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Probing EWPT in 2HDM with LHC and Future Lepton Colliders

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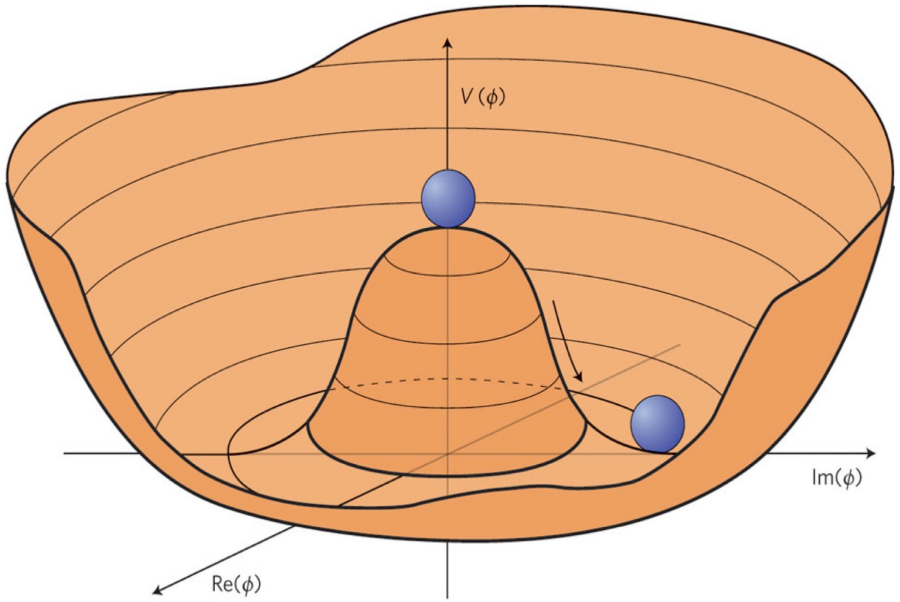
2011.04540 (WS, A G. Williams, M. Zhang)
2204.05085 (HY. Song, WS, M. Zhang)

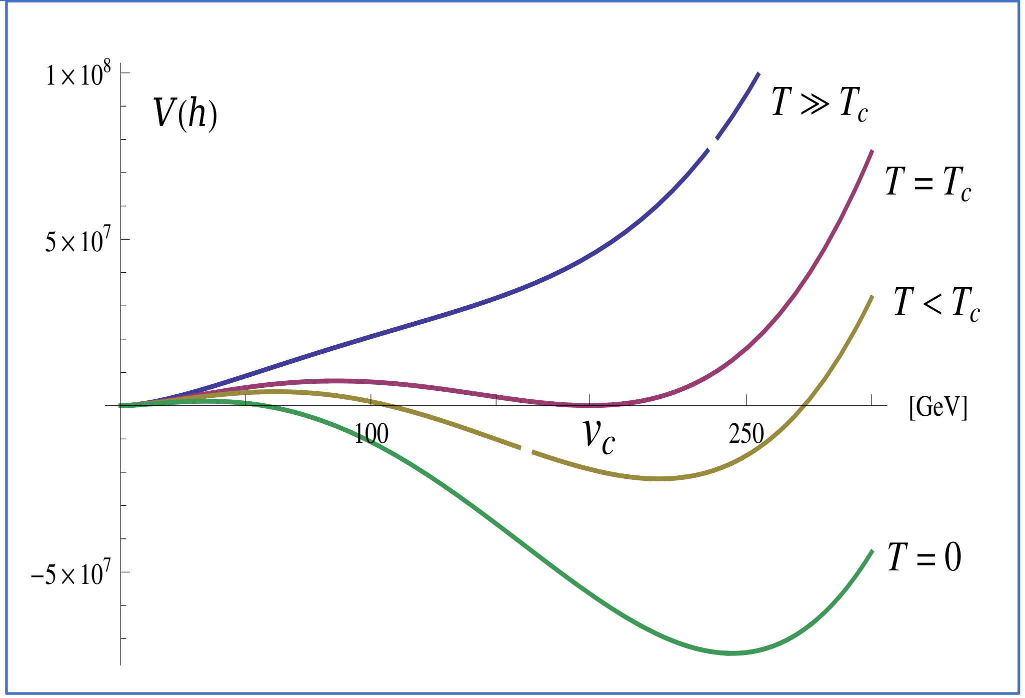
Outline

- 2HDM and Phase Transition
- Higgs/Z-pole Precision Measurements
- Results: 3 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

BAU, PT ⟷ Higgs sector ⟷ LHC,CEPC, FCC-ee…

2HDM: Brief Introduction

- Two Higgs Doublet Model

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

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

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

	Φ_1	Φ_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)

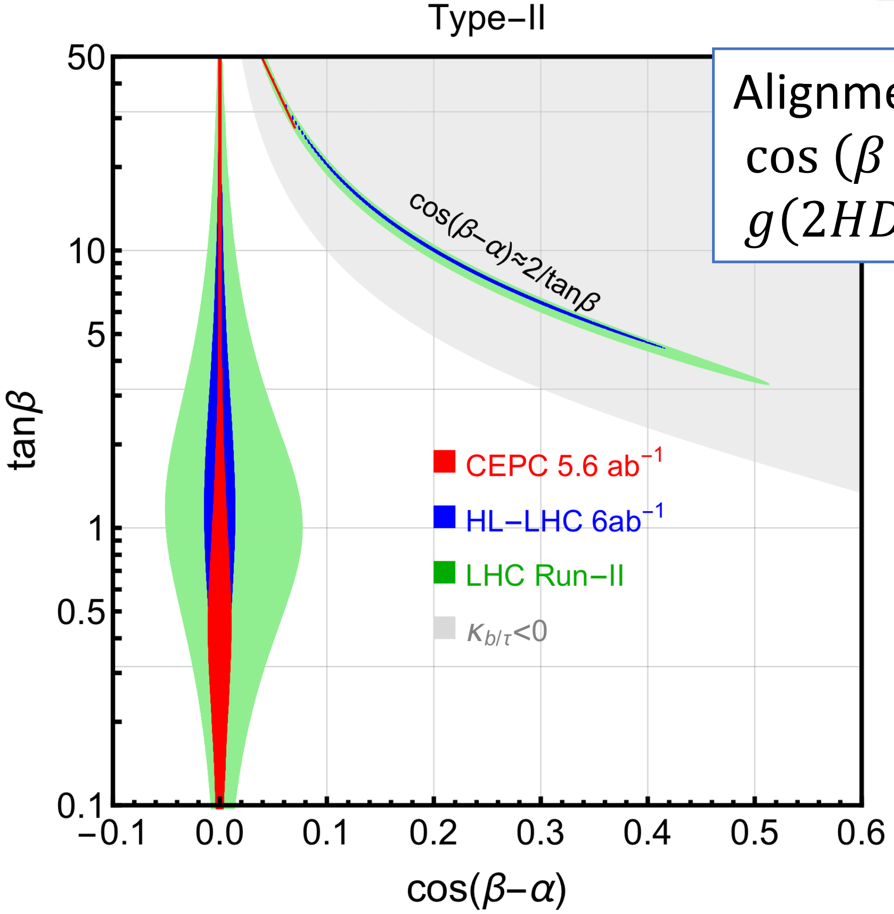
$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

v → 246 GeV; m_h → 125. GeV

Soft Z_2 symmetry breaking: m_{12}^2

2HDM: precision

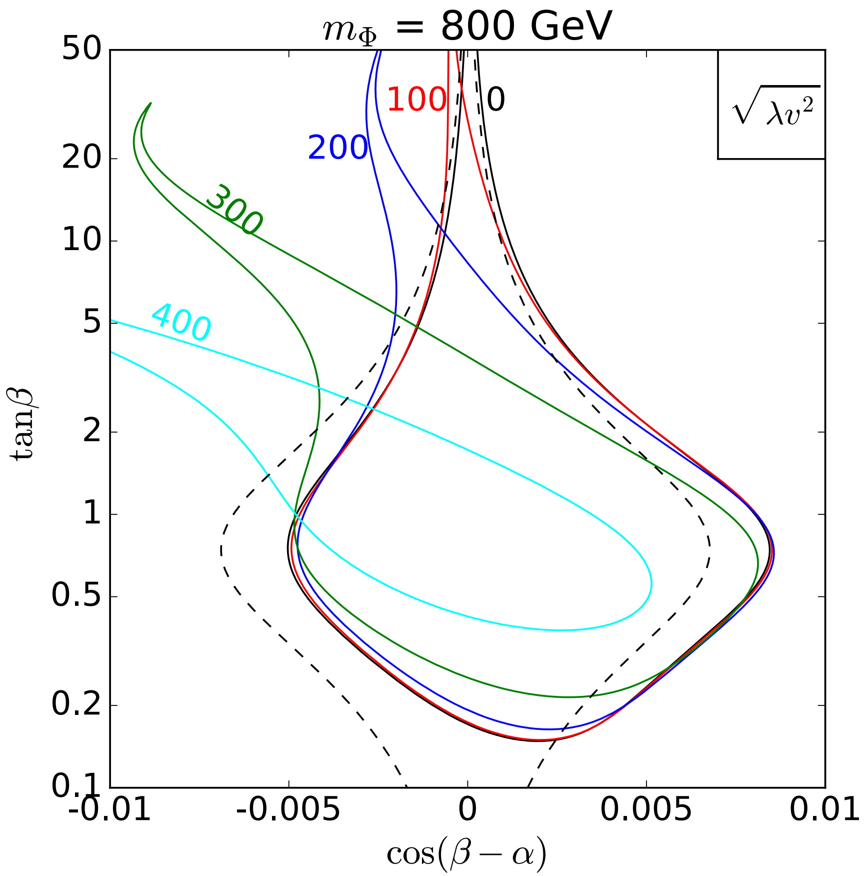
Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$



Alignment limit :

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

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



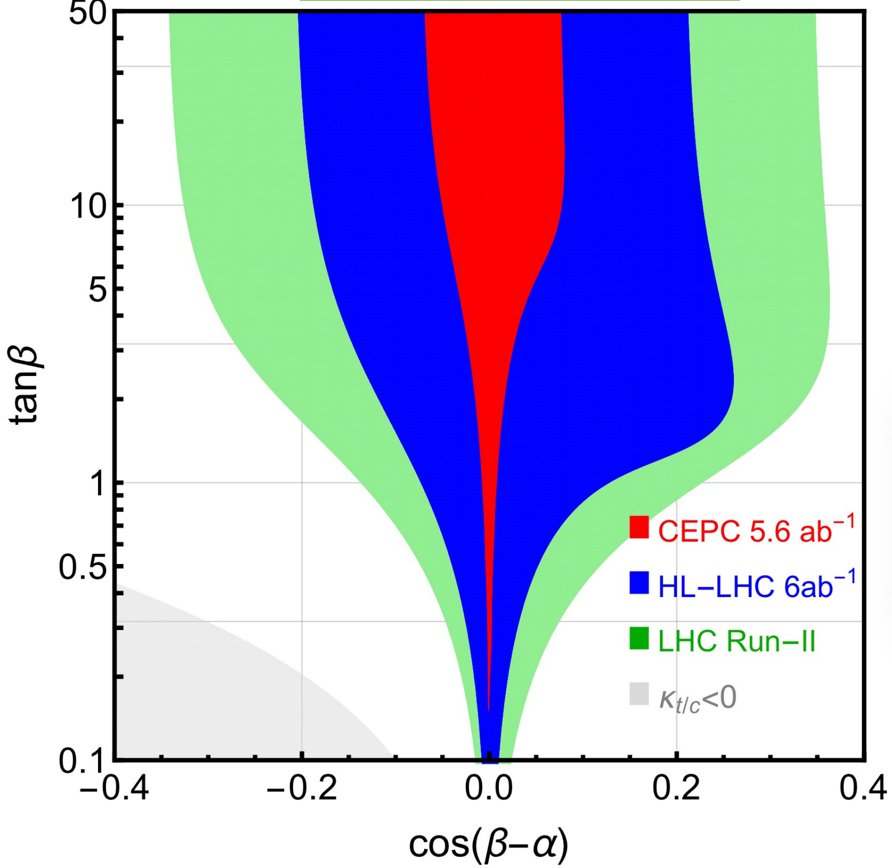
1910.06269 WS

1808.02037 N. Chen, T. Han, S. Su, WS, Y. Wu

2HDM: Tree Level

Model	κ_V	κ_u	κ_d	κ_ℓ
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 :

