Workshop on CEPC 2021

Probing EWPT in 2HDM with Future Lepton Colliders

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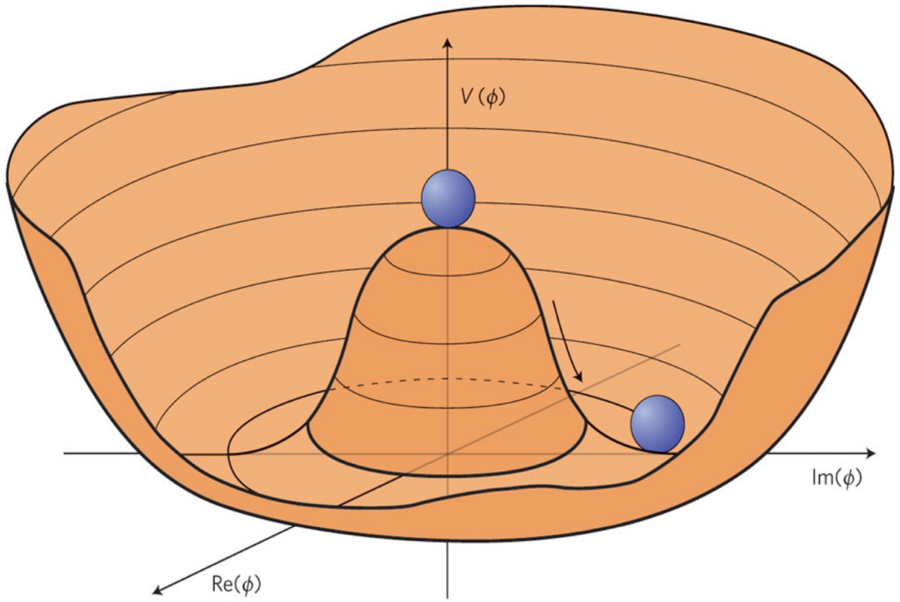
arXiv: 2011.04540 WS, A G. Williams, M. Zhang

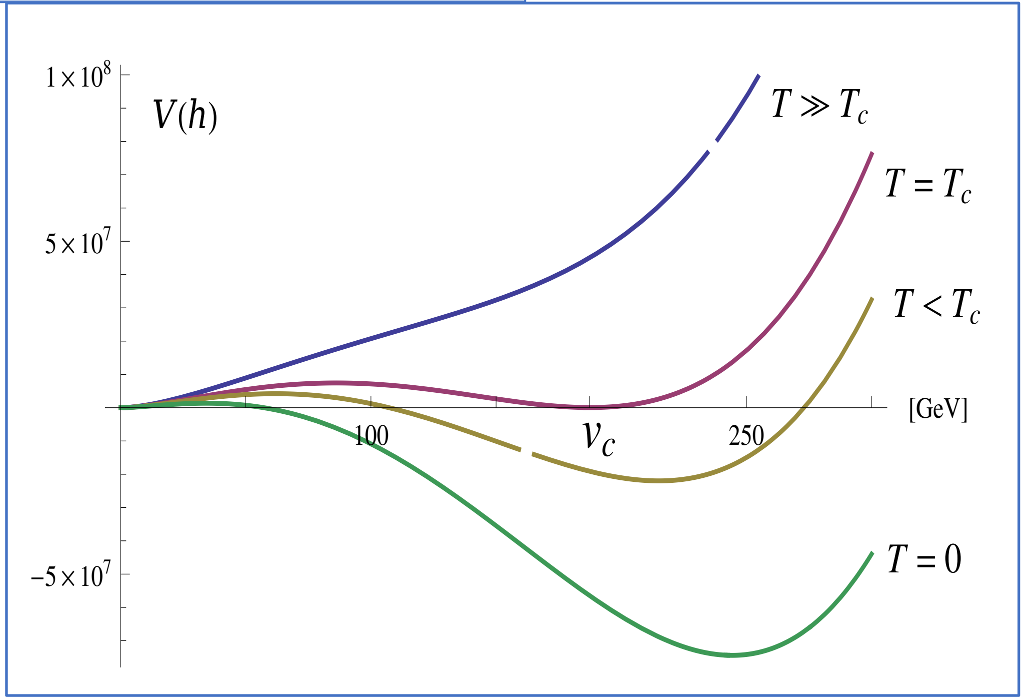
Outline

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

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)

