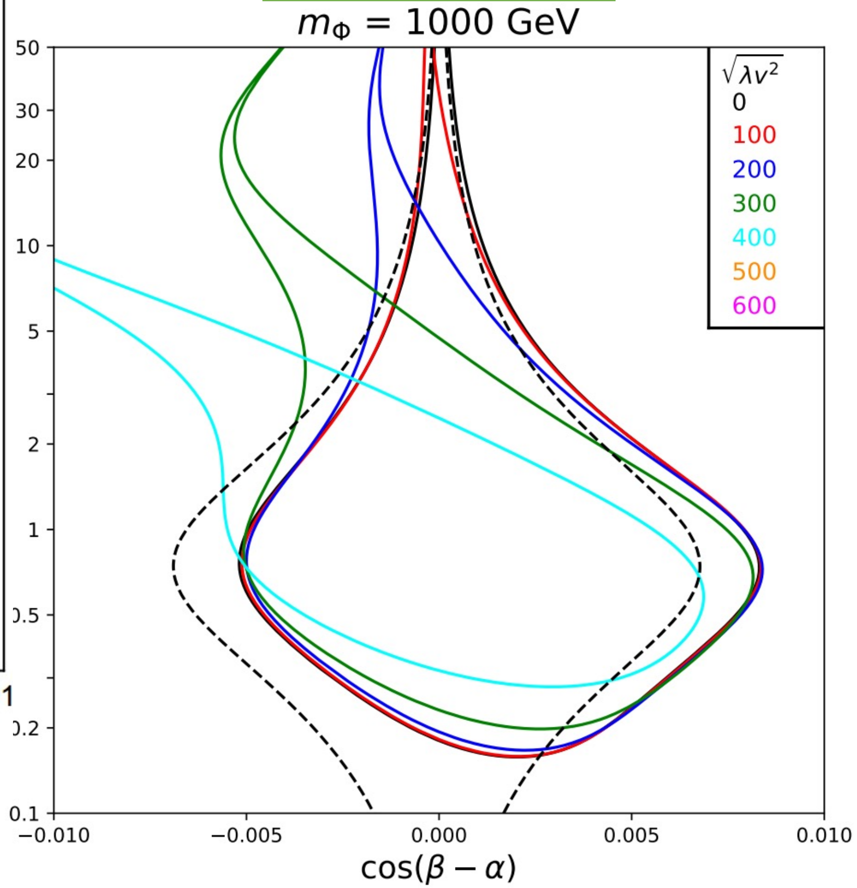


# 2HDM: $Tree + Loop\ +\ degenerate$




Tree-level

Loop-level



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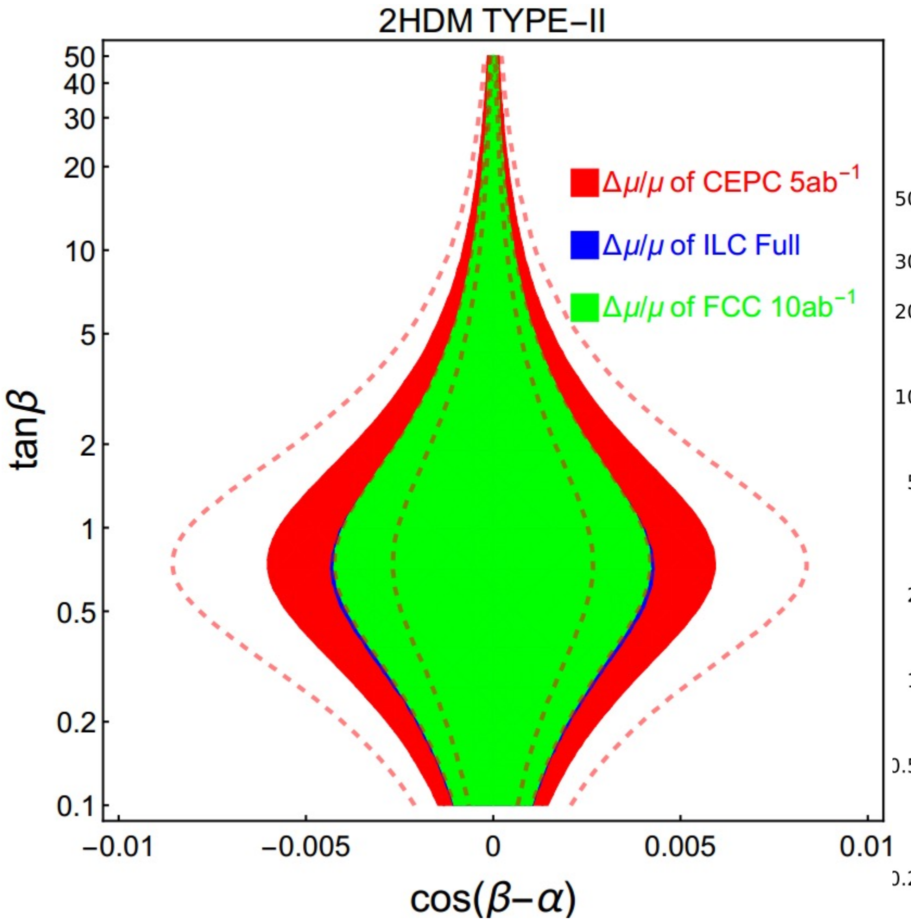
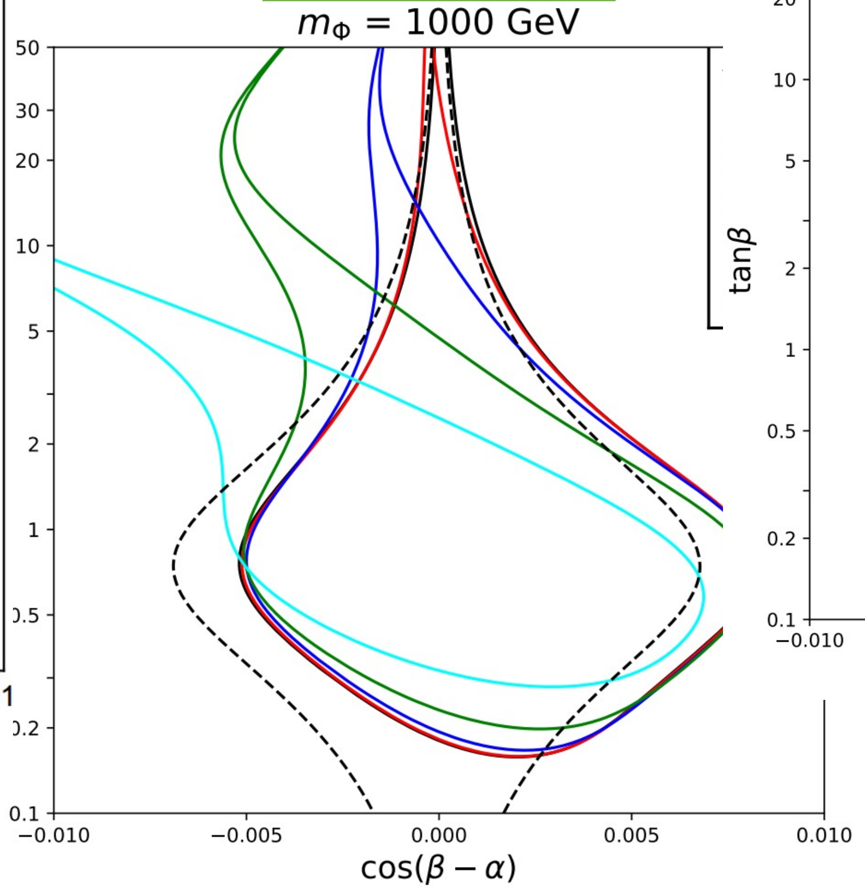
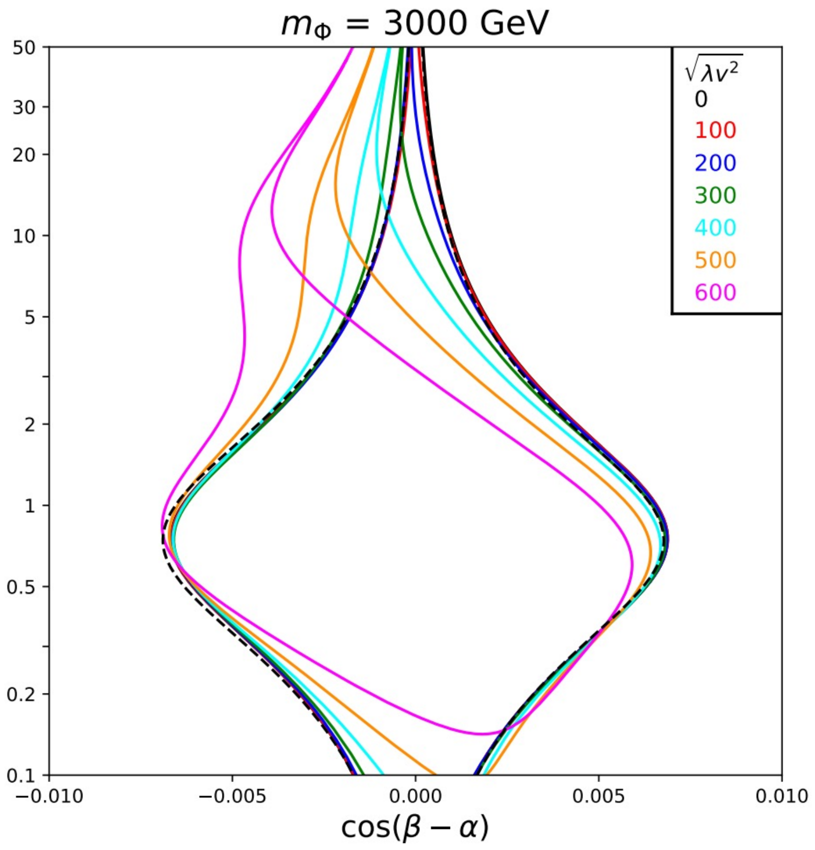