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

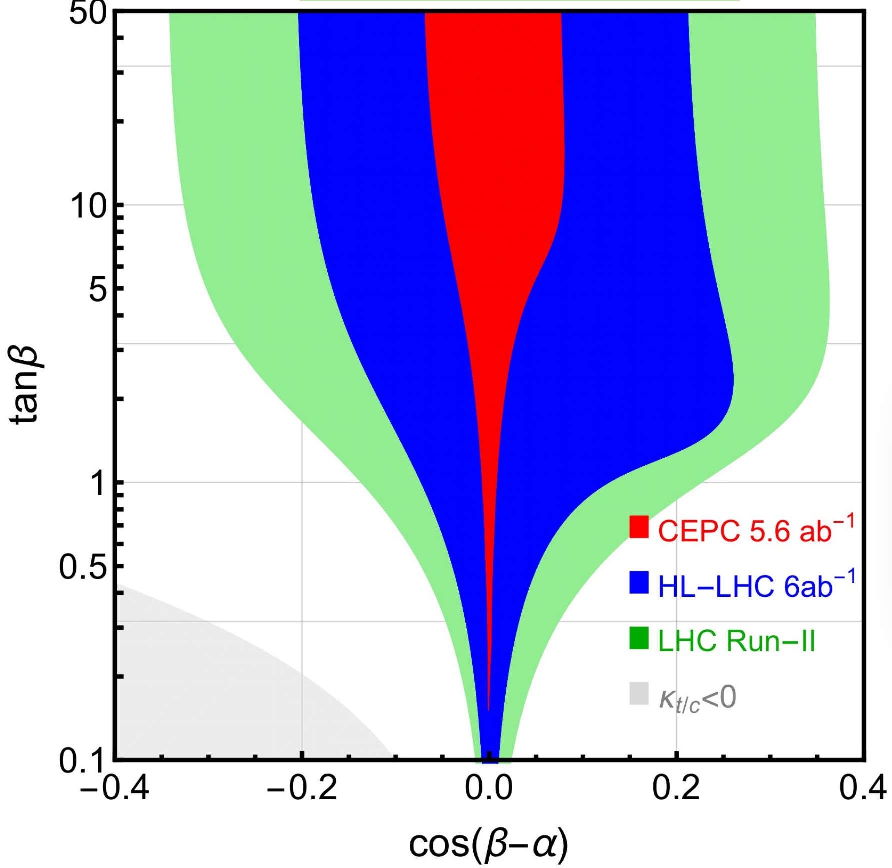
$g(2HDM)=g(SM)$

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

2HDM: Tree Level

Model	κ_V	κ_u	κ_d	κ_ℓ
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	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