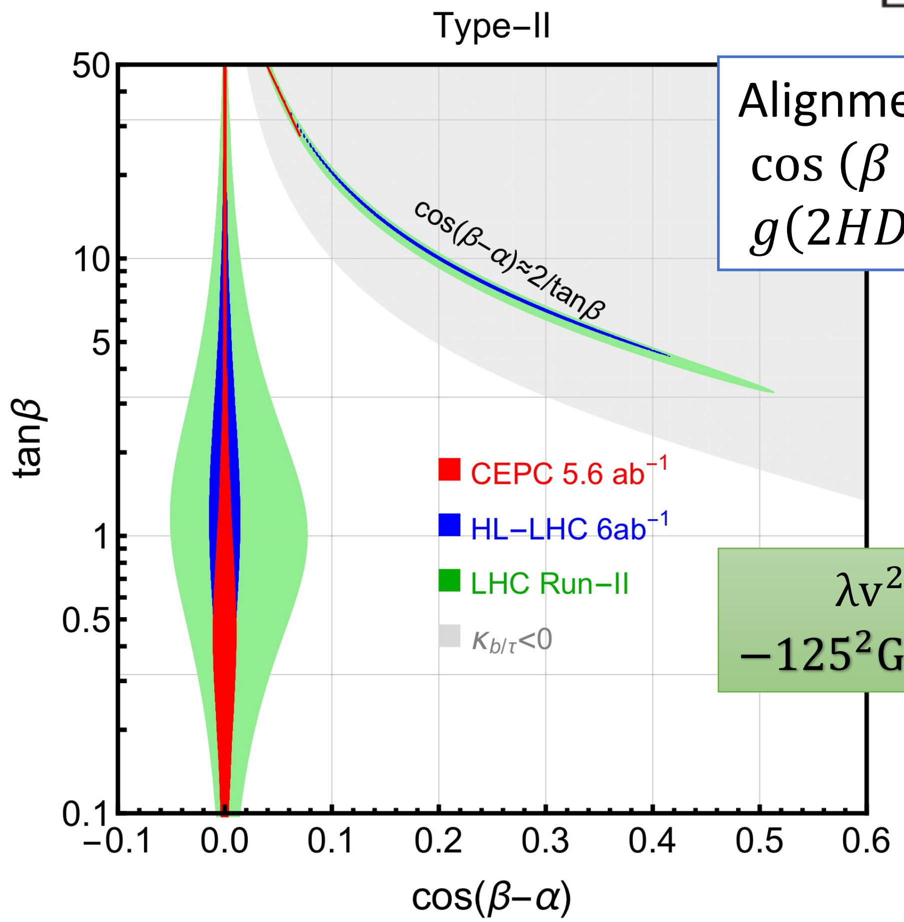
$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

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	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

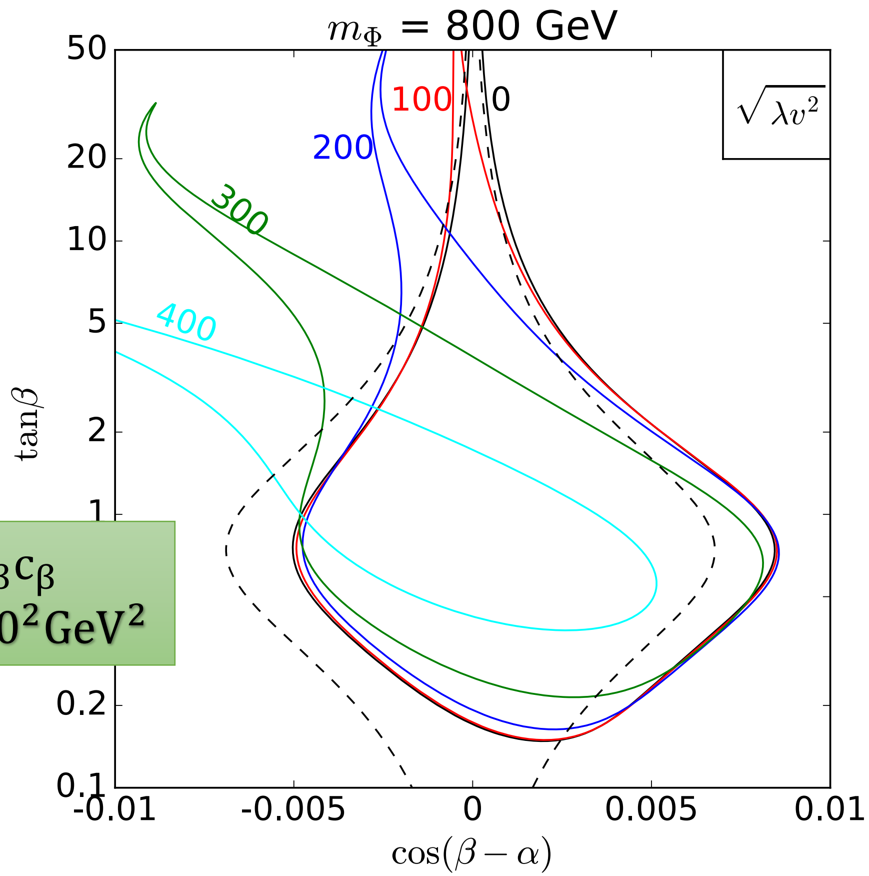


Alignment limit :

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

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

$$\lambda v^2 \equiv m_\Phi^2 - m_{12}^2/s_\beta c_\beta$$
$$-125^2\text{GeV}^2 < \lambda v^2 < 600^2\text{GeV}^2$$