Tree-level

Loop-level




Loop-level decouple

# 2HDM: $Tree + Loop + non - degenerate$

## Z Pole Precision

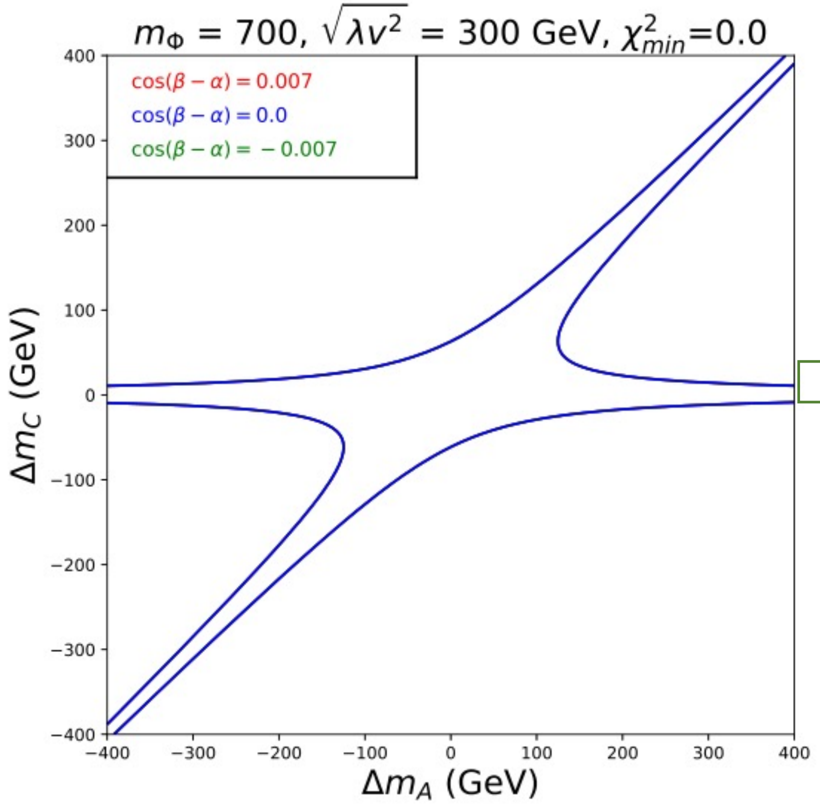
| | Current ($1.7 \times 10^7$ $Z$'s) | | | | CEPC ($10^{10} Z$'s) | | | | FCC-ee ($7 \times 10^{11} Z$'s) | | | | ILC ($10^9 Z$'s) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\sigma$ | correlation | | | $\sigma$ | correlation | | | $\sigma$ | correlation | | |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

# 2HDM: $Tree + Loop\ + non - degenerate$

## Z Pole Precision

CEPC fit

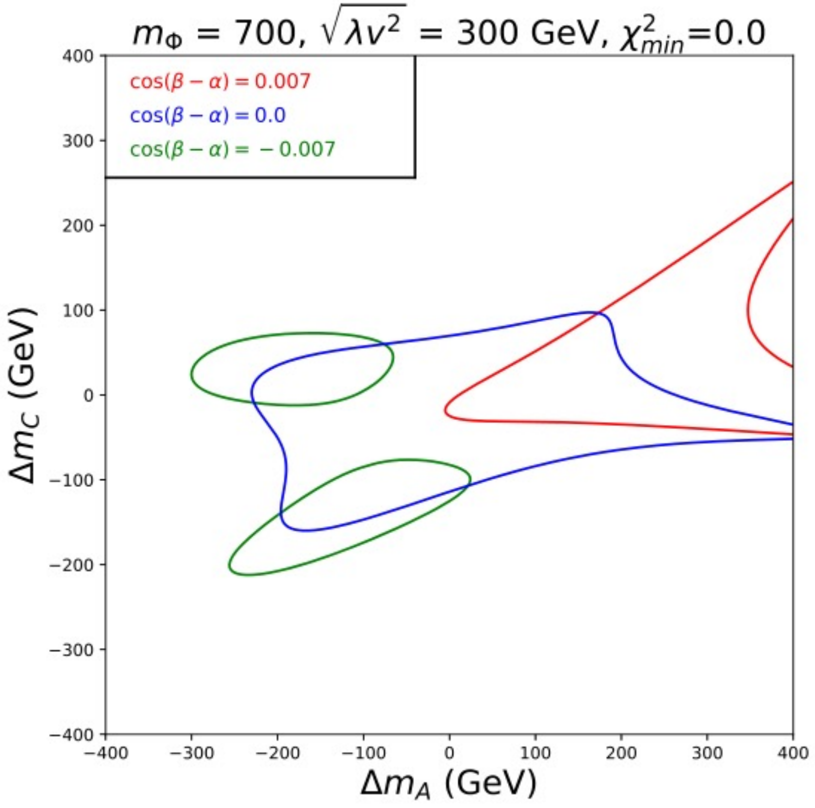
$$\Delta m_A = m_A - m_H,$$
$$\Delta m_C = m_{H^\pm} - m_H,$$
$$m_H = 700\ \text{GeV}$$