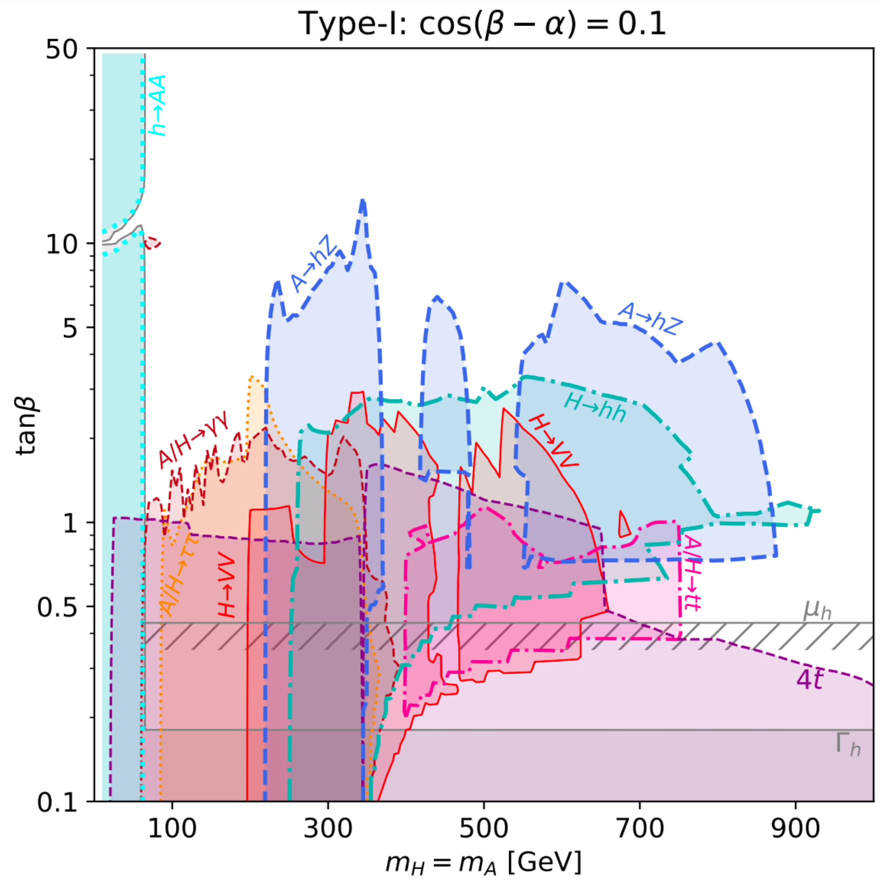
2HDM Type-I



Alignme
$\cos(\beta$
$g(2HD$

$\Delta\kappa_u,$

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



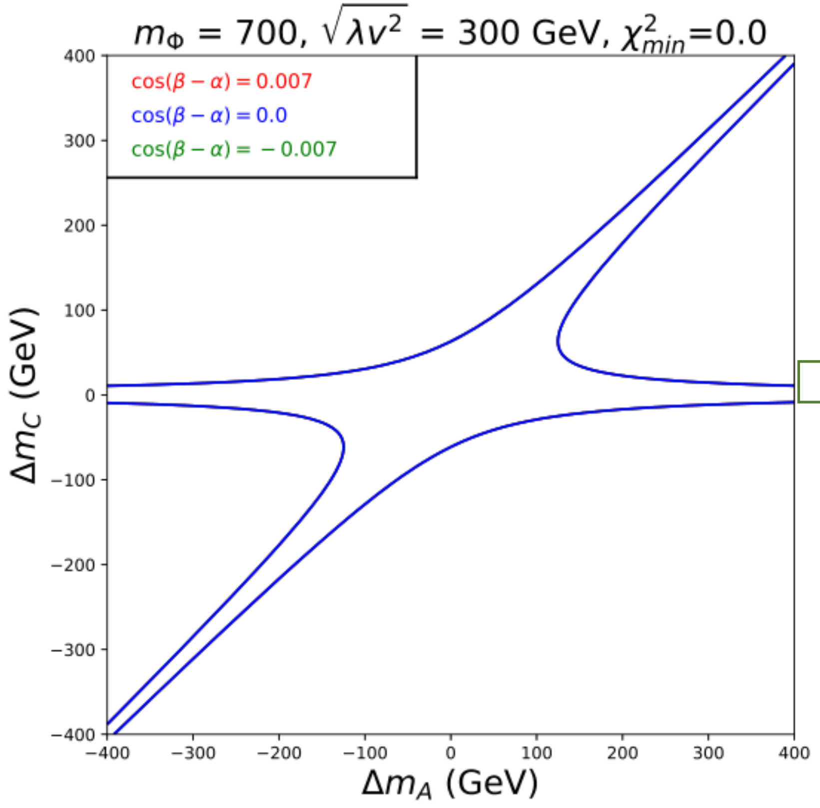
2004.04172
F. Kling, S. Su, WS

2HDM: *Loop*

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:*Loop*

[1808.02037](1808.02037) N. Chen, T. Han, S. Su, WS, Y. Wu

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

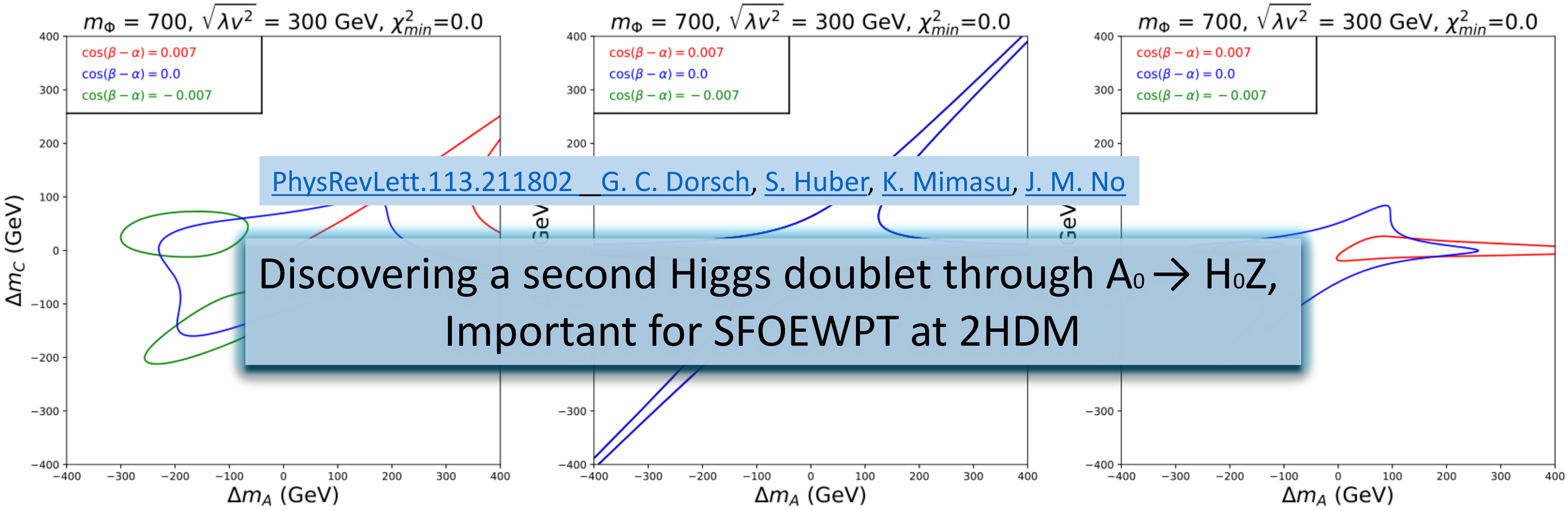
2HDM:Loop

$m_H = 700\ \mathrm{GeV}$

Complementary to each other

2HDM: *Loop*

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



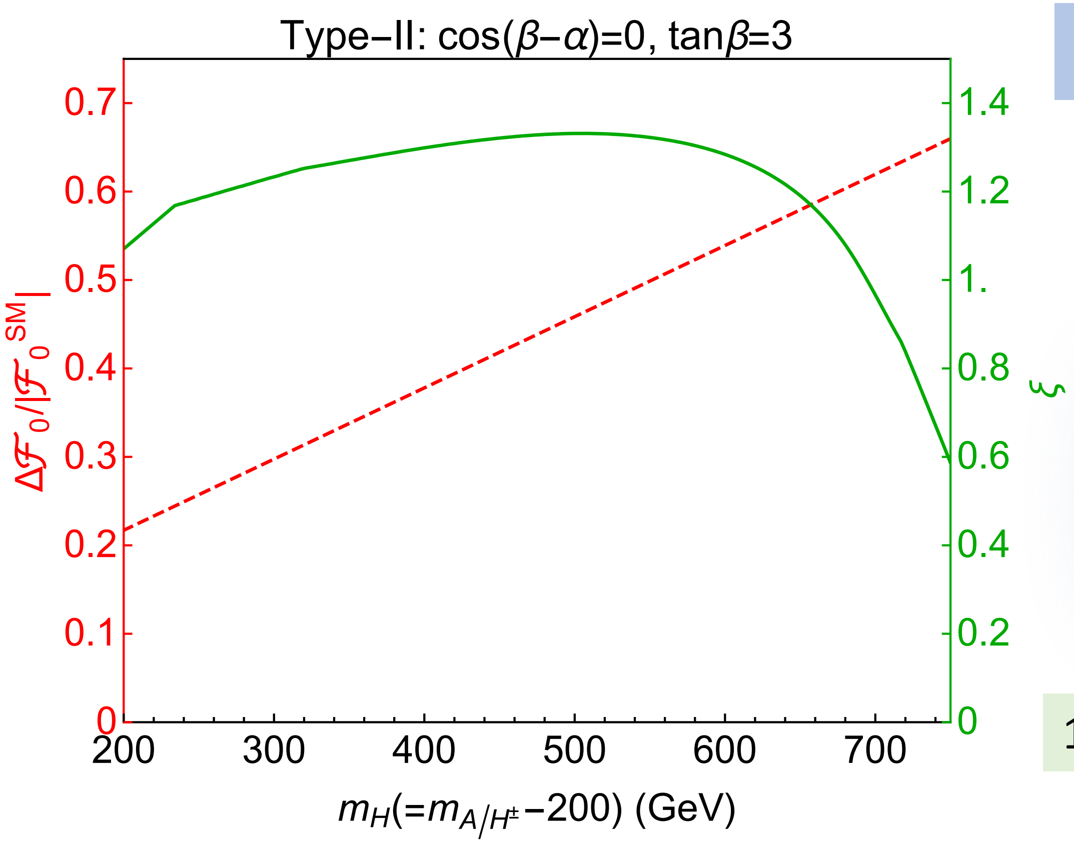
PhysRevLett.113.211802 __G. C. Dorsch, S. Huber, K. Mimasu, J. M. No

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

$m_H = 700$ GeV

Complementary to each other

PT vs. vacuum uplifting



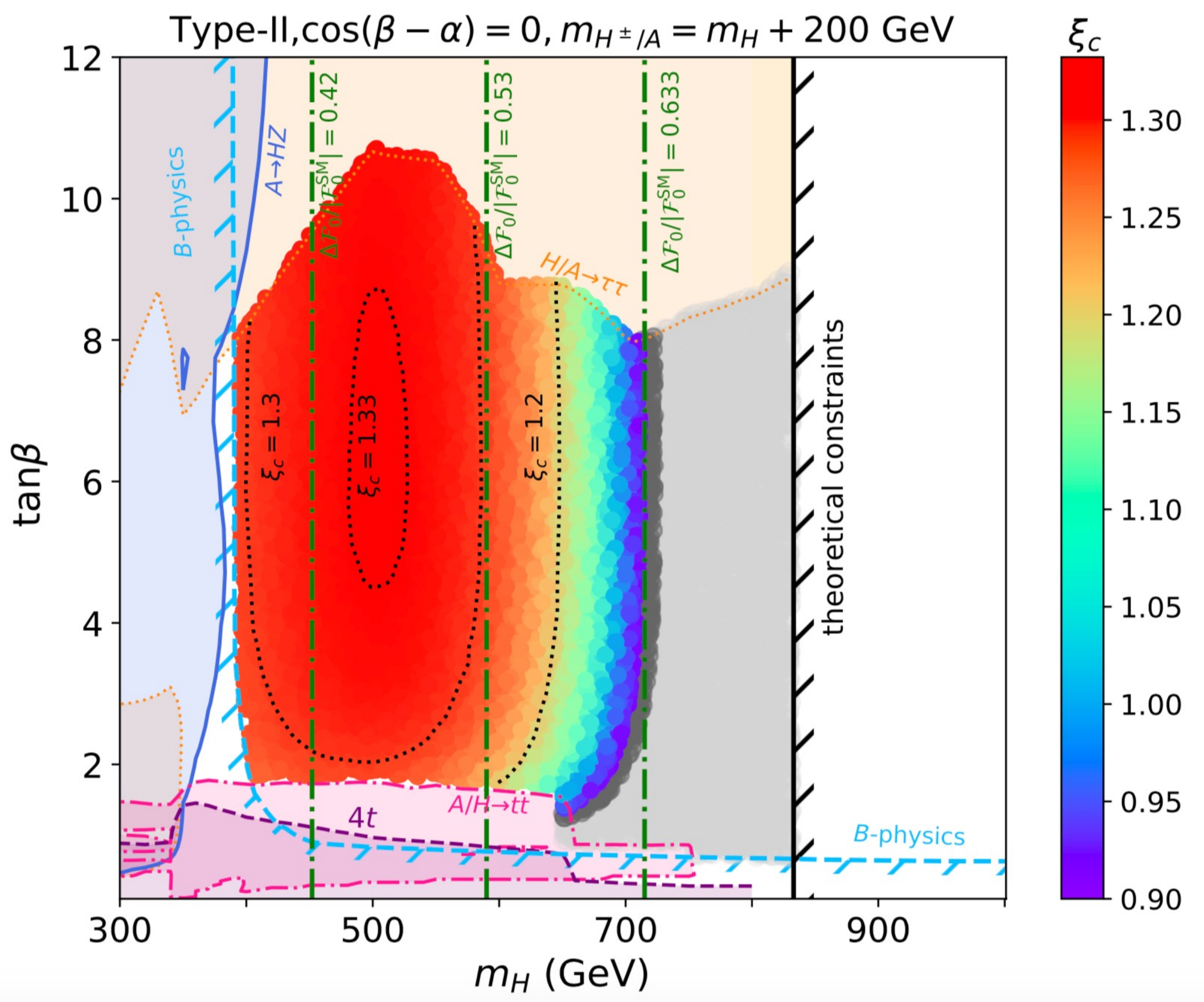
Vacuum energy F

$$\mathcal{F}_0^{\rm SM} = -\frac{m_h^2 v^2}{8} + \frac{1}{64\pi^2}\left(3m_W^4 + \frac{3}{2}m_Z^4 - 6m_t^4\right) + \frac{m_h^4}{64\pi^2}(3+\log 2)$$

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

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

Results: Case-1

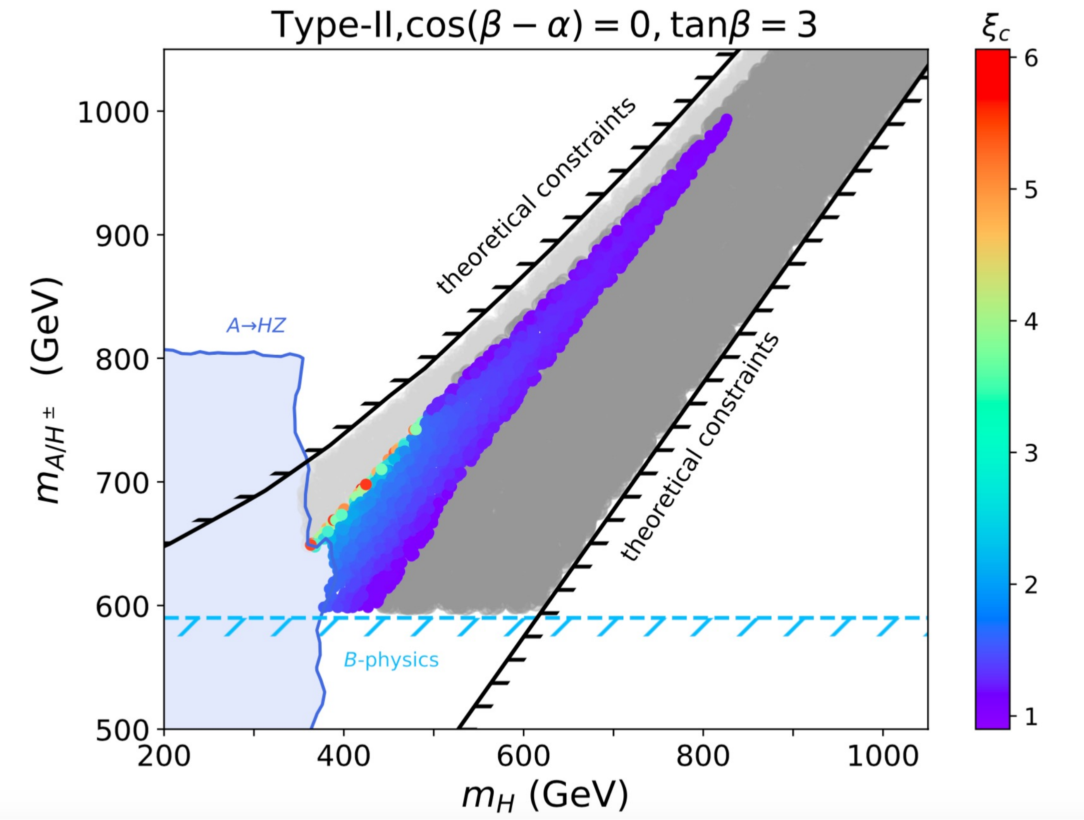


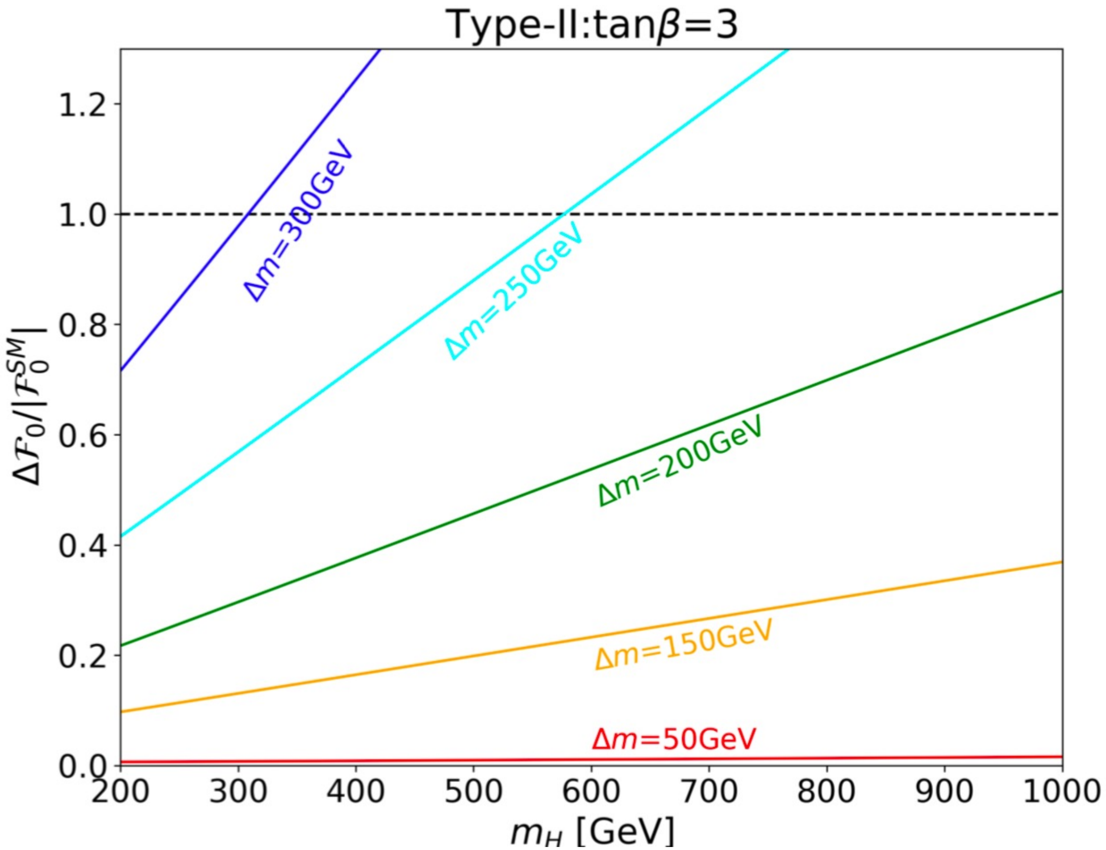
Type-II
fixed mass splitting 200 GeV

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

Results: Case-2

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





Too large or small mass splitting can not generate SFOEWPT

Results: Case-2

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

High T approximation:

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

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

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

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

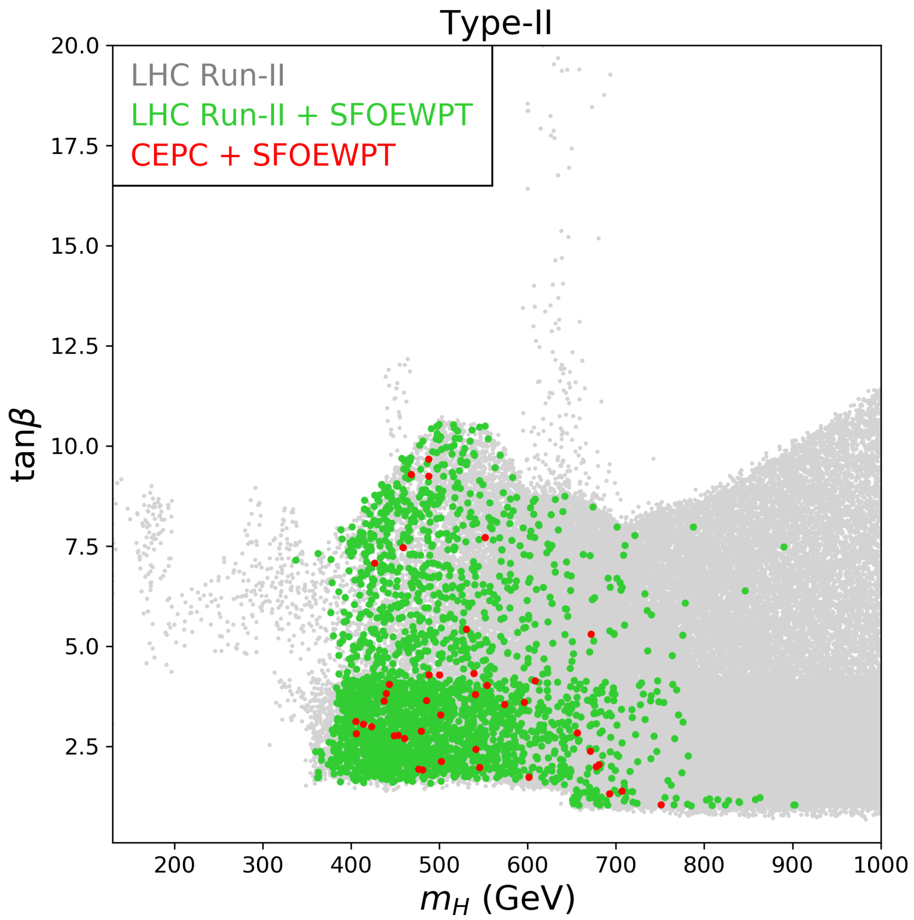
Vacuum uplifting:

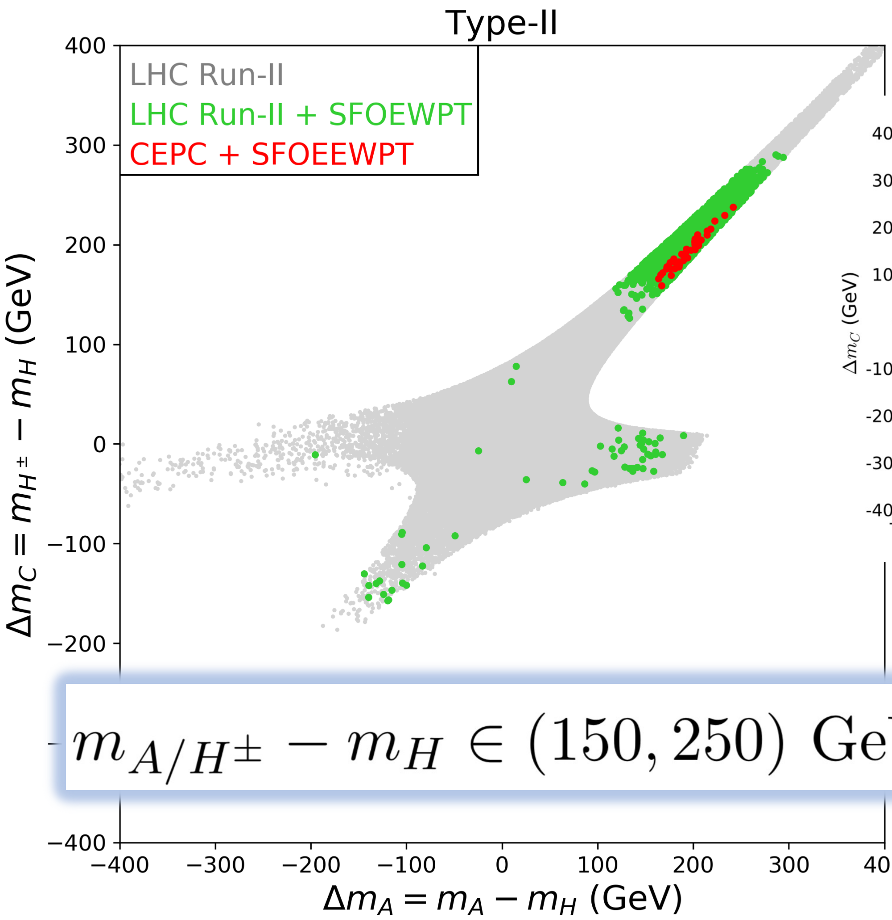
$$\Delta\mathcal{F}_0=\frac{1}{64\pi^2}\left[\left(m_h^2-2M^2\right)^2\left(\frac{3}{2}+\frac{1}{2}\log\left[\frac{4m_Am_Hm_{H^\pm}^2}{\left(m_h^2-2M^2\right)^2}\right]\right)\right.$$

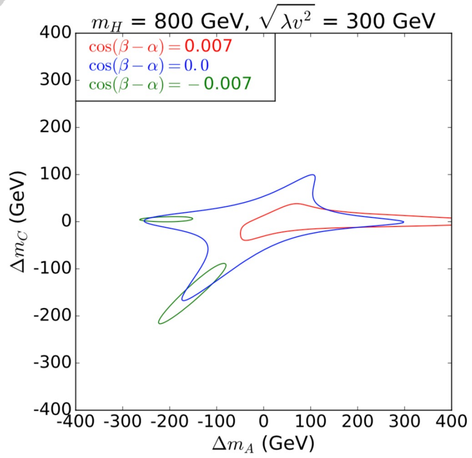
$$\left.+\frac{1}{2}\left(m_A^4+m_H^4+2m_{H^\pm}^4\right)+\left(m_h^2-2M^2\right)\left(m_A^2+m_H^2+2m_{H^\pm}^2\right)\right]$$