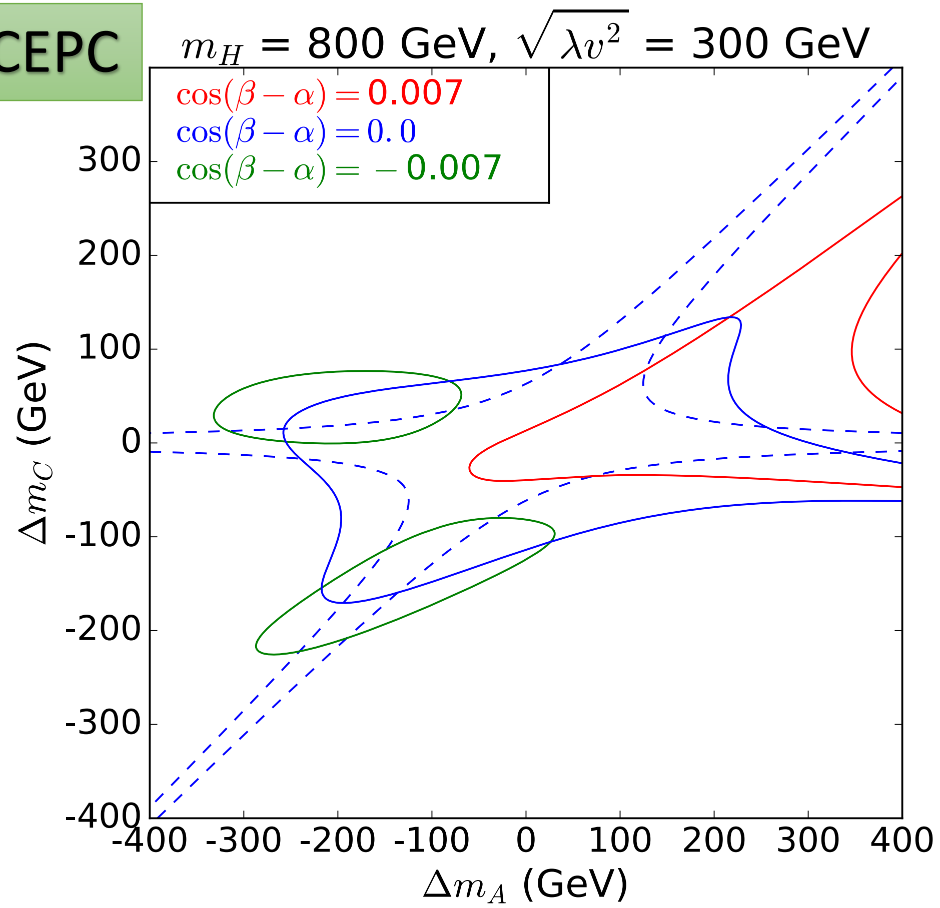
1910.06269 WS

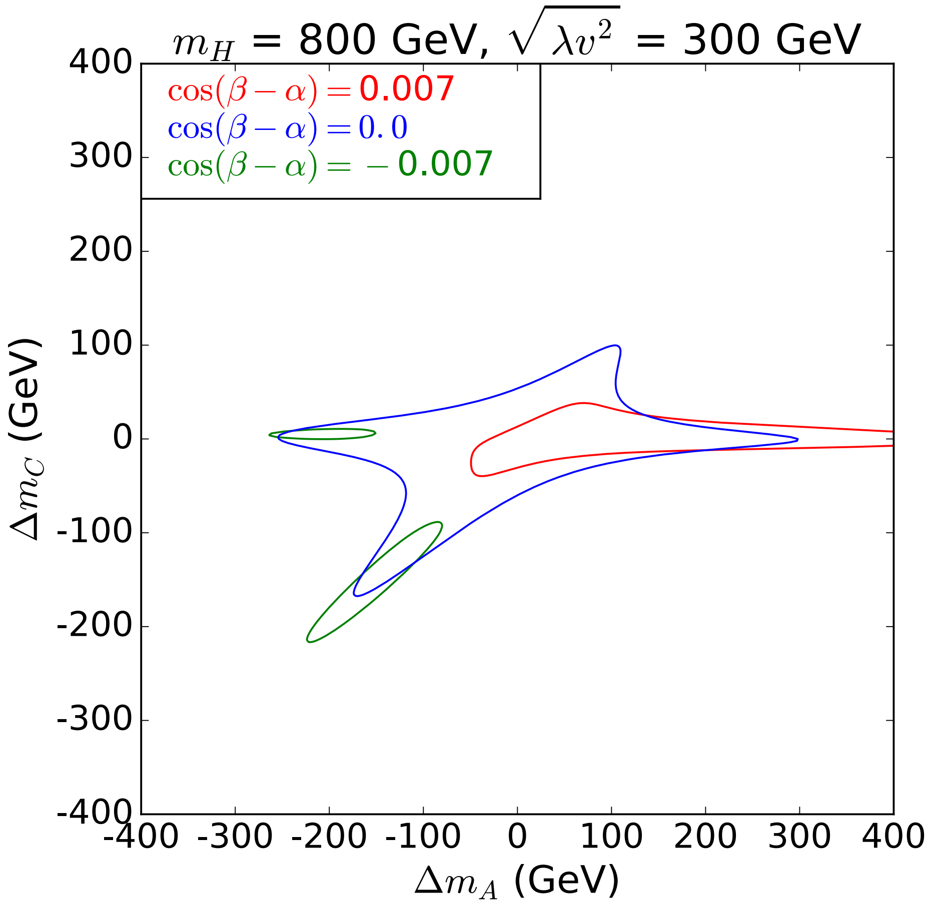
1808.02037 N. Chen, T. Han, S. Su, WS, Y. Wu