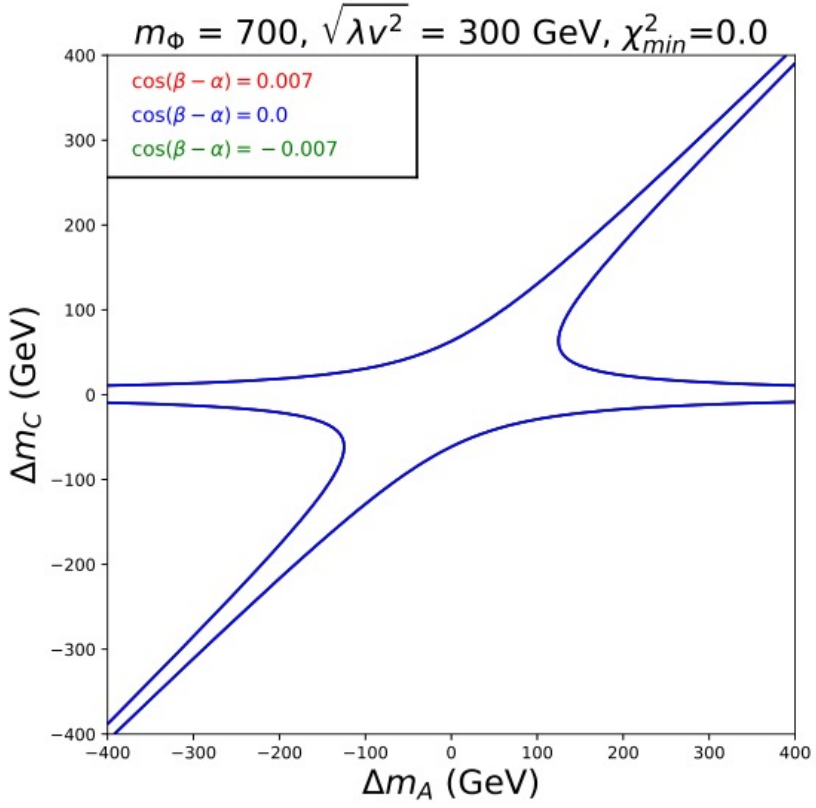

$$m_{H^\pm} = m_H$$
$$m_{H^\pm} = m_A$$

# 2HDM: $Tree + Loop \ + non - degenerate$

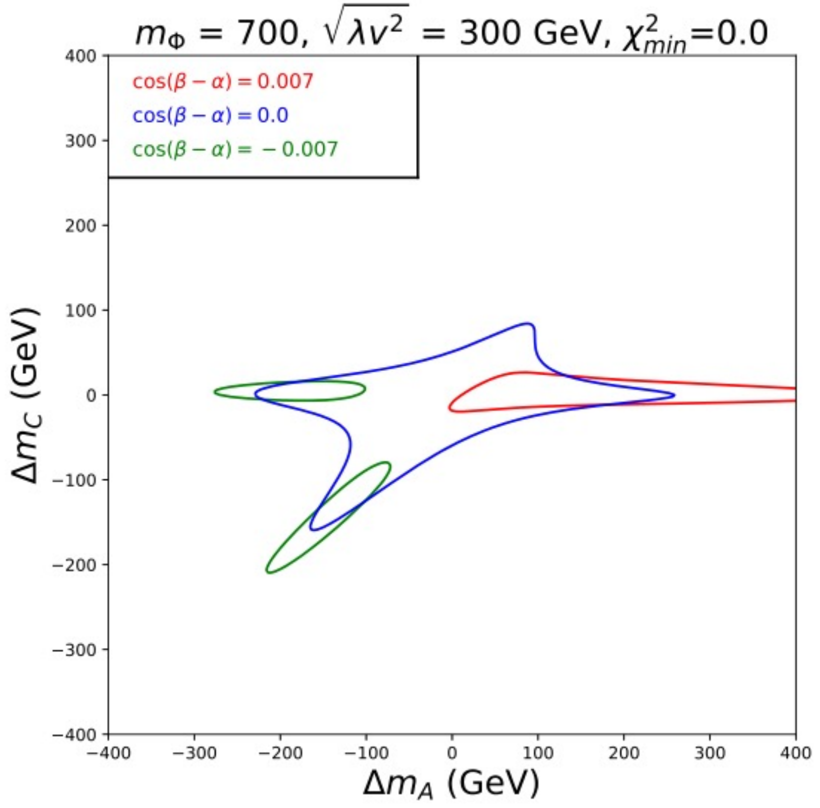
**Higgs Precision**




**Z Pole Precision**




**Combined**

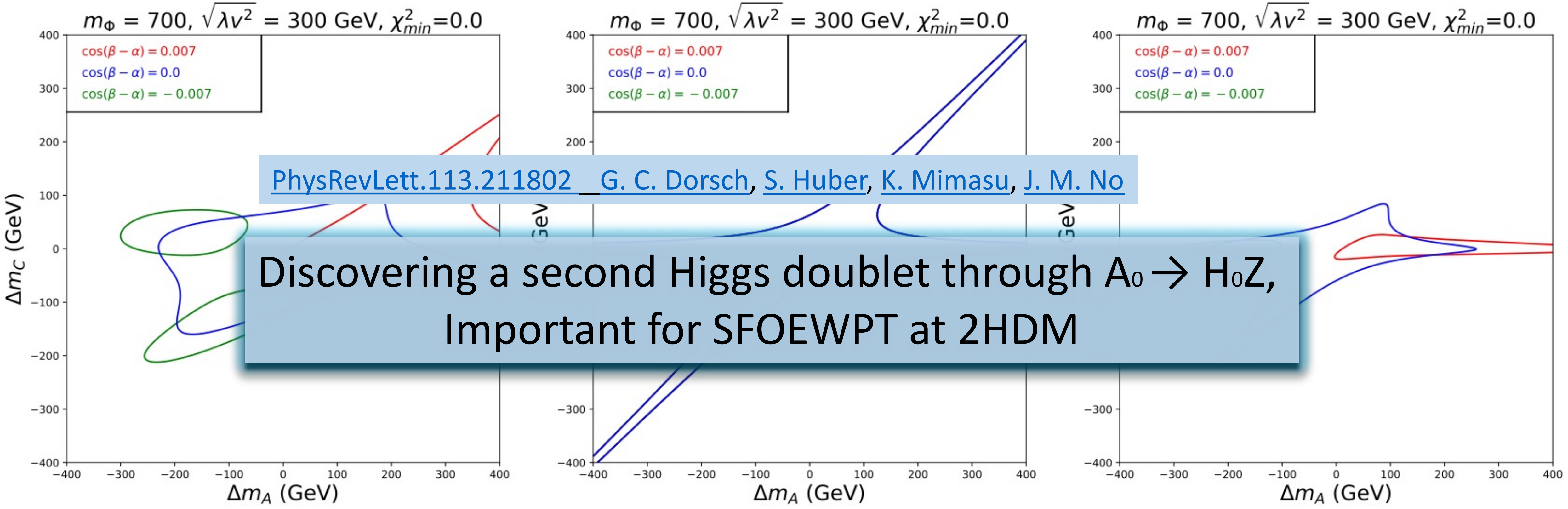



$m_H = 700$ GeV

Complementary to each other

# 2HDM: $\mathit{Tree} + \mathit{Loop}\ + \mathit{non} - \mathit{degenerate}$

**Higgs Precision** | **Z Pole Precision** | **Combined**




PhysRevLett.113.211802 G. C. Dorsch, S. Huber, K. Mimasu, J. M. No

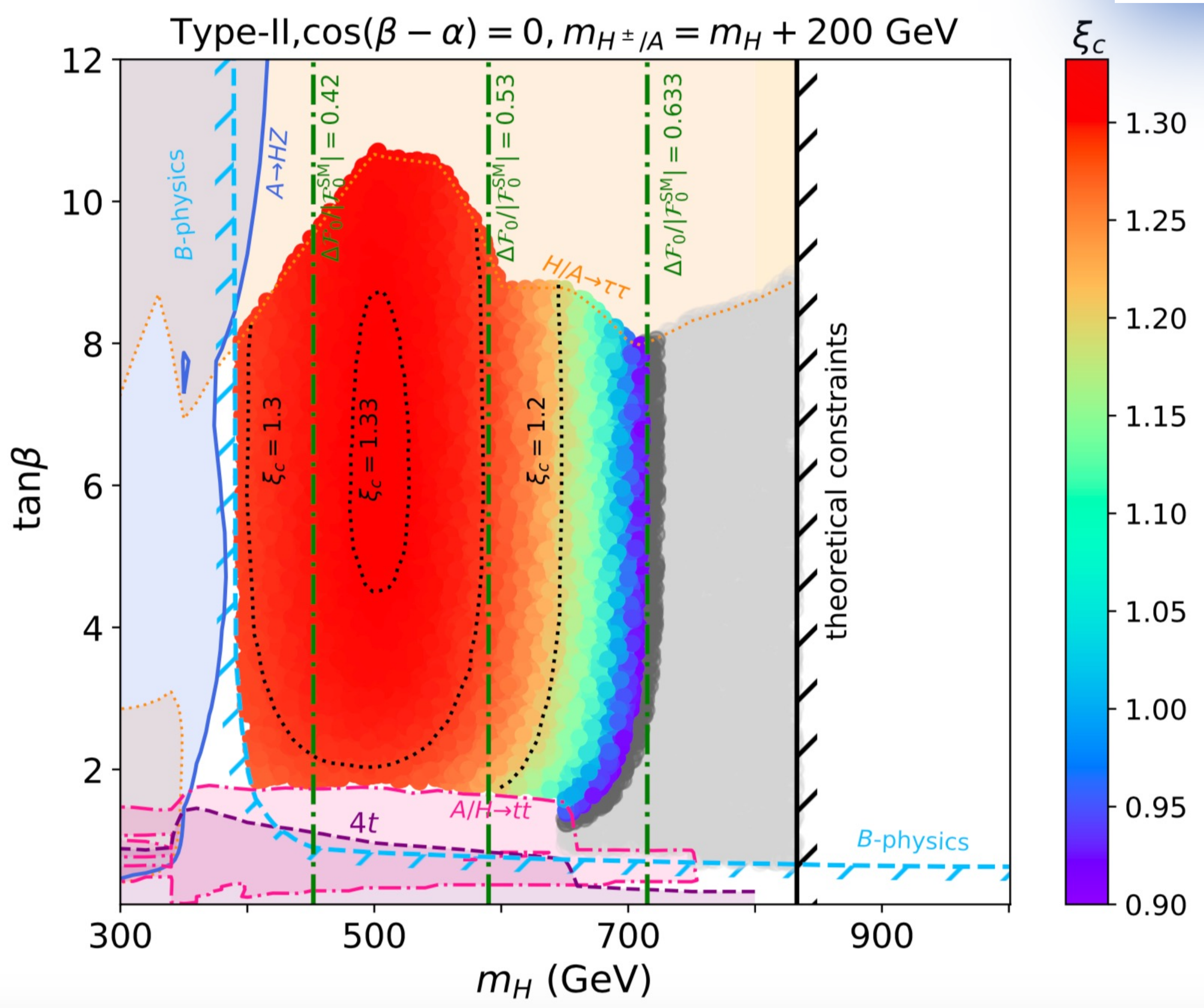
Discovering a second Higgs doublet through $A_0 \to H_0 Z$, Important for SFOEWPT at 2HDM

$m_H = 700$ GeV

Complementary to each other

# Results: Case-1

$$\xi_c \equiv \frac{v_c}{T_c}$$




Type-II
fixed mass splitting 200 GeV

$m_H < 710$ GeV
$tan\beta \ \epsilon \ (1.8,10)$

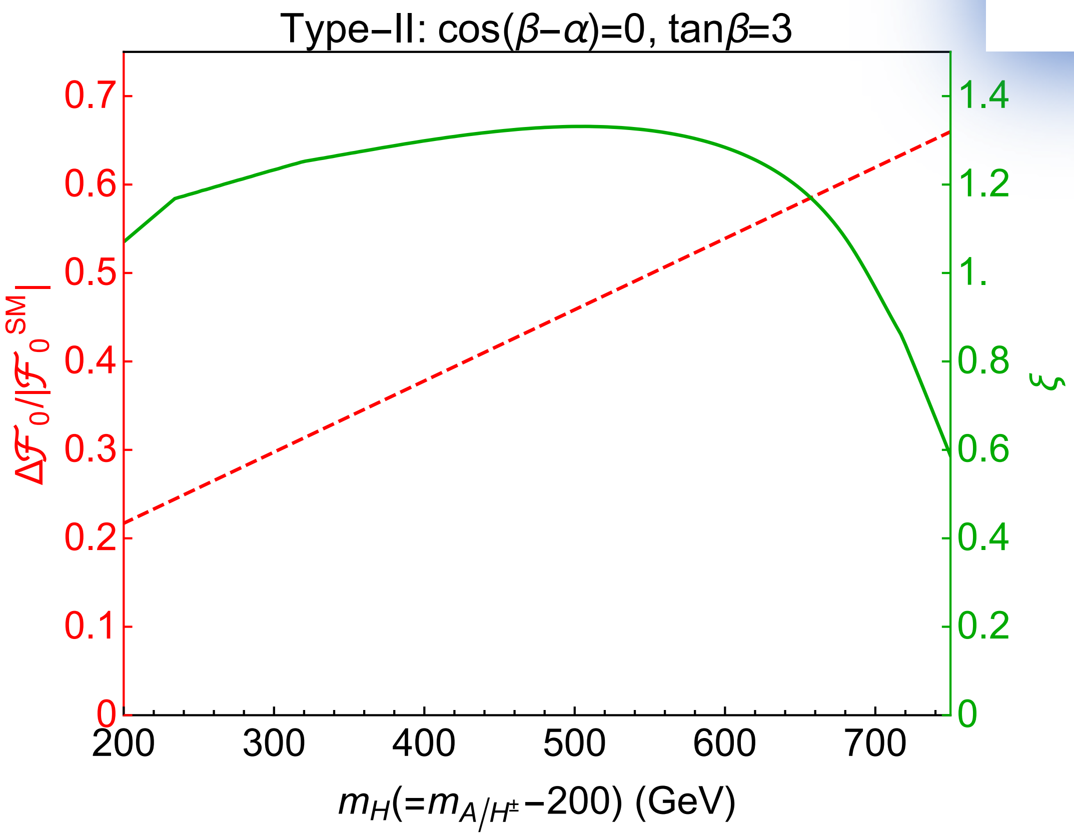
Vacuum uplifting:

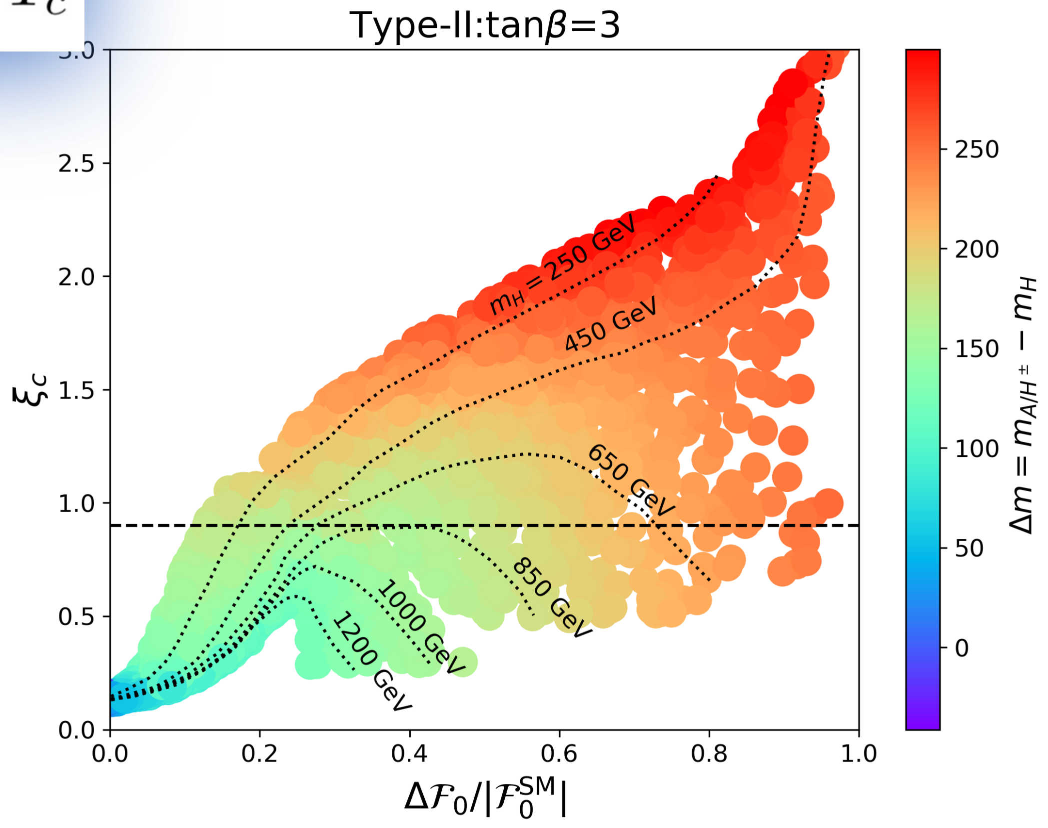
arXiv:1705.09186
G. C. Dorsch, S. Huber, K. Mimasu, J. M. No

$$\Delta\mathcal{F}_0 = \frac{1}{64\pi^2}\left[\left(m_h^2 - 2M^2\right)^2\left(\frac{3}{2} + \frac{1}{2}\log\left[\frac{4m_A m_H m_{H^\pm}^2}{\left(m_h^2 - 2M^2\right)^2}\right]\right)\right.$$
$$\left. + \frac{1}{2}\left(m_A^4 + m_H^4 + 2m_{H^\pm}^4\right) + \left(m_h^2 - 2M^2\right)\left(m_A^2 + m_H^2 + 2m_{H^\pm}^2\right)\right]$$

# PT vs. vacuum uplifting

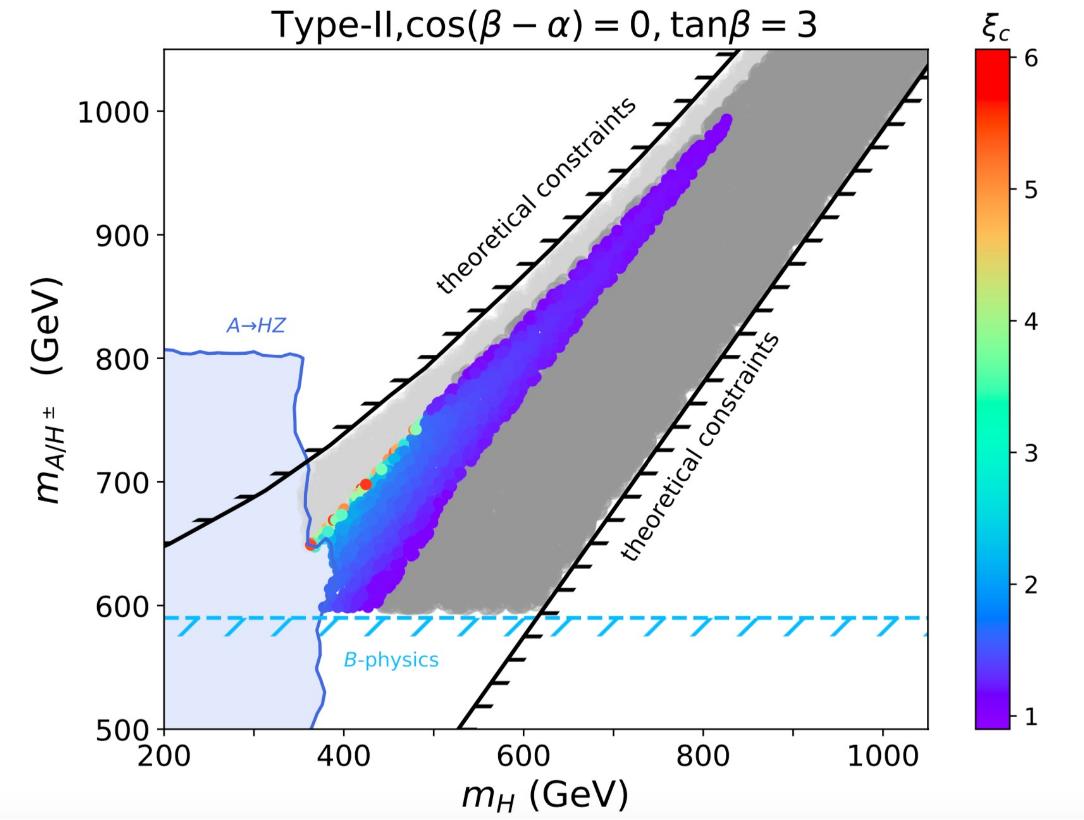
$$\xi_c \equiv \frac{v_c}{T_c}$$

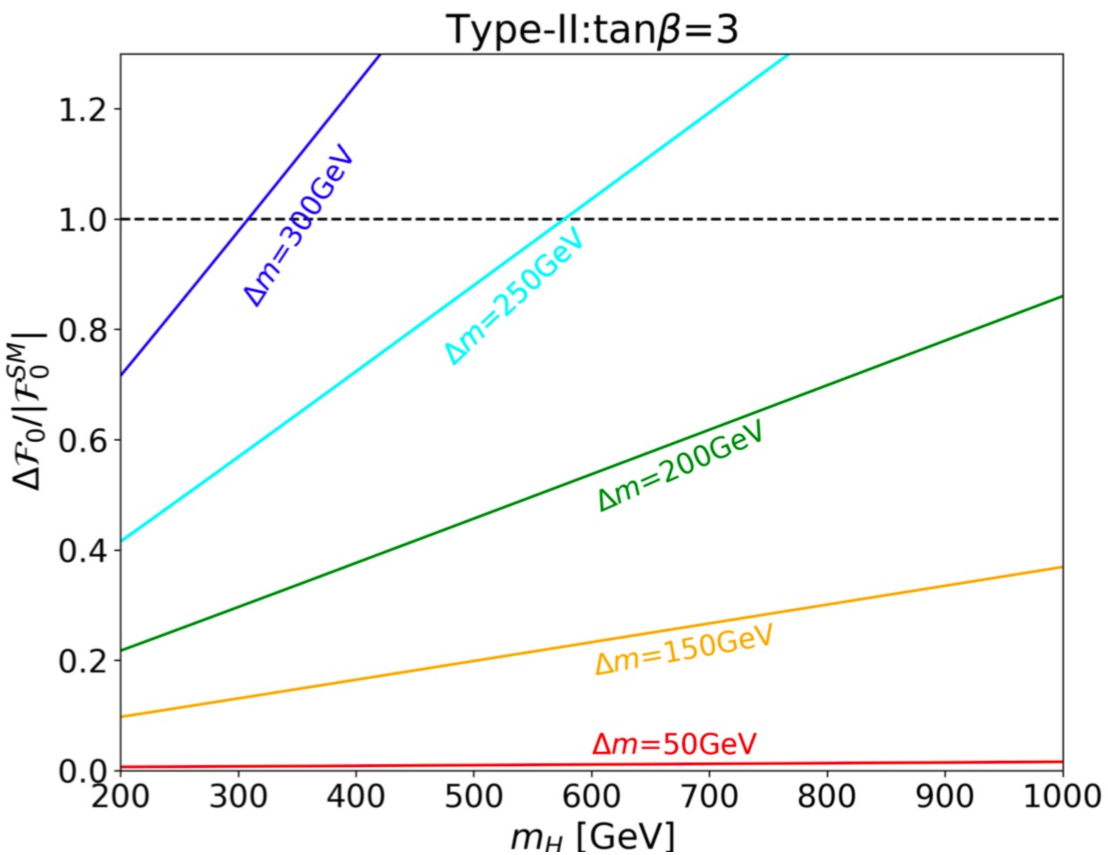


# Results: Case-2

$$m_A = m_{H^\pm} \ \tan\beta = 3$$




Too large or small mass splitting can not generate SFOEWPT

# Results: Case-2/3

$$V(\phi_h, T) \approx (DT^2 - \mu^2)\phi_h^2 - ET\phi_h^3 + \frac{\tilde{\lambda}}{4}\phi_h^4$$