Too large or small mass splitting can not generate SFOEWPT

Results: Type-II

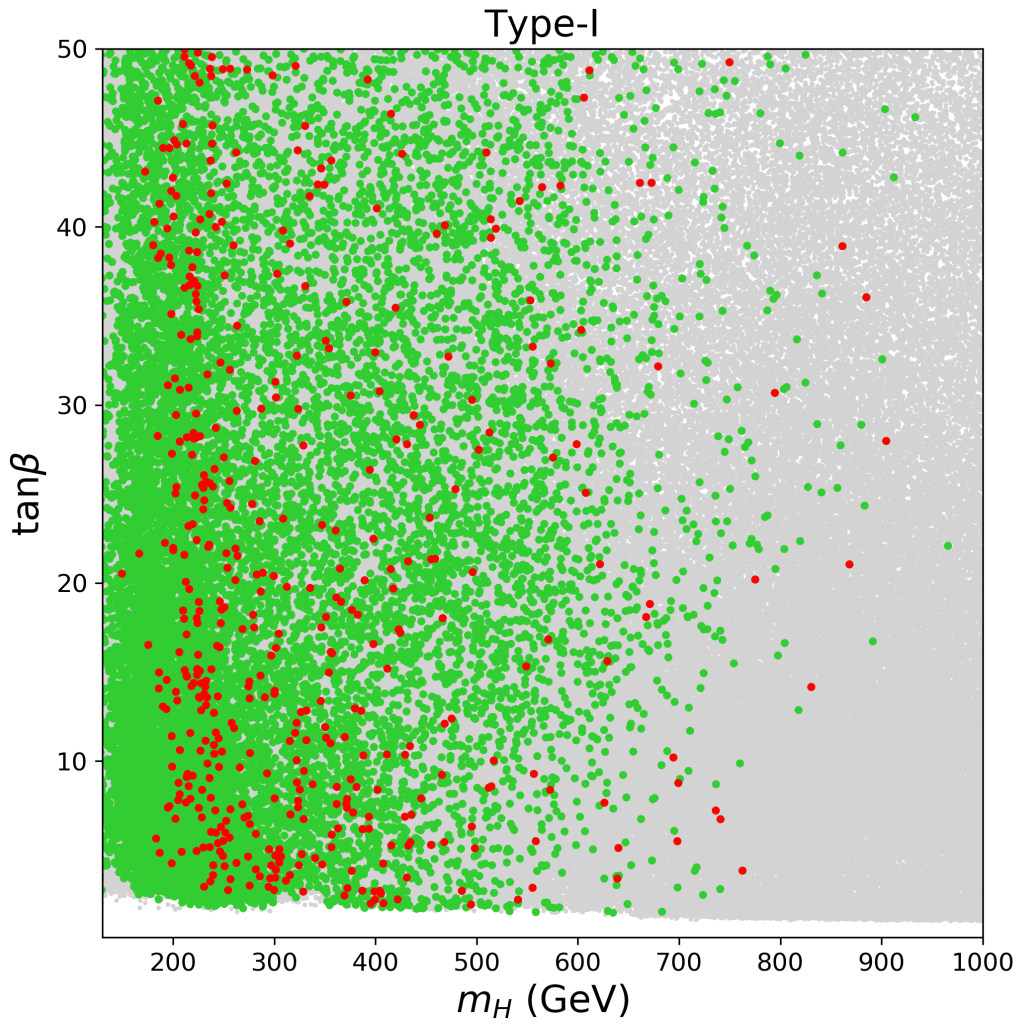


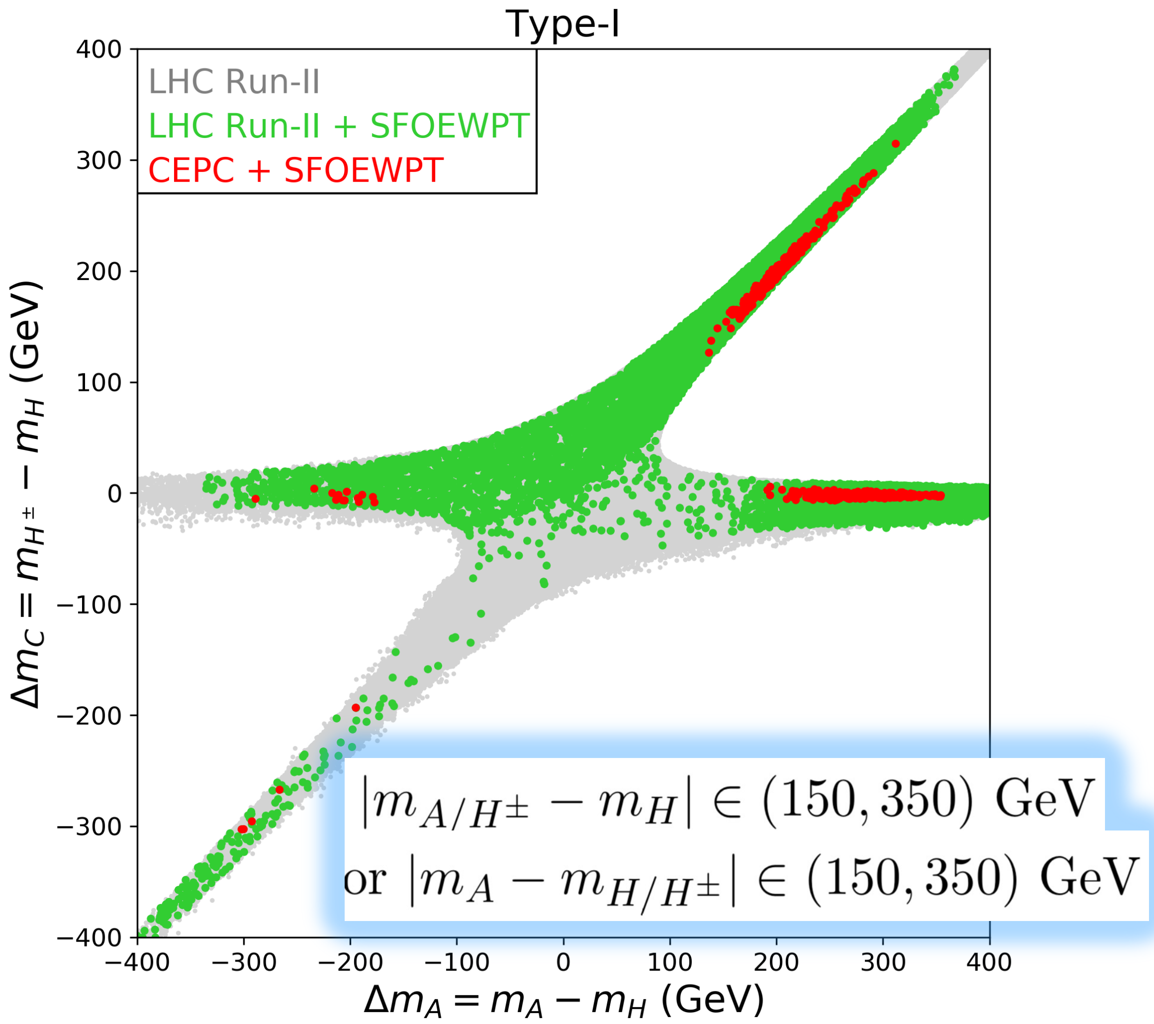




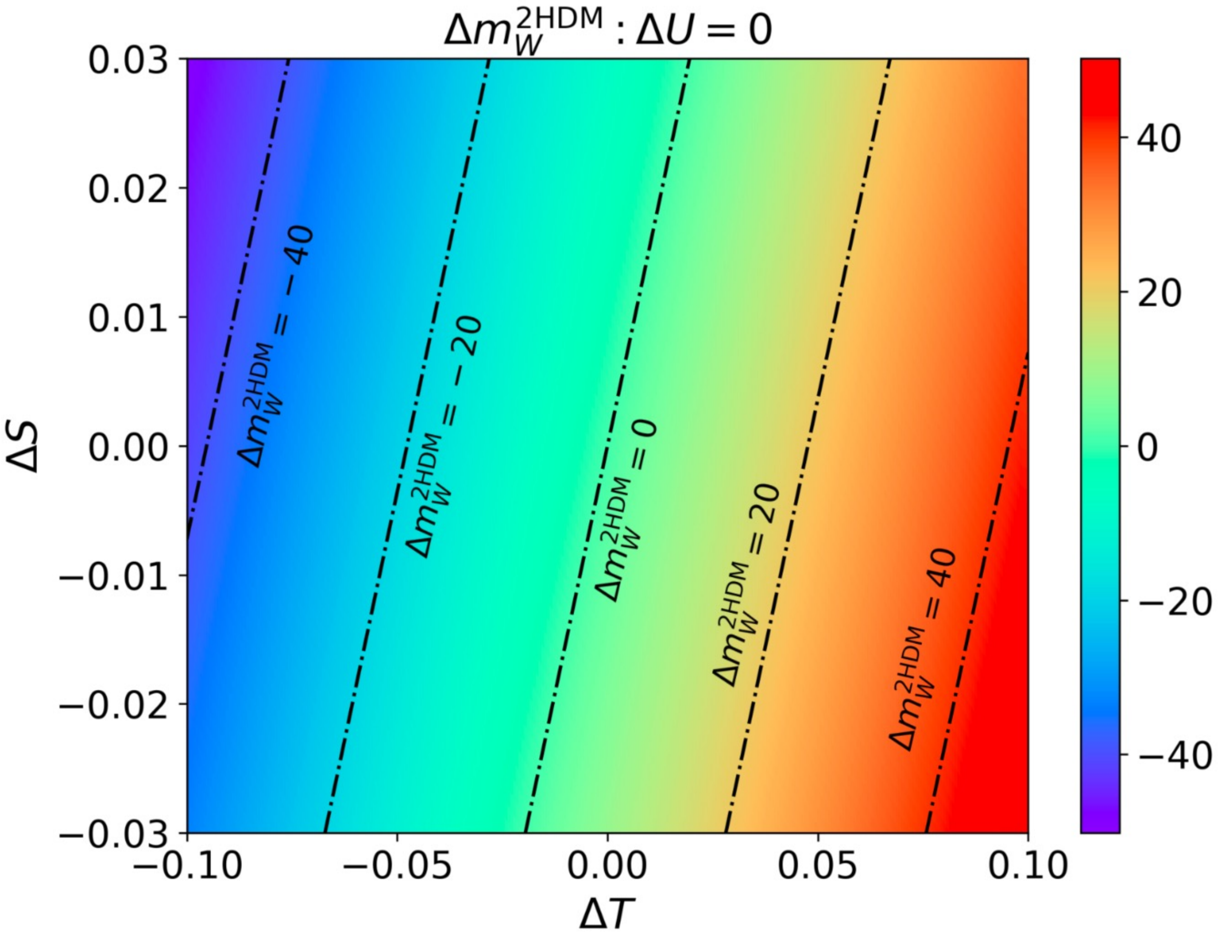
$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$