2HDM: precision

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

Type-II, CEPC





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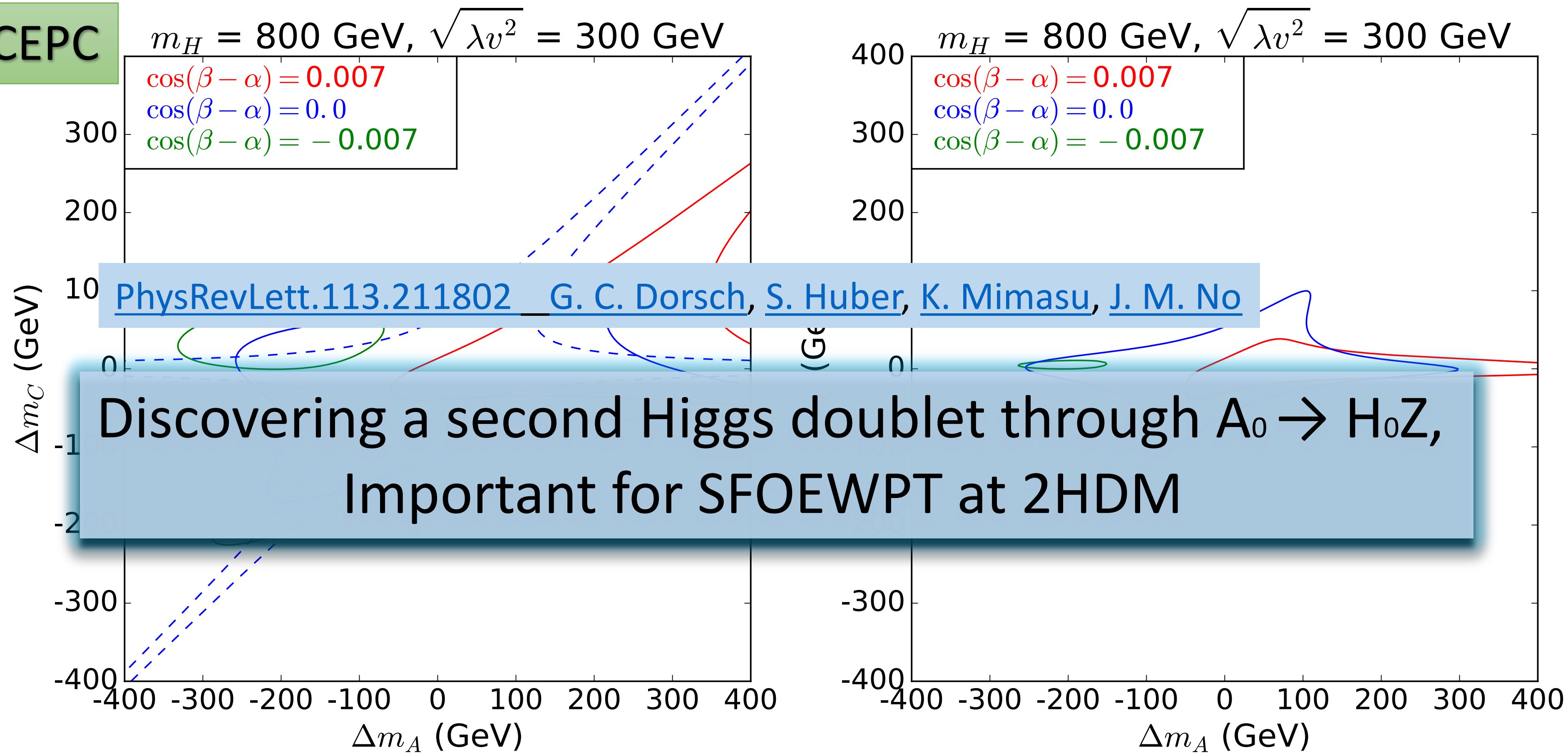
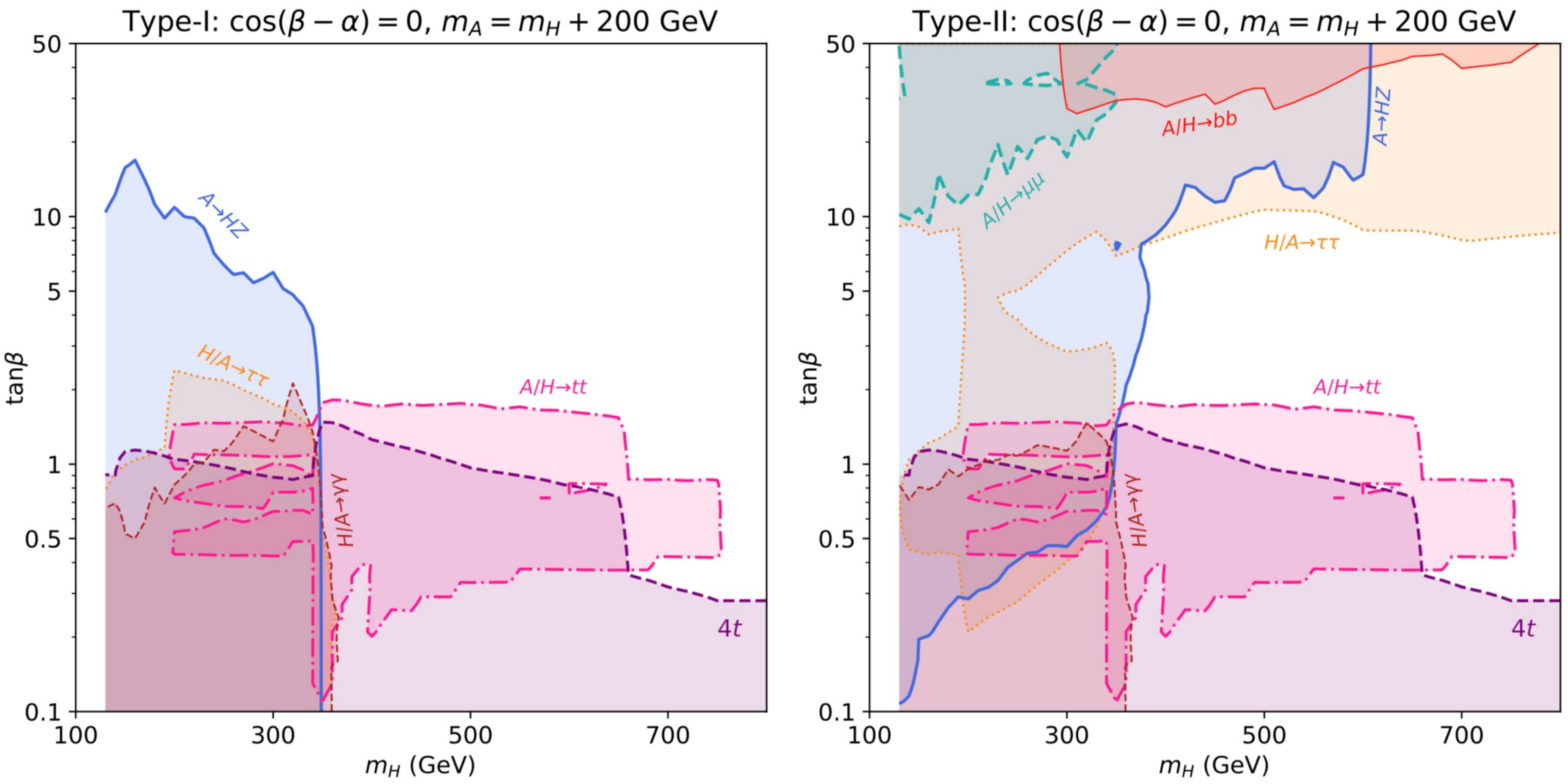