High T approximation:

$$D = \frac{1}{24}\left[6\frac{m_W^2}{v^2} + 3\frac{m_Z^2}{v^2} + \frac{m_h^2}{v^2} + 6\frac{m_t^2}{v^2} + \frac{m_H^2 - M^2}{v^2} + \frac{m_A^2 - M^2}{v^2} + 2\frac{m_{H^\pm}^2 - M^2}{v^2}\right]$$

$$E = \frac{1}{12\pi}\left[6\frac{m_W^3}{v^3} + 3\frac{m_Z^3}{v^3} + \frac{m_h^3}{v^3}\right] + E_{(H/A/H^\pm)}$$

$$E_{(\alpha)} \approx \begin{cases} \frac{1}{12\pi}\lambda_\alpha^{3/2} = \frac{1}{12\pi}\frac{m_\alpha^3}{v^3}, & M^2 \ll \lambda_\alpha\phi_h^2 \\ 0, & M^2 \gg \lambda_\alpha\phi_h^2 \end{cases}$$

$$\lambda_{A/H^\pm}v^2 = (\Delta m)^2 + 2m_H\Delta m$$

Vacuum uplifting:

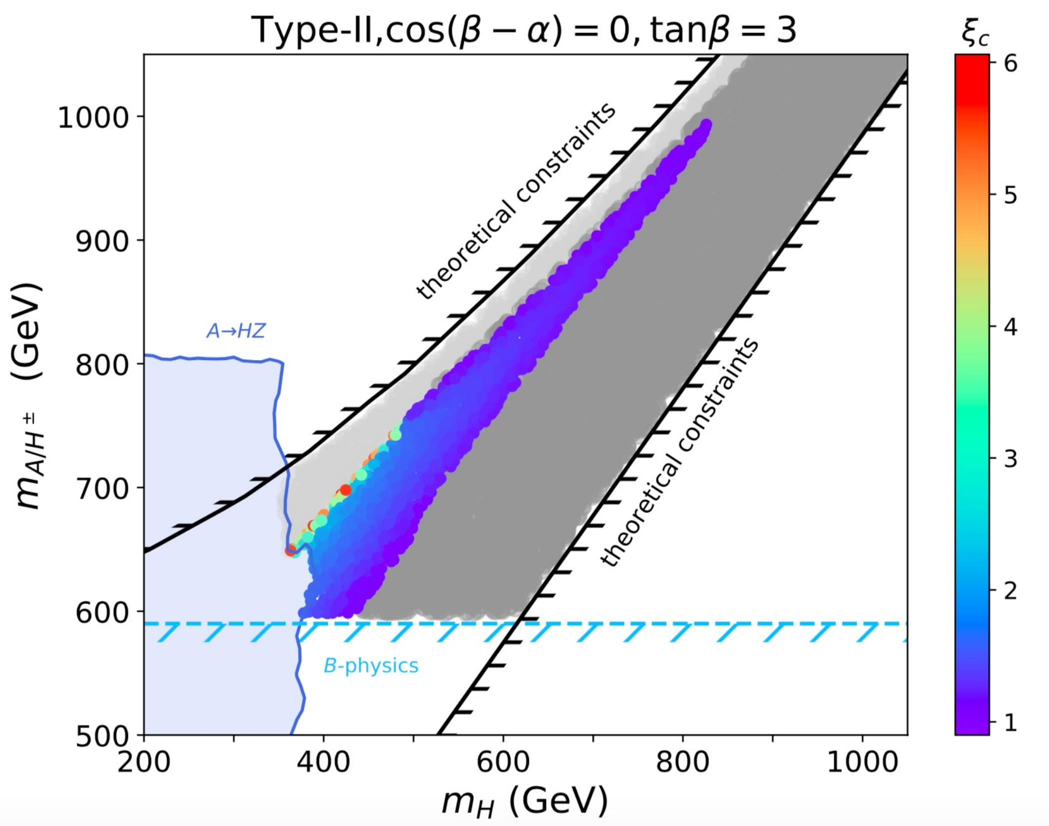
$$\Delta\mathcal{F}_0 = \frac{1}{64\pi^2}\left[\left(m_h^2 - 2M^2\right)^2\left(\frac{3}{2} + \frac{1}{2}\log\left[\frac{4m_A m_H m_{H^\pm}^2}{\left(m_h^2 - 2M^2\right)^2}\right]\right)\right.$$

$$\left. + \frac{1}{2}\left(m_A^4 + m_H^4 + 2m_{H^\pm}^4\right) + \left(m_h^2 - 2M^2\right)\left(m_A^2 + m_H^2 + 2m_{H^\pm}^2\right)\right]$$

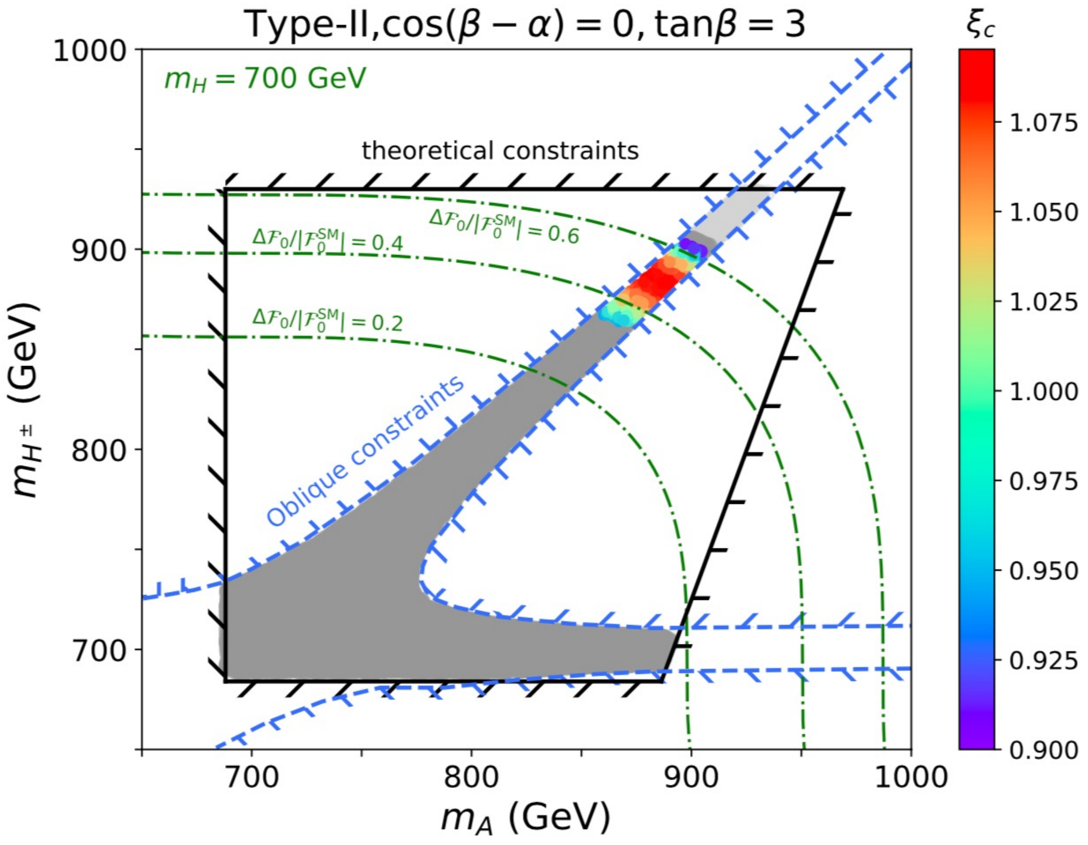
Too large or small mass splitting can not generate SFOEWPT