Results: Type-I



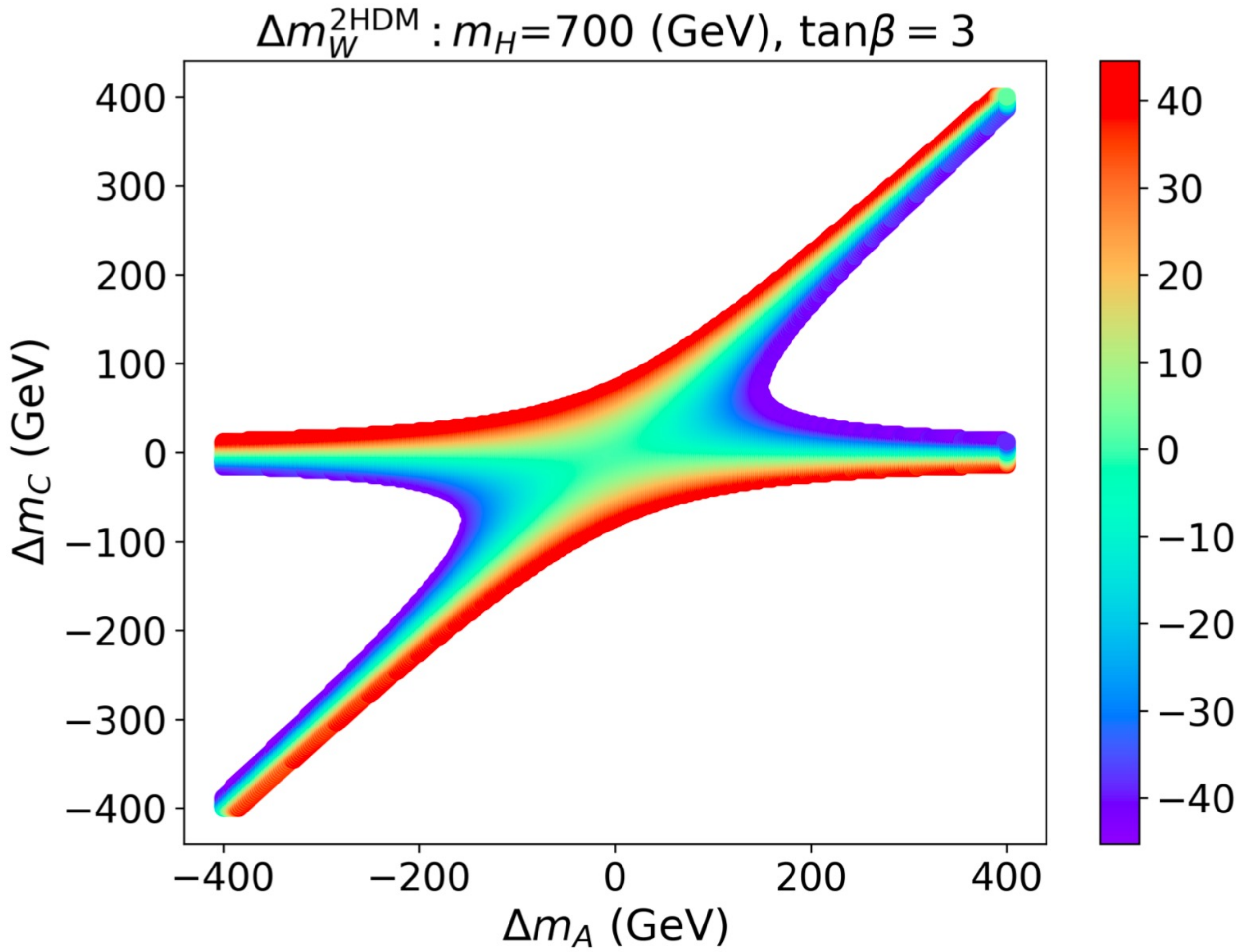


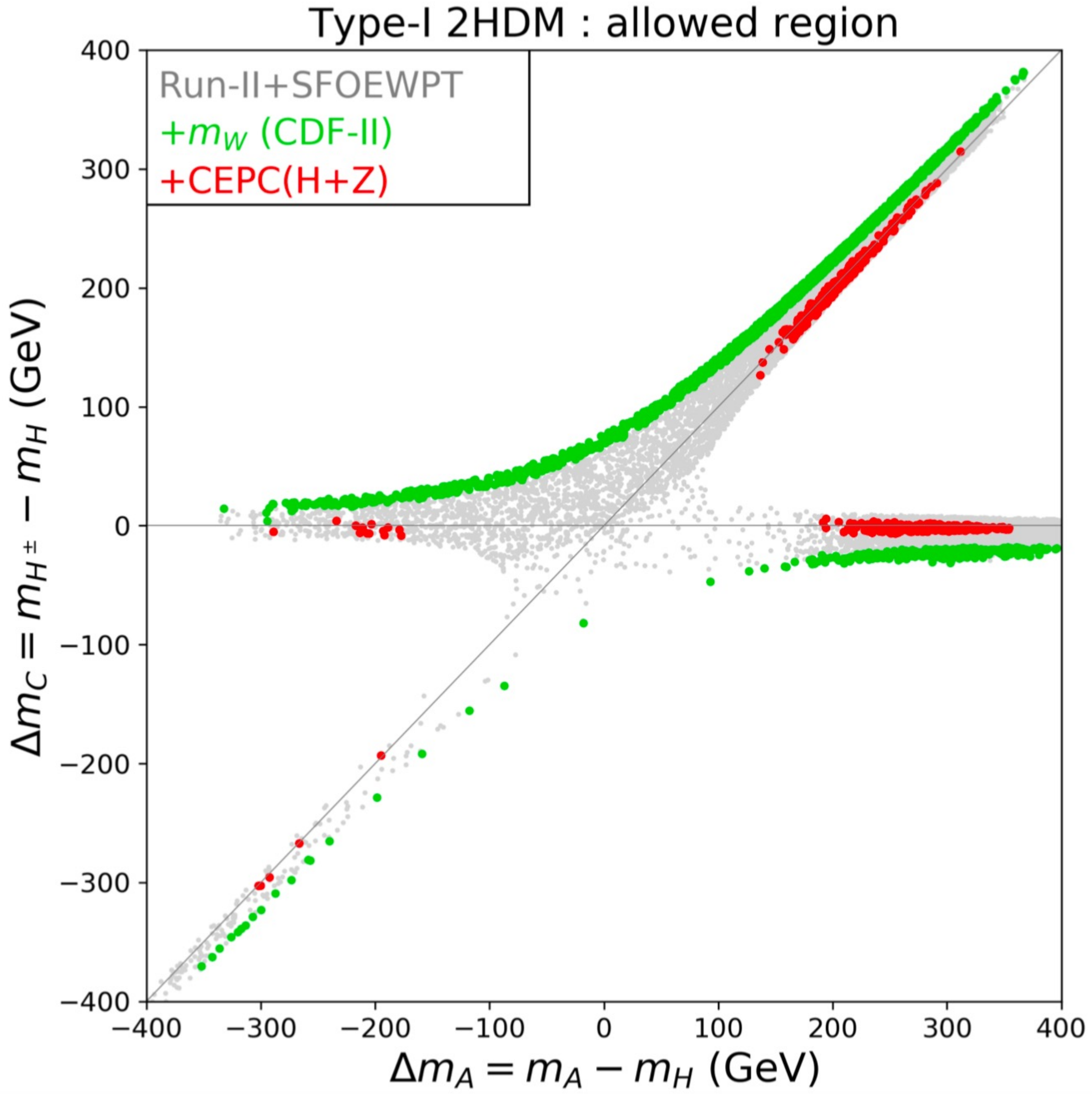
W mass



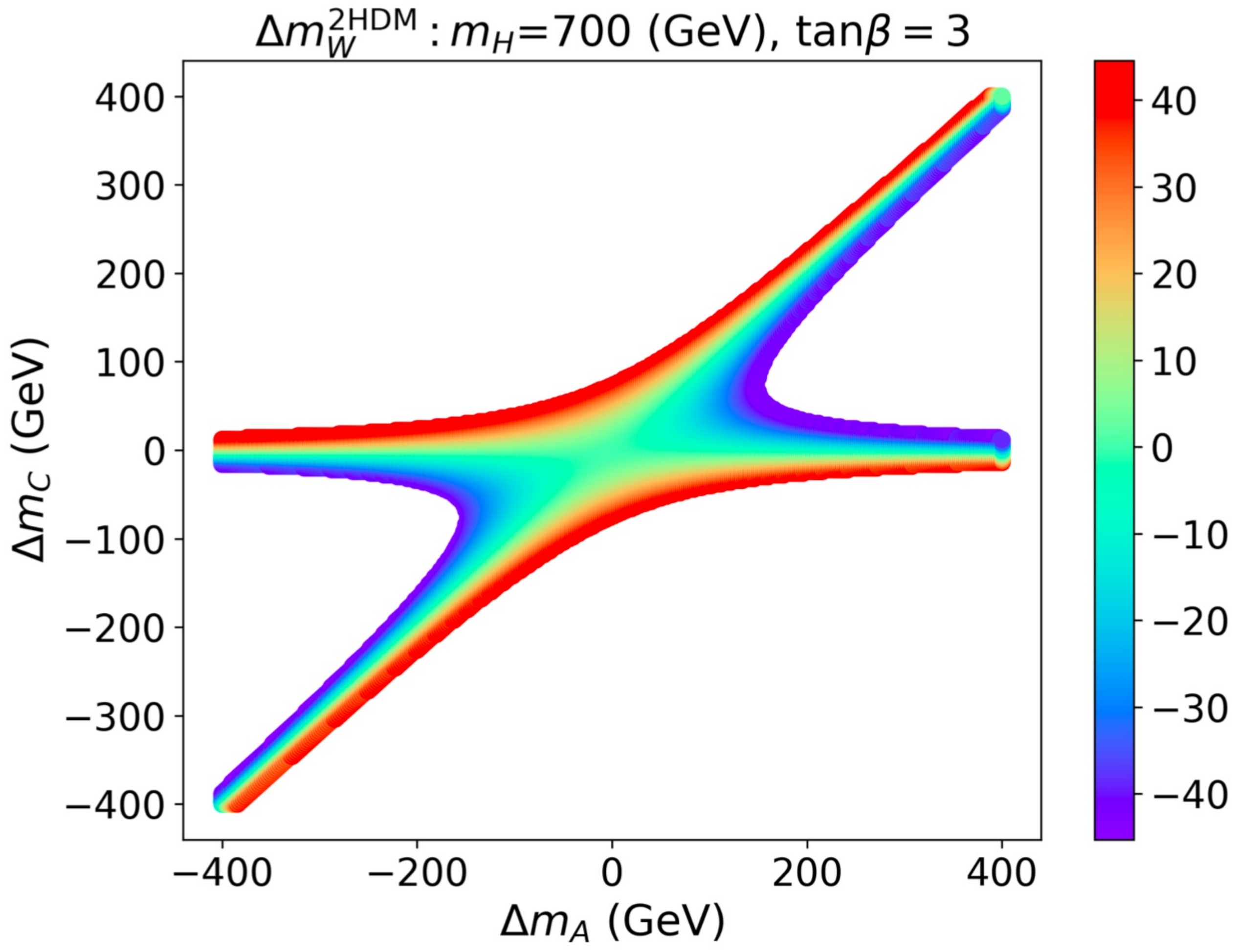
$\Delta m_W^{2HDM} : \Delta U = 0$
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
ΔS
−0.10
−0.05
0.00
0.05
0.10
ΔT
$\Delta m_W^{2HDM} = -40$
$\Delta m_W^{2HDM} = -20$
$\Delta m_W^{2HDM} = 0$
$\Delta m_W^{2HDM} = 20$
$\Delta m_W^{2HDM} = 40$
40
20
0
−20
−40

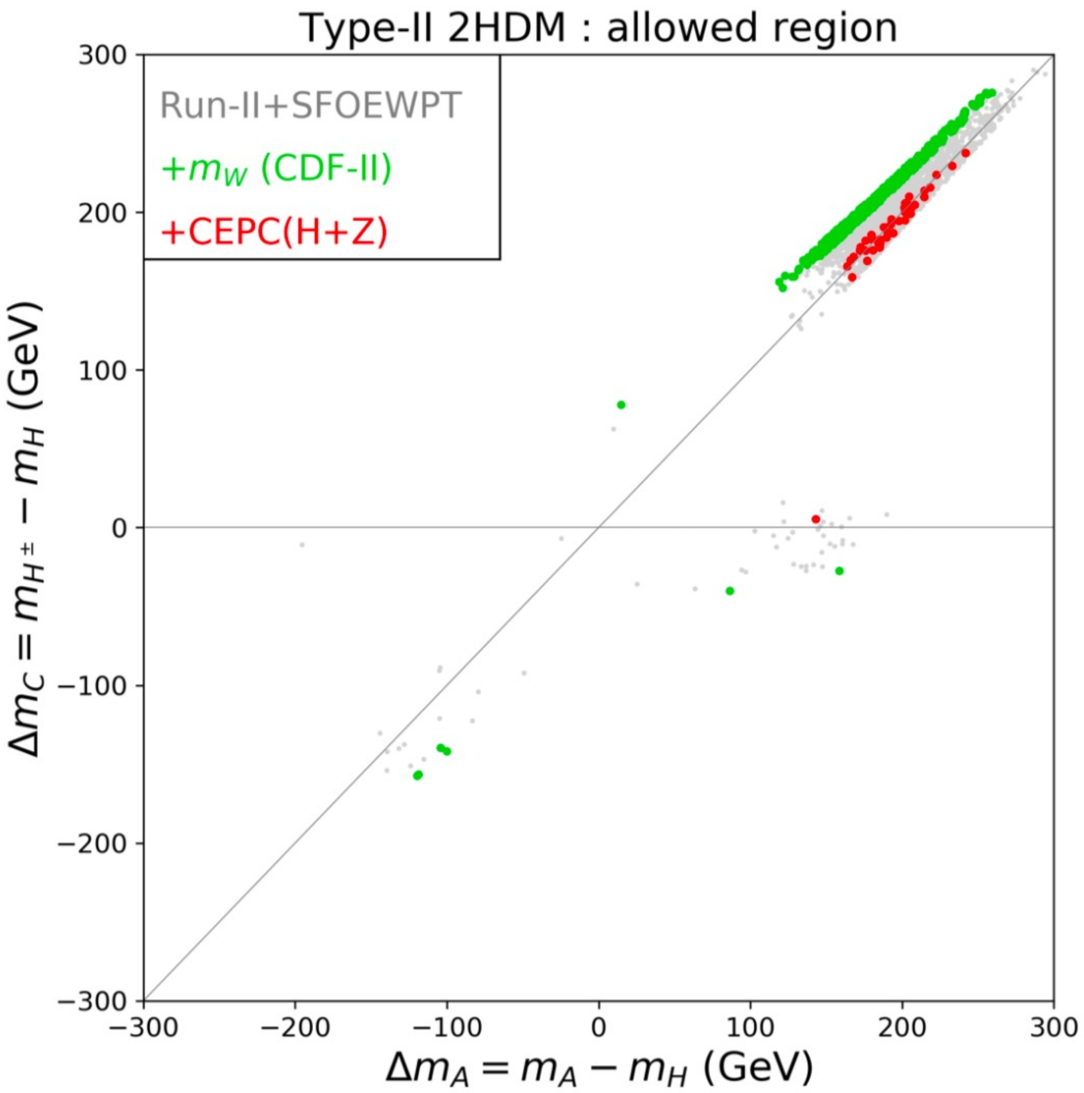
W mass


$\Delta m_W^{2HDM} : m_H$=700 (GeV), tan$\beta = 3$
Δm_C (GeV)
Δm_A (GeV)
400
300
200
100
0
−100
−200
−300
−400
40
30
20
10
0
−10
−20
−30
−40