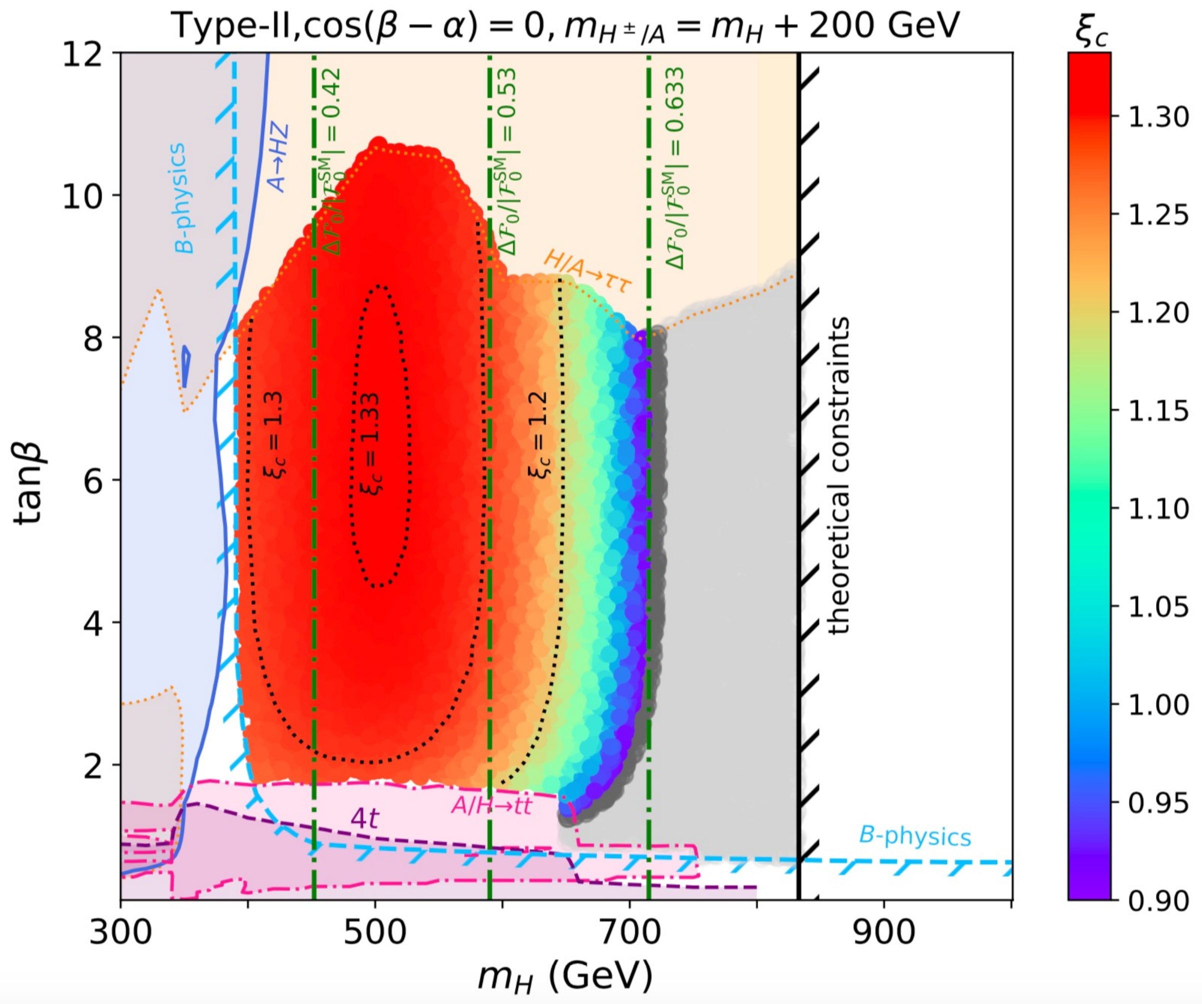
PhysRevLett.113.211802 G. C. Dorsch, S. Huber, K. Mimasu, J. M. No