# Results: Case-2/3

$m_A = m_{H^\pm}\ \tan\beta = 3$

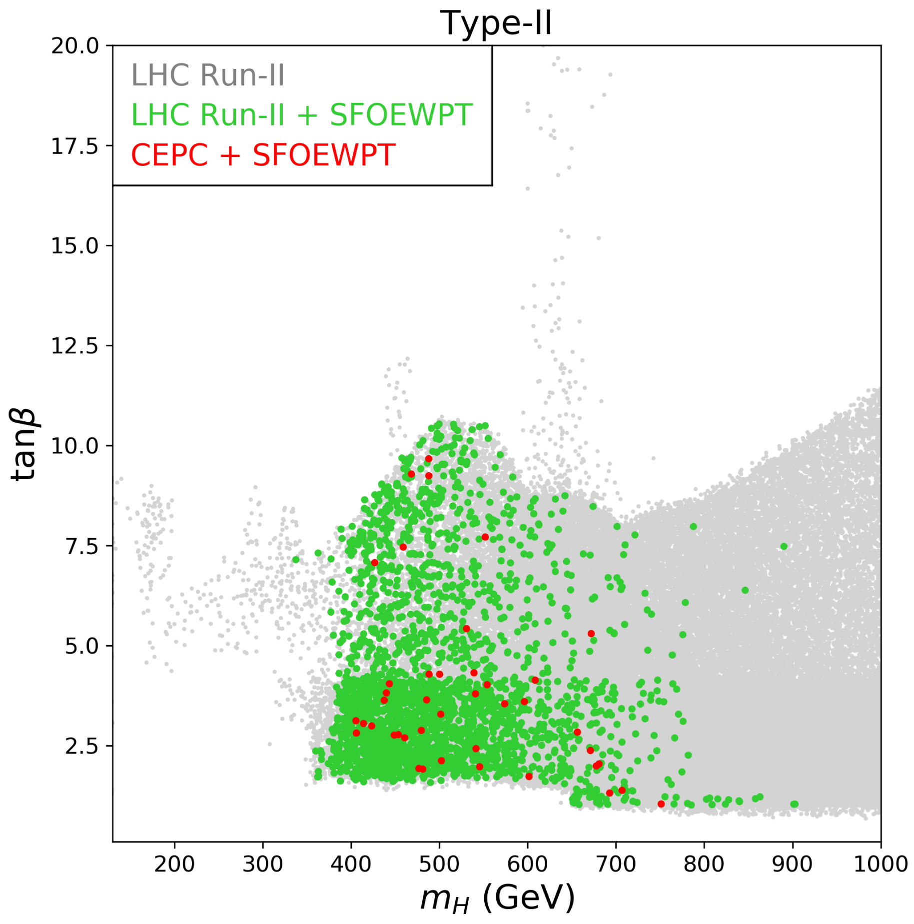


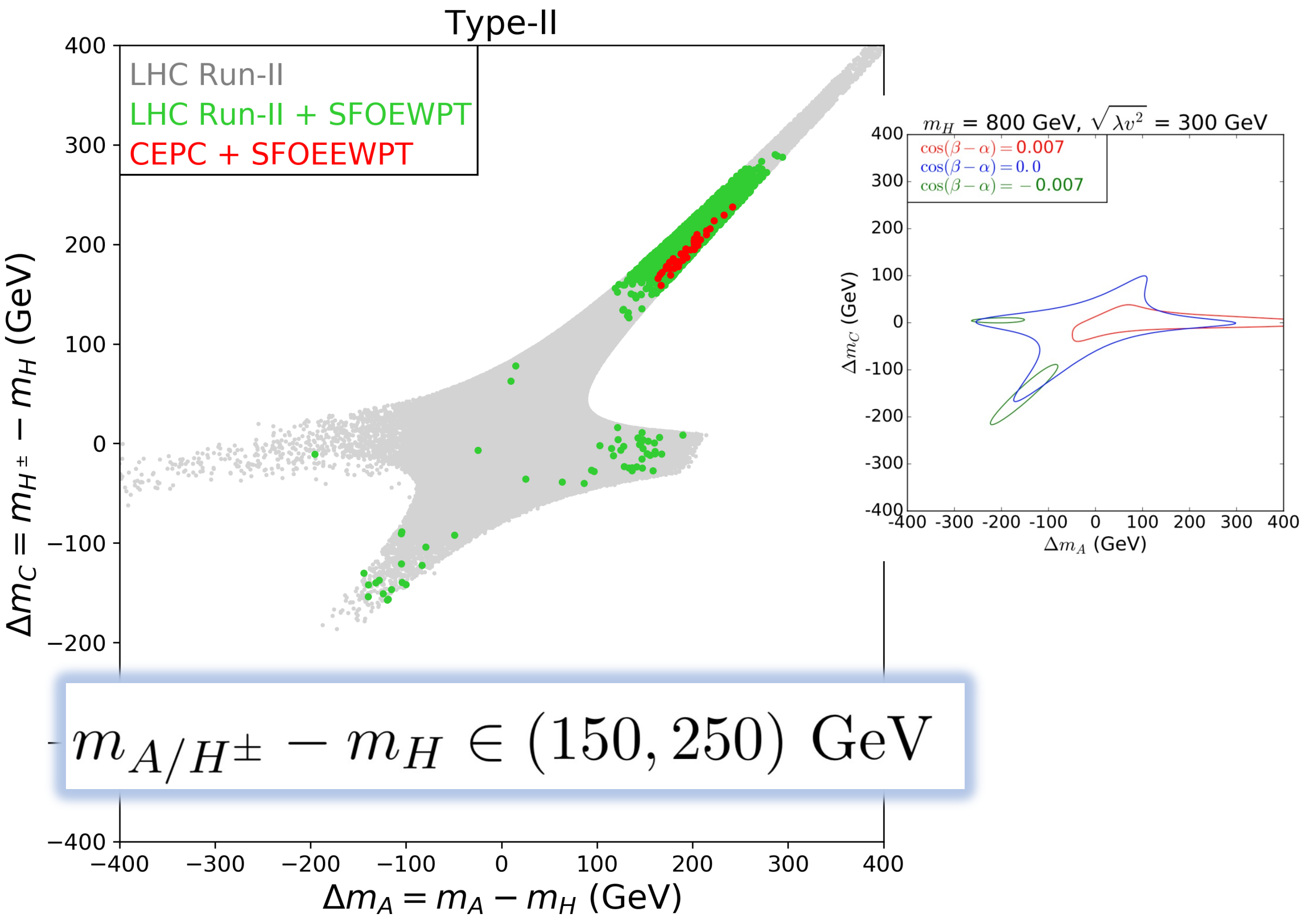

$m_H$=**700 GeV**




Too large or small mass splitting can not generate SFOEWPT

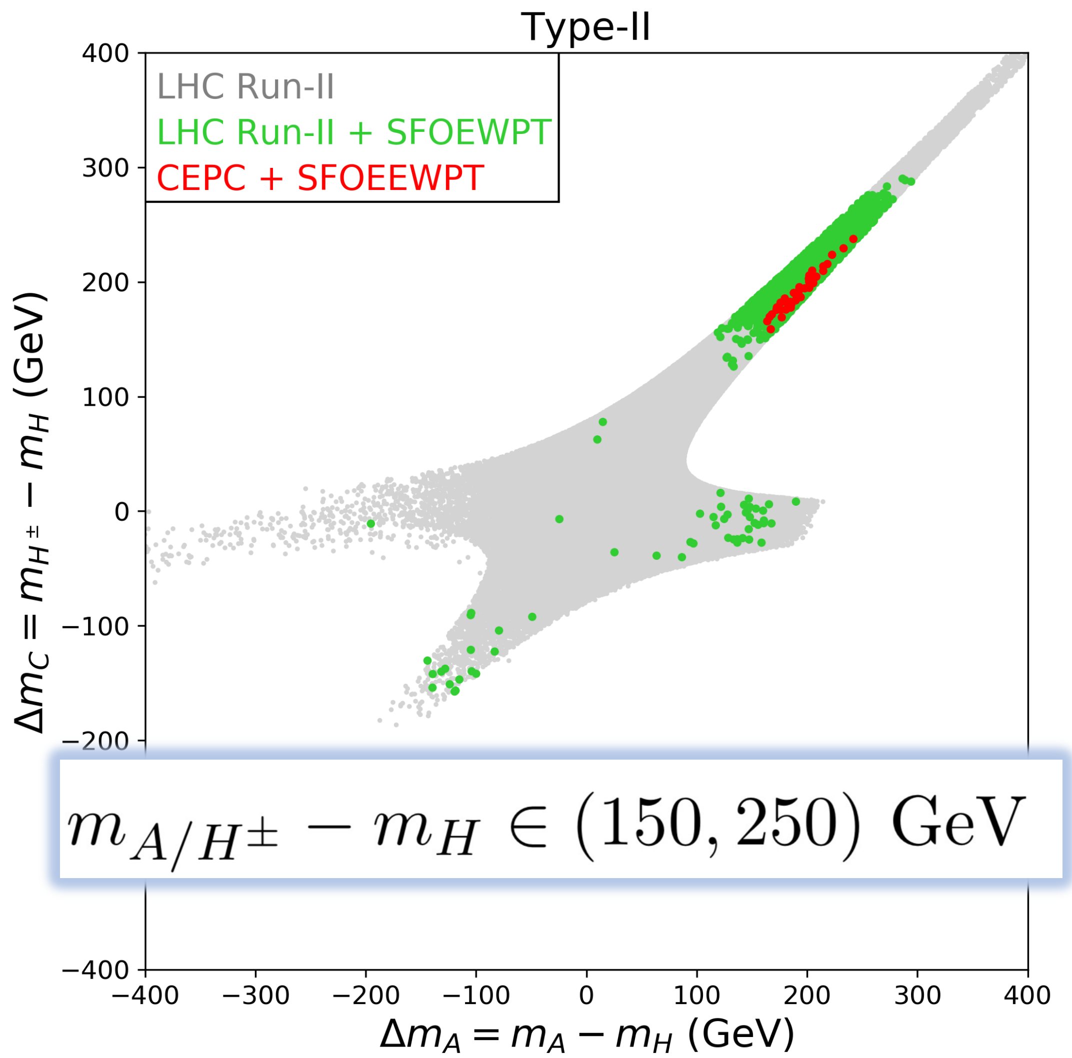
# Results: Type-II



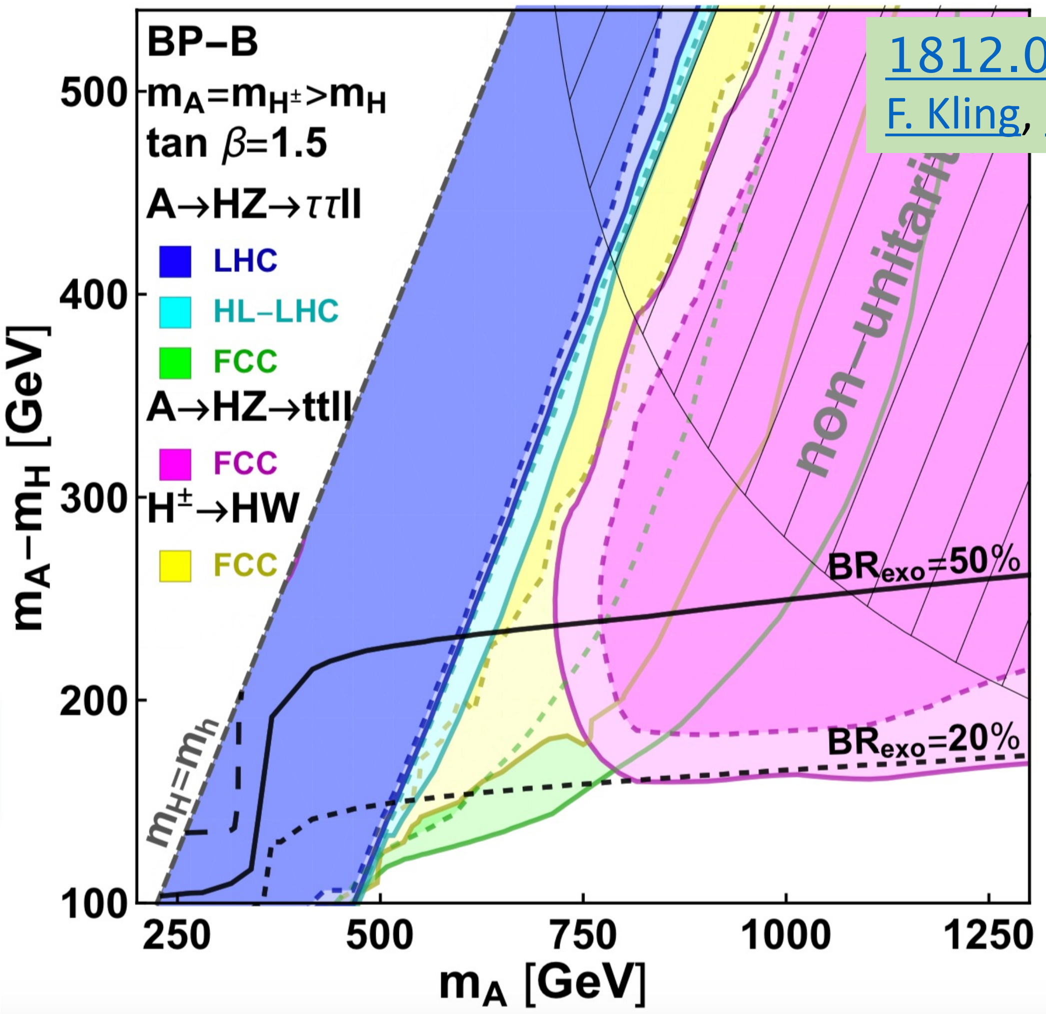




$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$

# Future

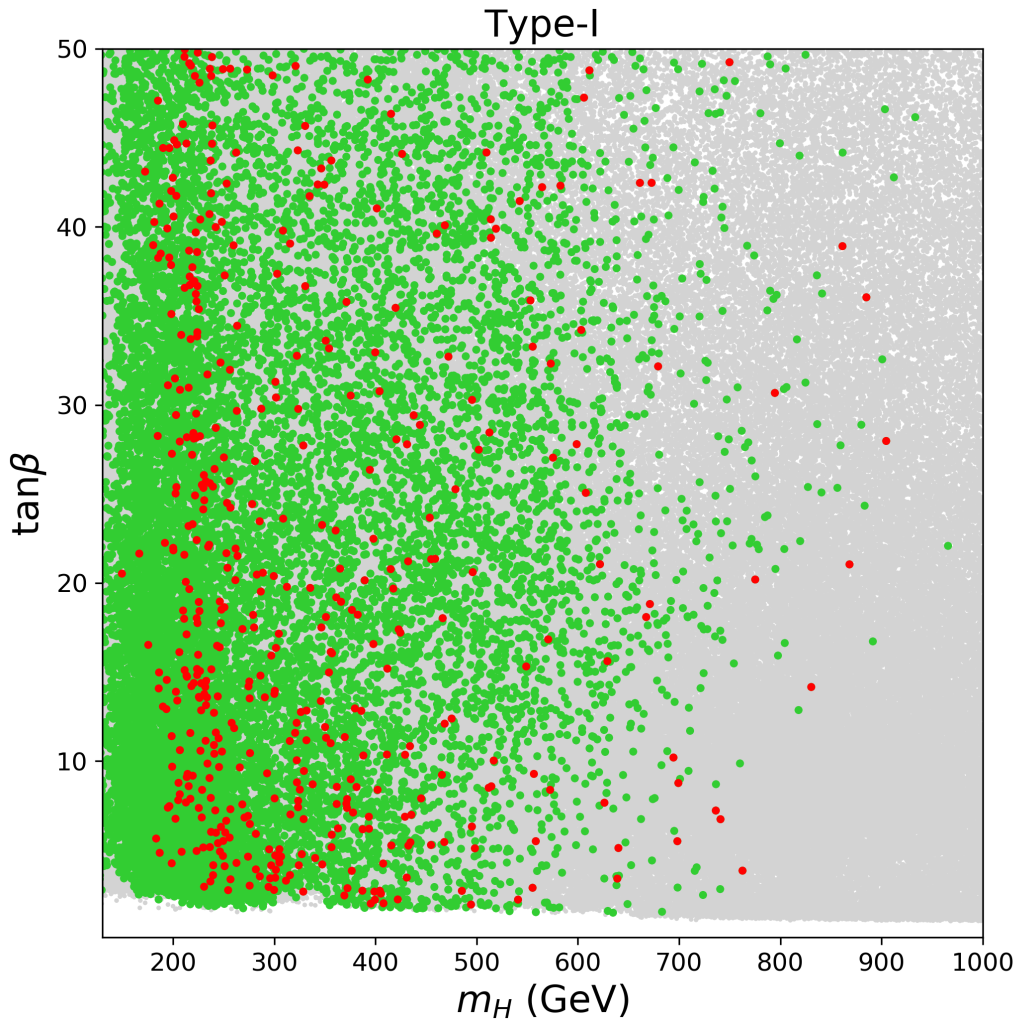


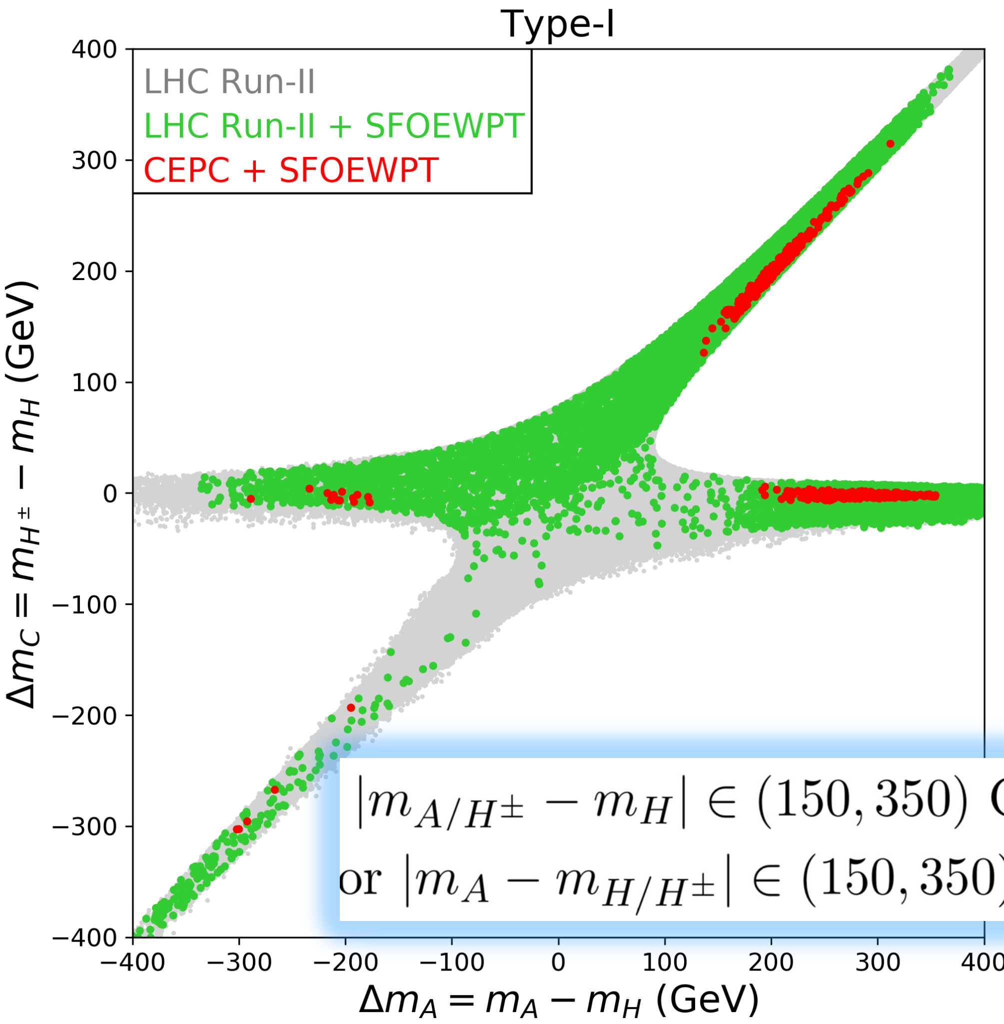

$$m_{A/H^\pm} - m_H \in (150, 250)\ \mathrm{GeV}$$




1812.01633
F. Kling, H. Li, etc

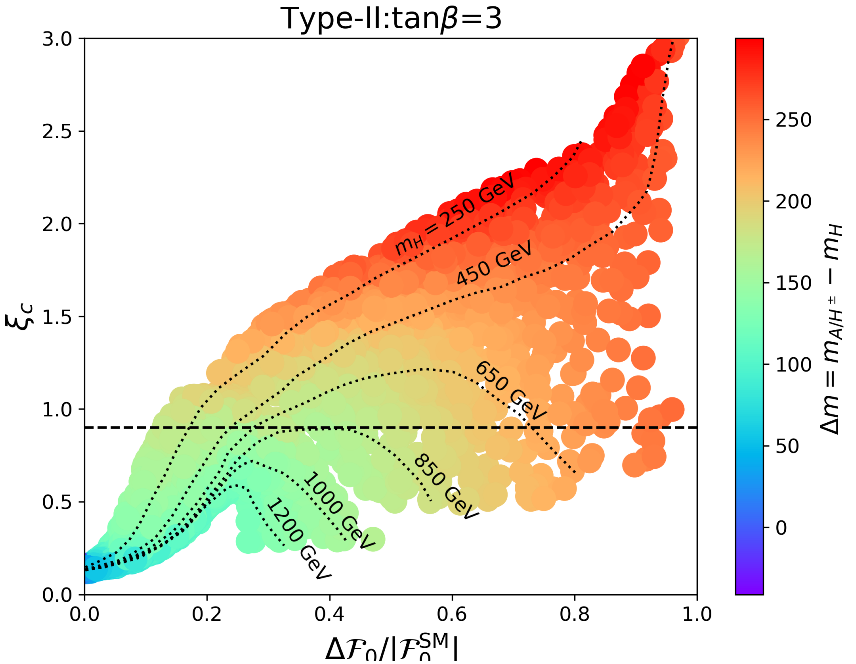
# Results: Type-I

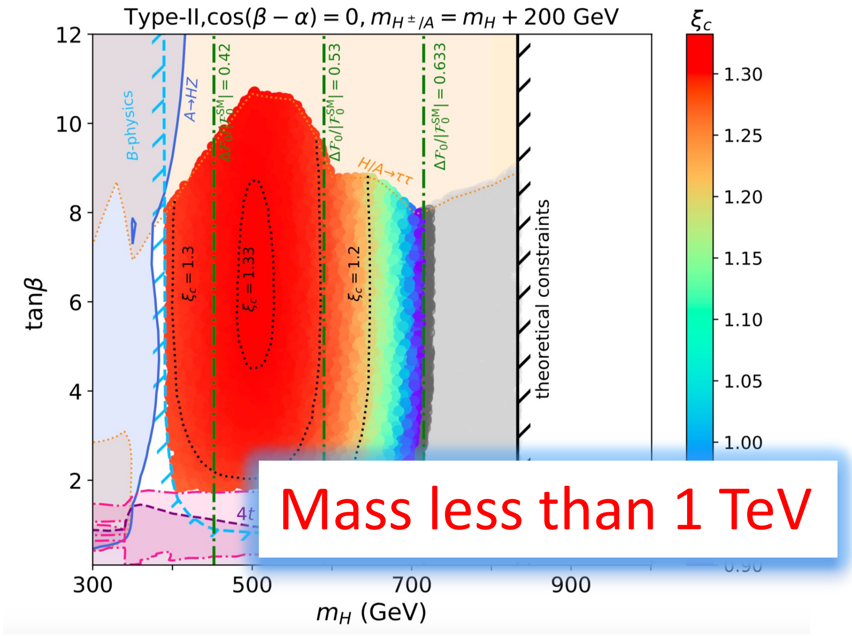


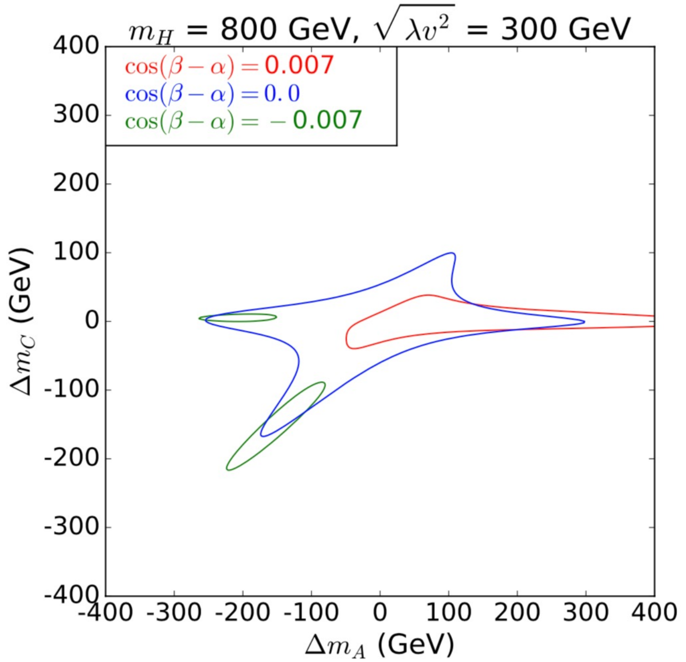