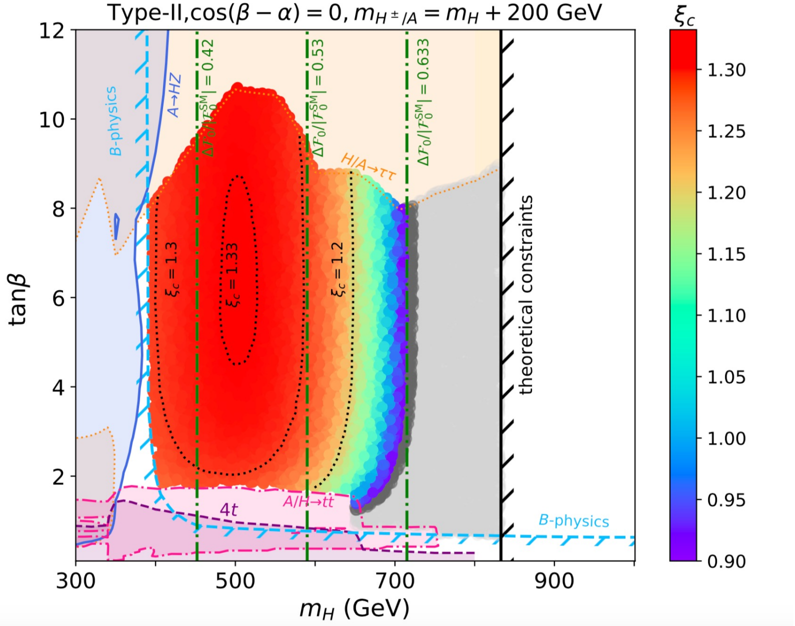

Type-I 2HDM : allowed region
Run-II+SFOEWPT
$+m_W$ (CDF-II)
+CEPC(H+Z)
$\Delta m_C = m_{H^\pm} - m_H$ (GeV)
$\Delta m_A = m_A - m_H$ (GeV)
400
300
200
100
0
−100
−200
−300
−400

W mass

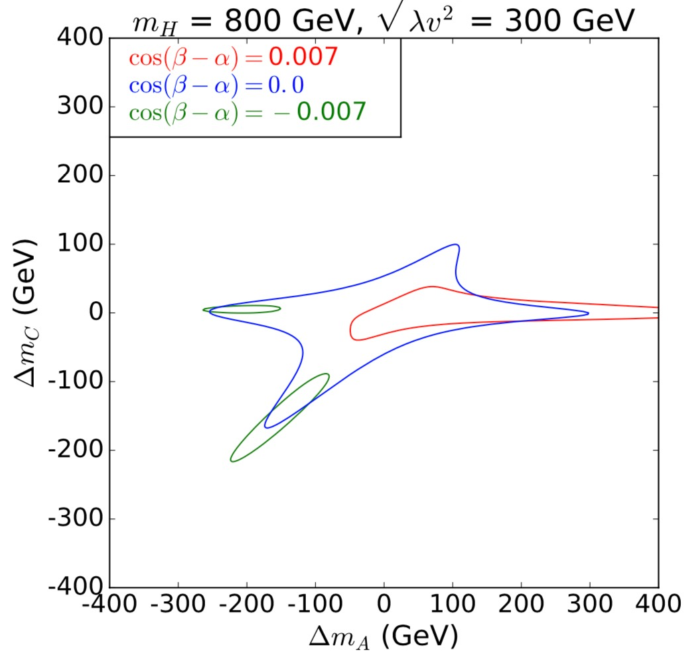

$\Delta m_W^{2HDM} : m_H$=700 (GeV), tan$\beta = 3$
400
300
200
100
0
−100
−200
−300
−400
Δm_C (GeV)
−400
−200
0
200
400
Δm_A (GeV)
40
30
20
10
0
−10
−20
−30
−40

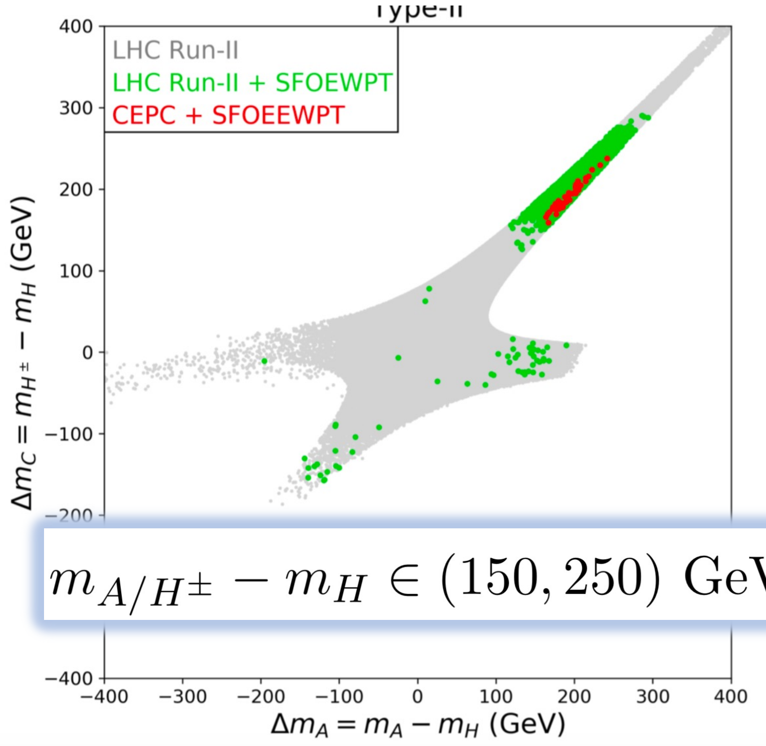

Type-II 2HDM : allowed region
Run-II+SFOEWPT
$+m_W$ (CDF-II)
+CEPC(H+Z)
300
200
100
0
−100
−200
−300
$\Delta m_C = m_{H^\pm} - m_H$ (GeV)
−300
−200
−100
0
100
200
300
$\Delta m_A = m_A - m_H$ (GeV)

Conclusion

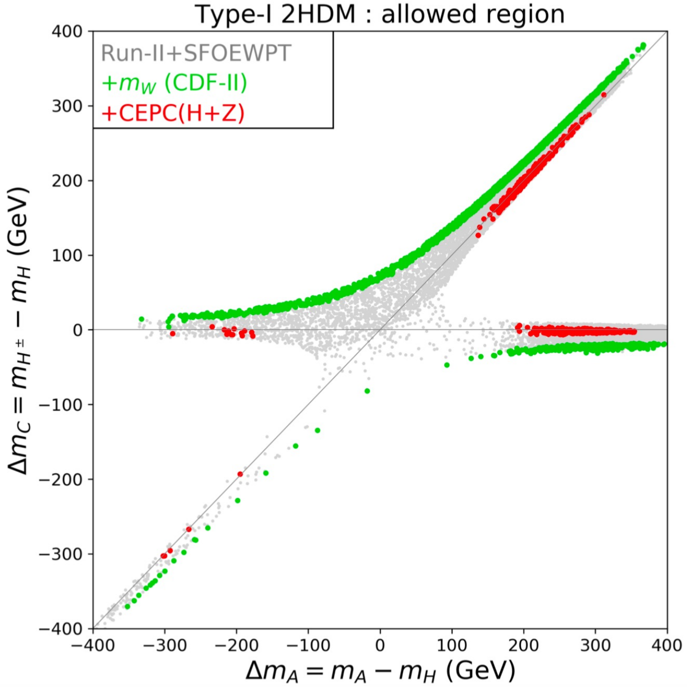


Mass less than 1 TeV





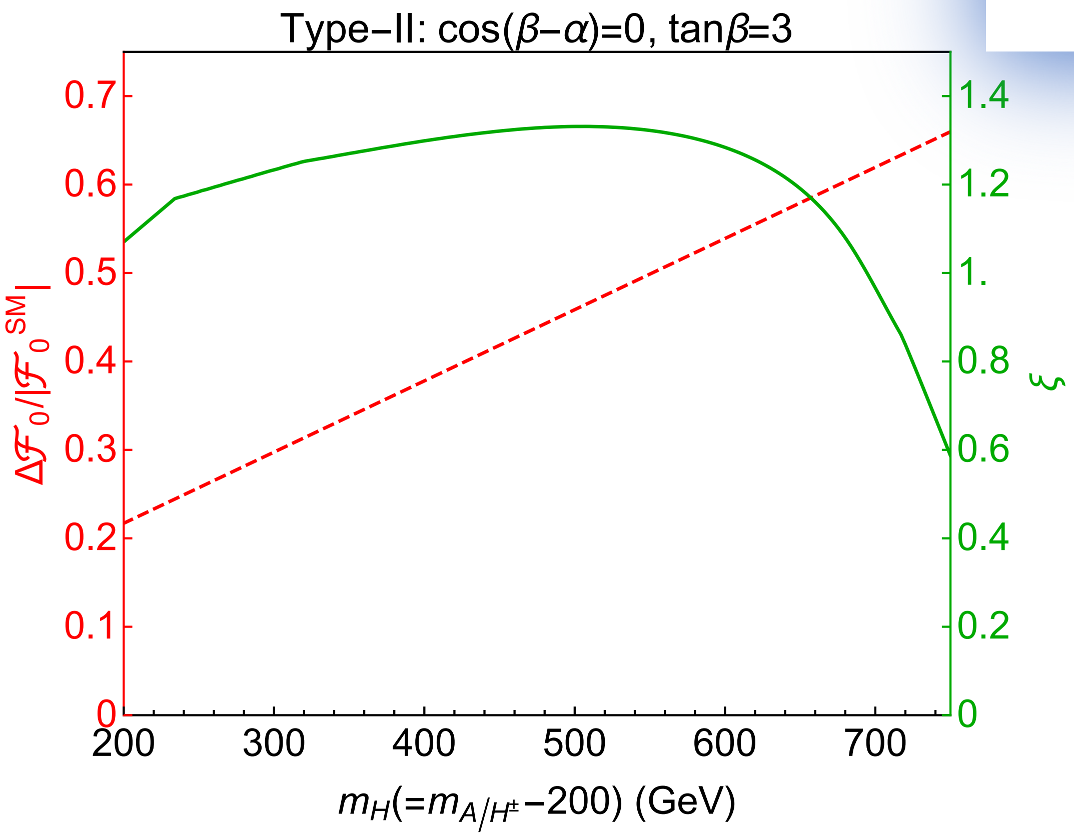
$$m_{A/H^\pm} - m_H \in (150, 250)\ \mathrm{GeV}$$