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

2HDM: LHC direct search



Results: Case-1



Type-II
fixed mass splitting 200 GeV

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

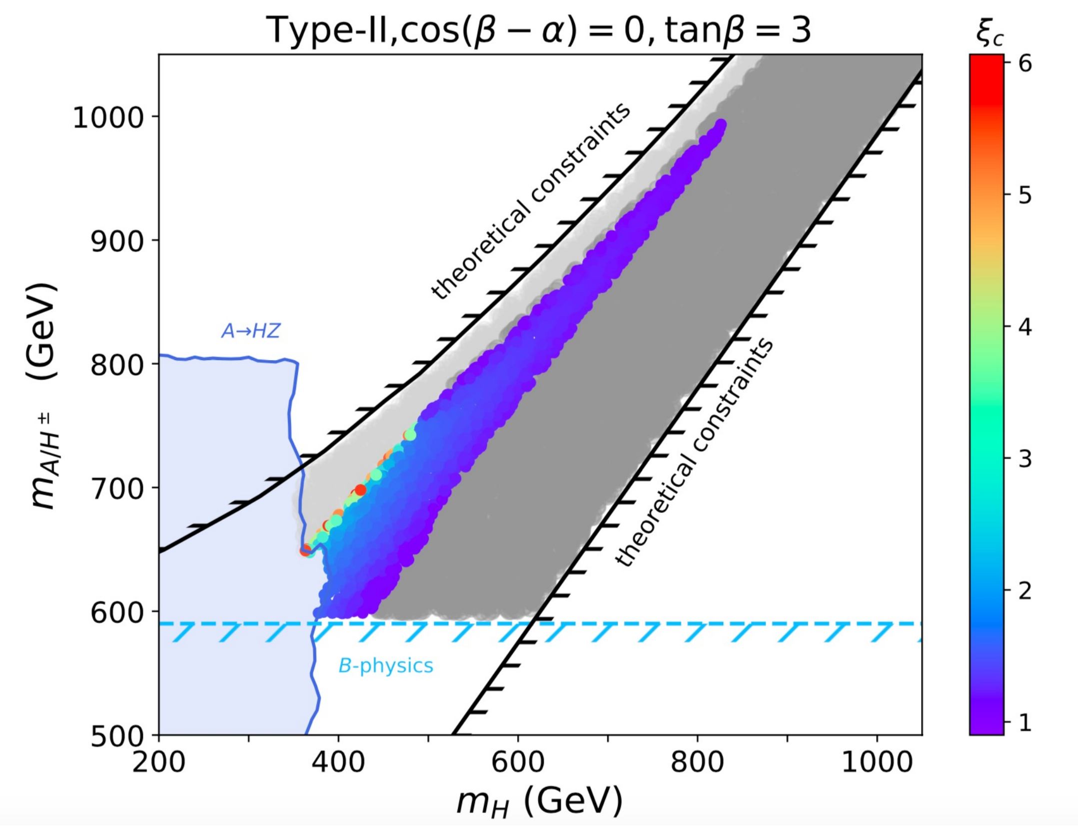
Vacuum uplifting:

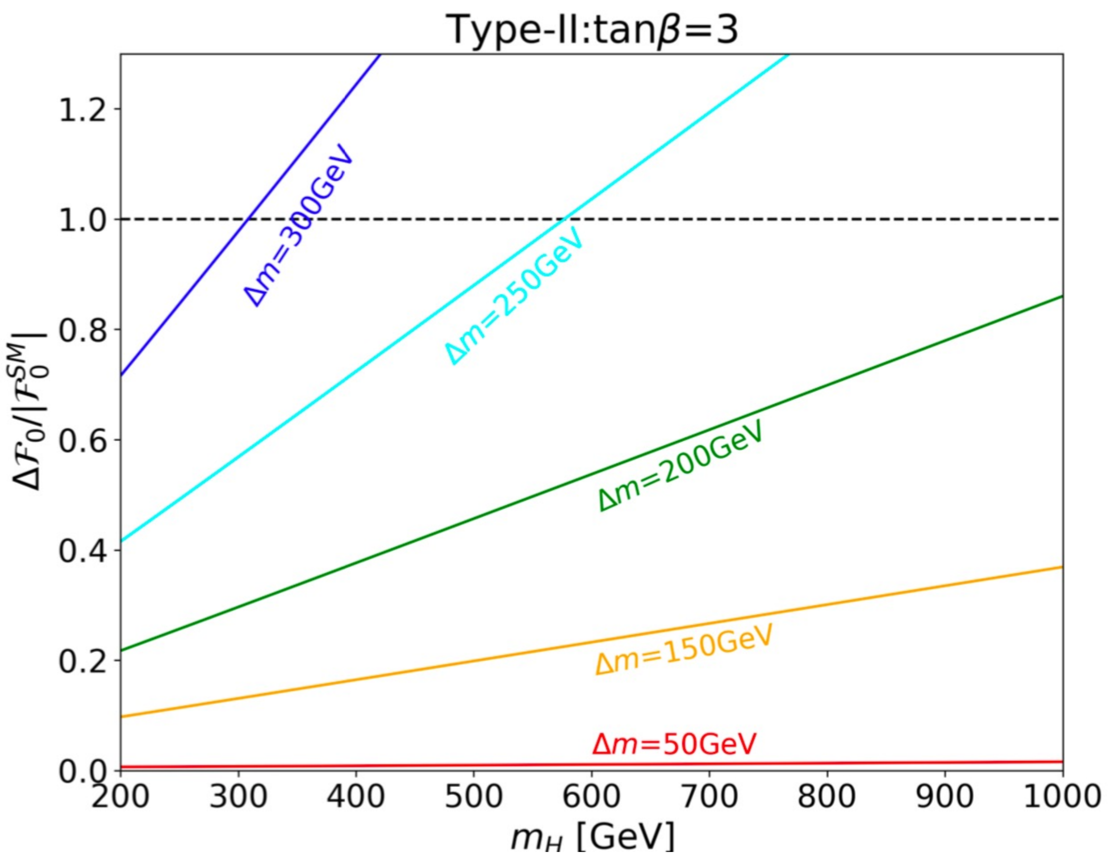
arXiv:1705.09186
G. C. Dorsch, S. Huber, K. Mimasu, J. M. No