$|m_{A/H^\pm} - m_H| \in (150, 350)$ GeV
or $|m_A - m_{H/H^\pm}| \in (150, 350)$ GeV

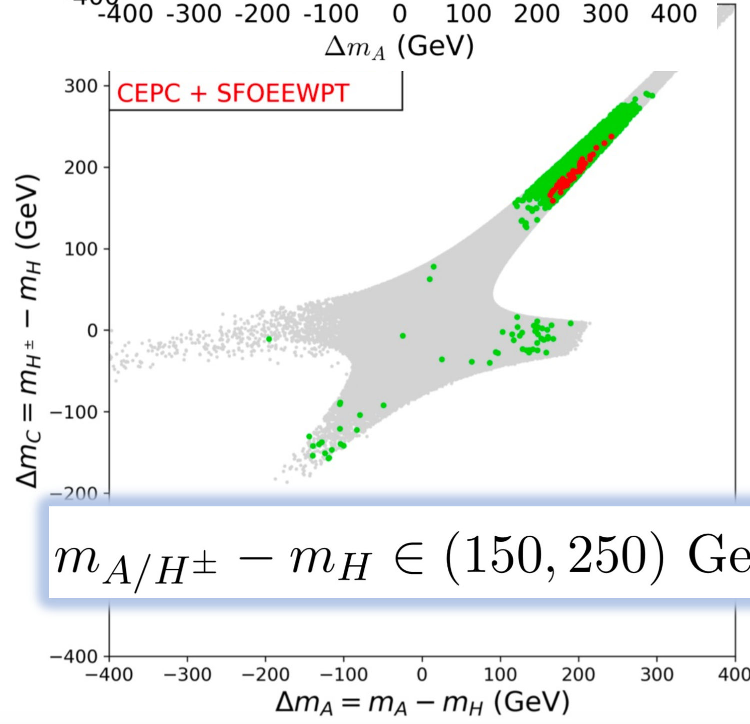
# Conclusion



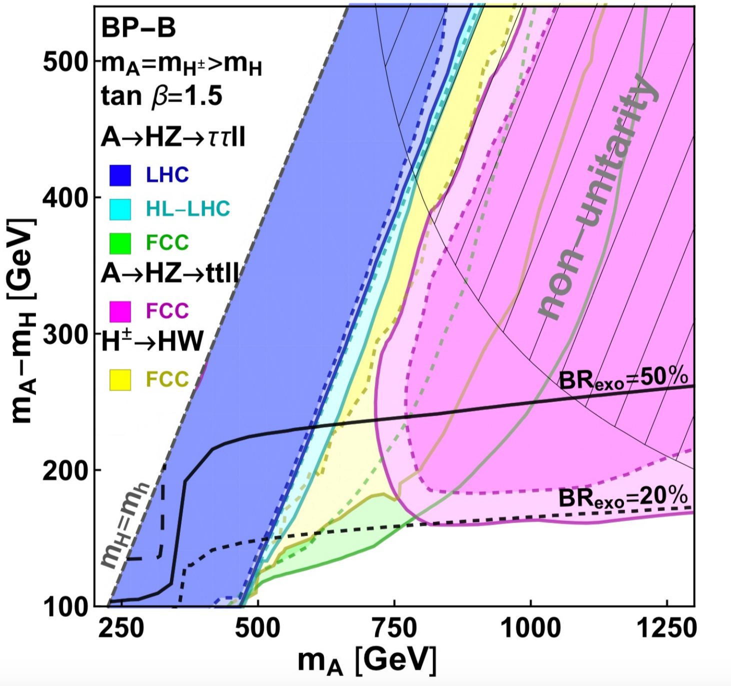




Mass less than 1 TeV




$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$



Thanks for your attention!

Questions ?

# Backup

# 2HDM: theoretical consideration

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2},$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

- Unitary $\quad |\lambda_i| \leq 4\pi$

- Perturbativity $\quad |\Lambda_i \leq 16\pi|$

$$\Lambda_{1,2} = \lambda_3 \pm \lambda_4,$$

$$\Lambda_{3,4} = \lambda_3 \pm \lambda_5,$$

$$\Lambda_{5,6} = \lambda_3 + 2\lambda_4 \pm 3\lambda_5,$$

$$\Lambda_{7,8} = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right],$$

$$\Lambda_{9,10} = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2}\right],$$

$$\Lambda_{11,12} = \frac{1}{2}\left[3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}\right]$$

# 2HDM: theoretical consideration

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$

- Unitary $|\lambda_i| \leq 4\pi$

- Perturbativity $|\Lambda_i \leq 16\pi|$

$\cos(\beta - \alpha) = 0,$

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

$$\begin{aligned} v^2\lambda_1 &= m_h^2 + t_\beta^2 \lambda v^2, \\ v^2\lambda_2 &= m_h^2 + \lambda v^2 / t_\beta^2, \\ v^2\lambda_3 &= m_h^2 + \lambda v^2, \\ v^2\lambda_4 &= -\lambda v^2, \\ v^2\lambda_5 &= -\lambda v^2. \end{aligned}$$

2 Free parameters