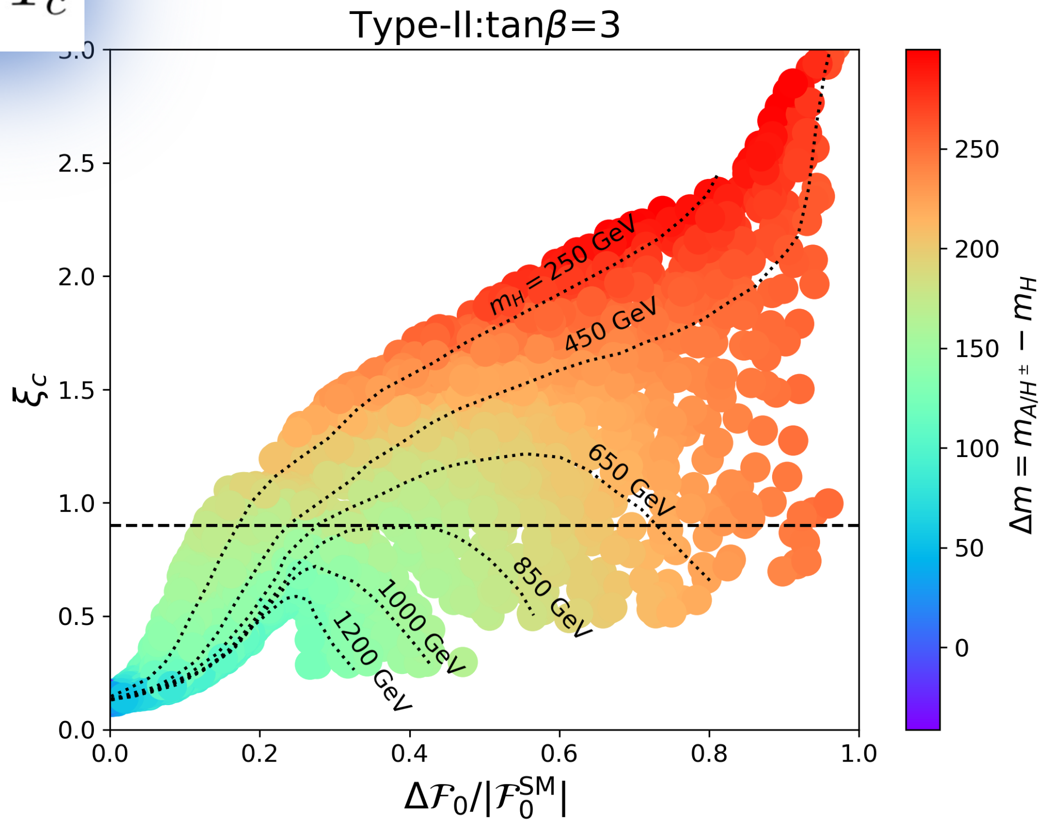


Thanks!

PT vs. vacuum uplifting

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

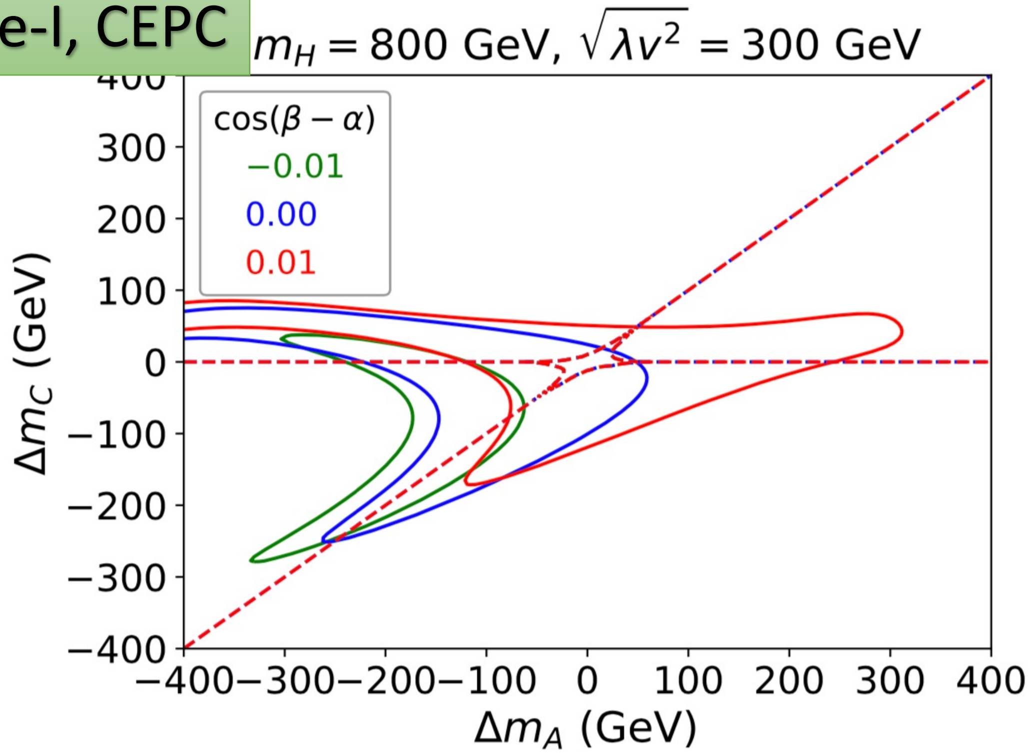


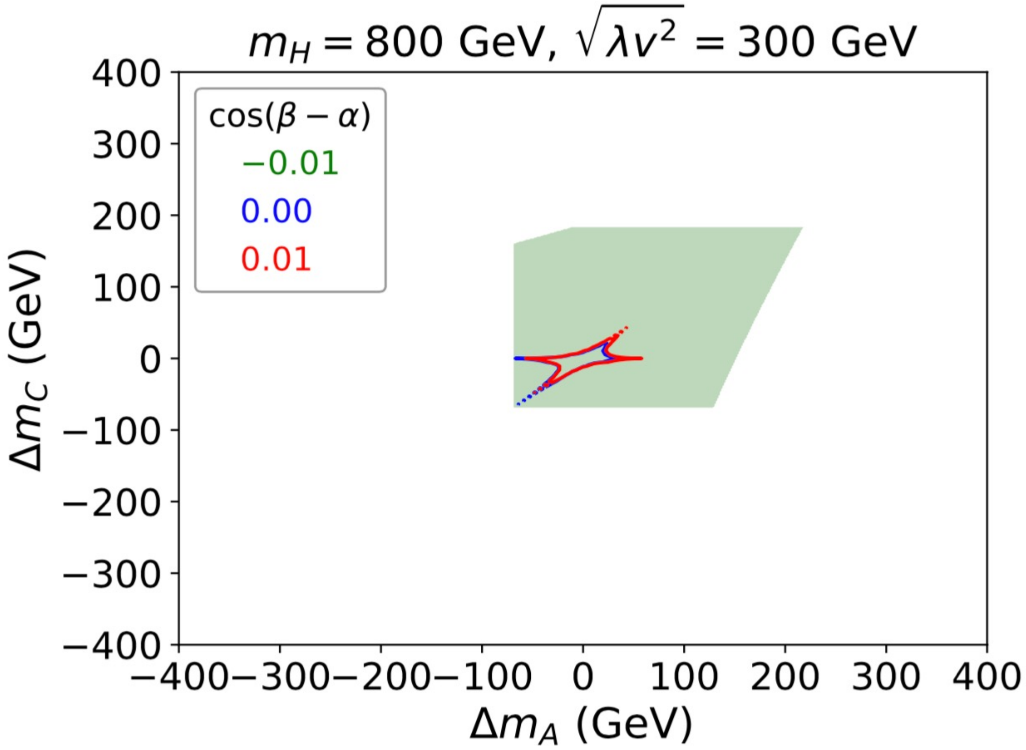


2HDM: precision

[1912.01431](https://arxiv.org/abs/1912.01431) N. Chen, T. Han, S. Li, S. Su, WS, Y. Wu

Type-I, CEPC





The precisions changed for Type-I and Type-II

2HDM: precision

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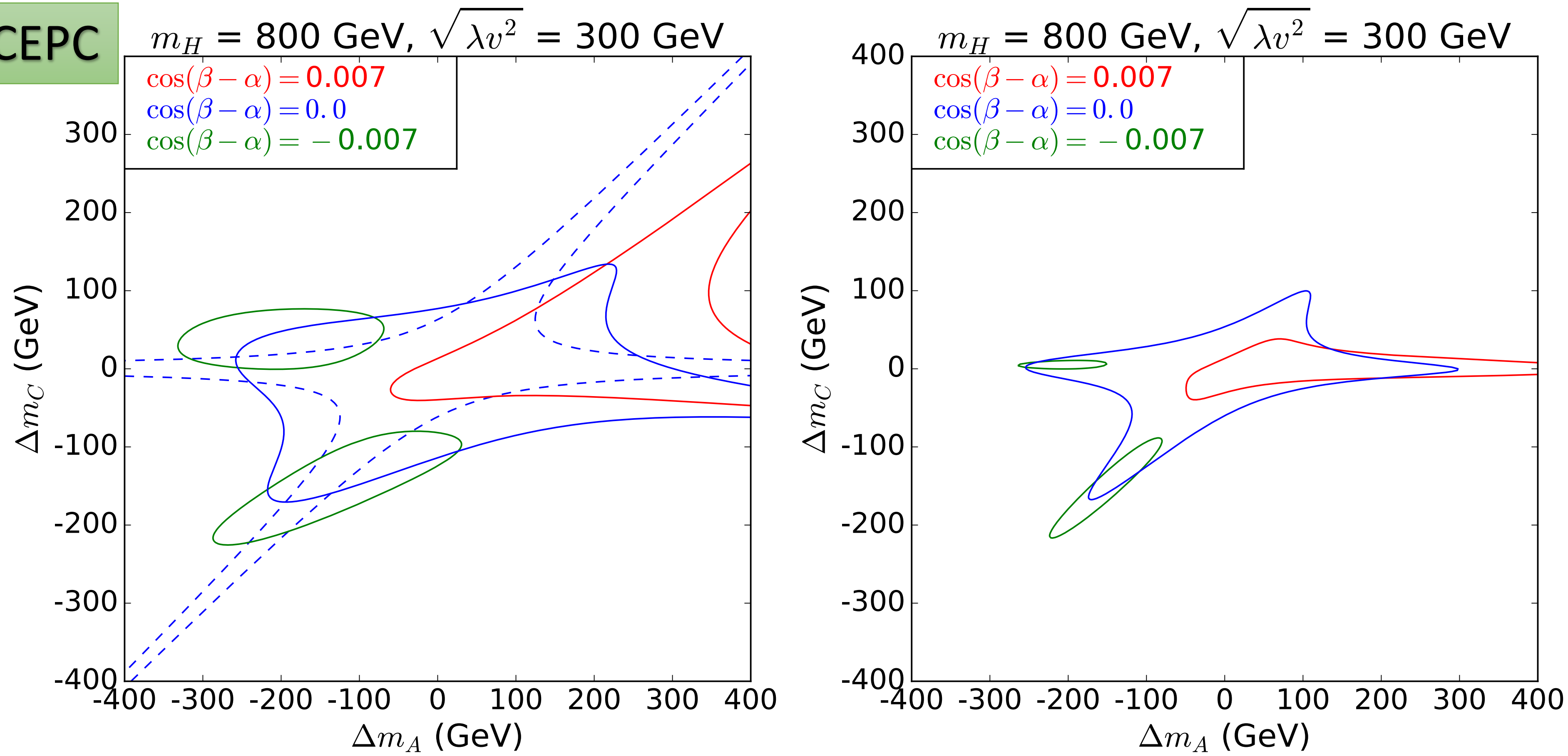
Type-II, CEPC



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