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

Results: Case-2

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

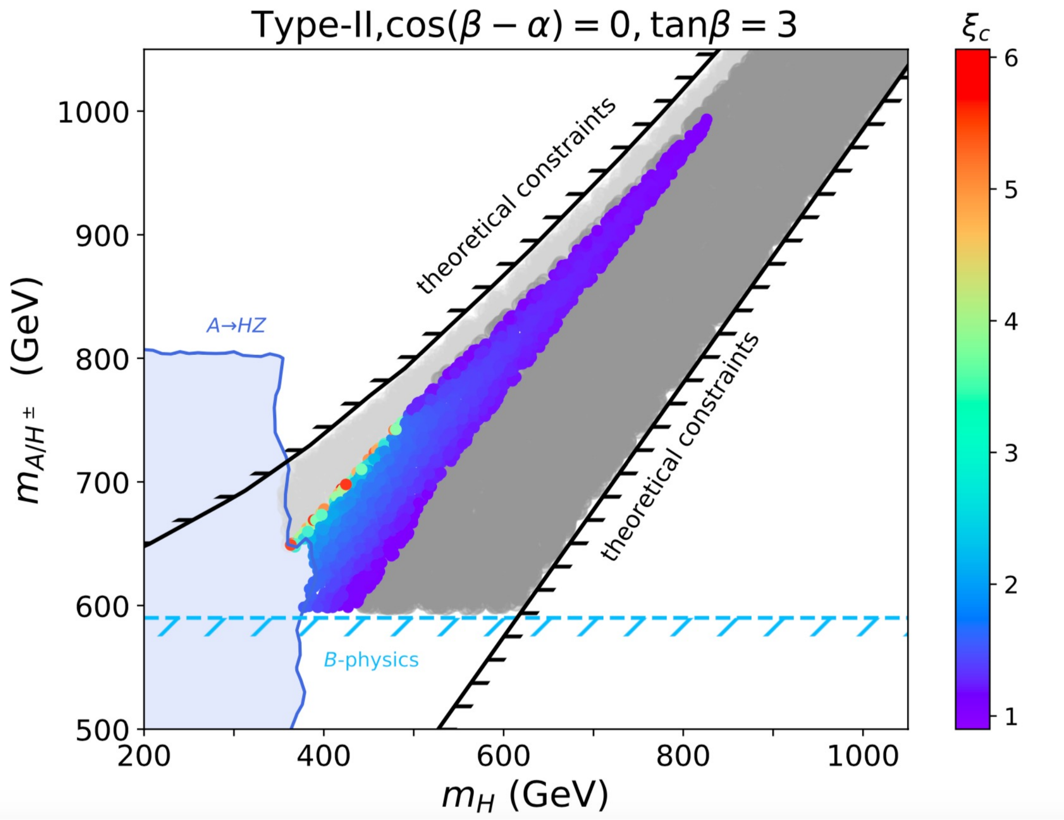




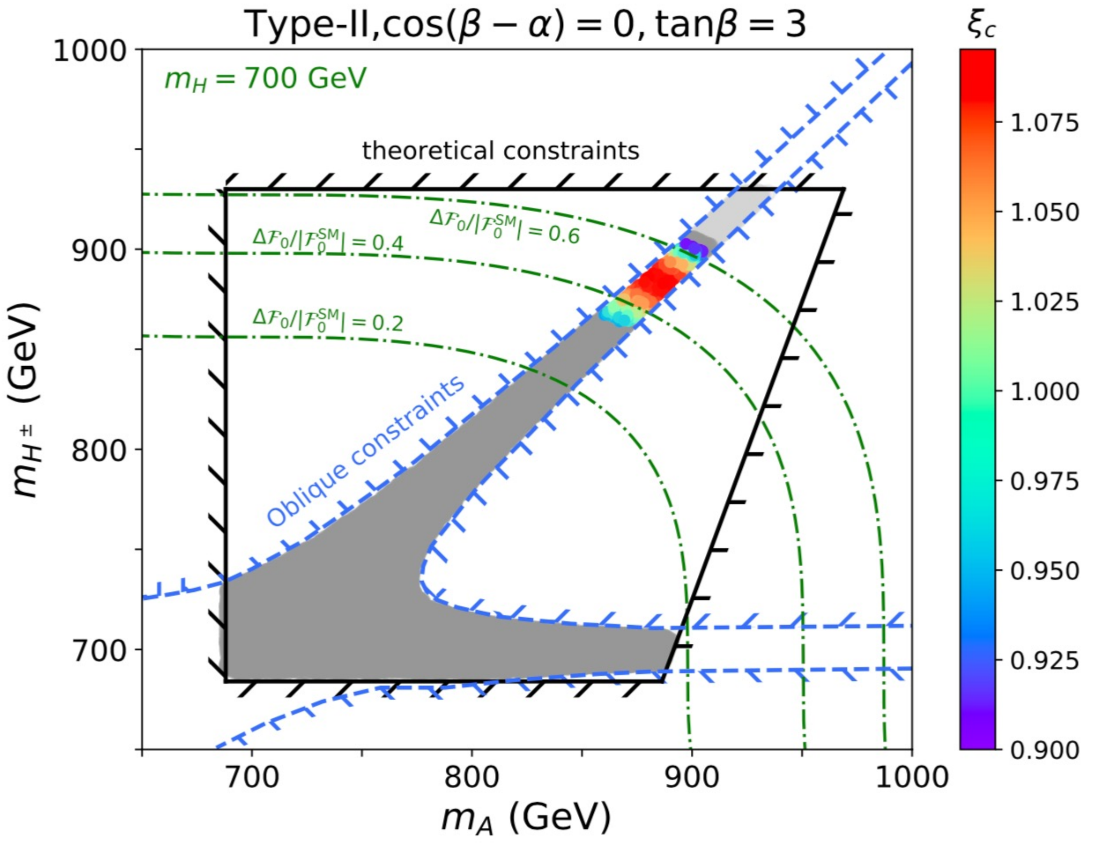
Too large masses or mass splitting can not generate SFOEWPT

Results: Case-2/3

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

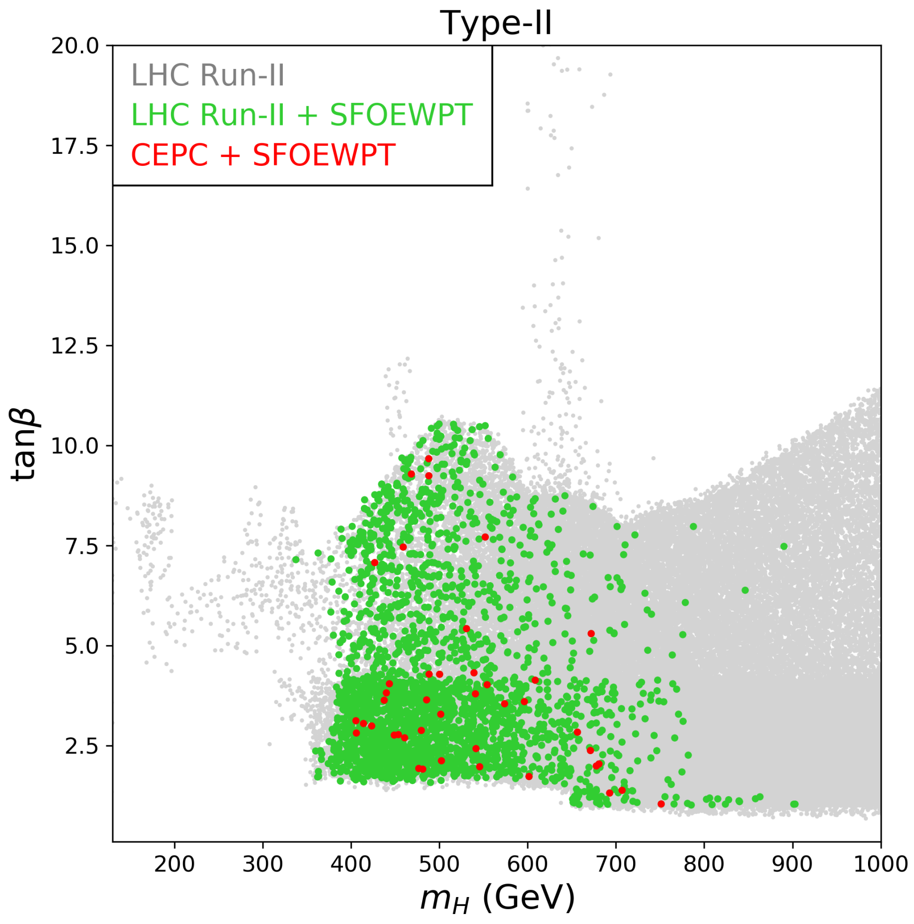


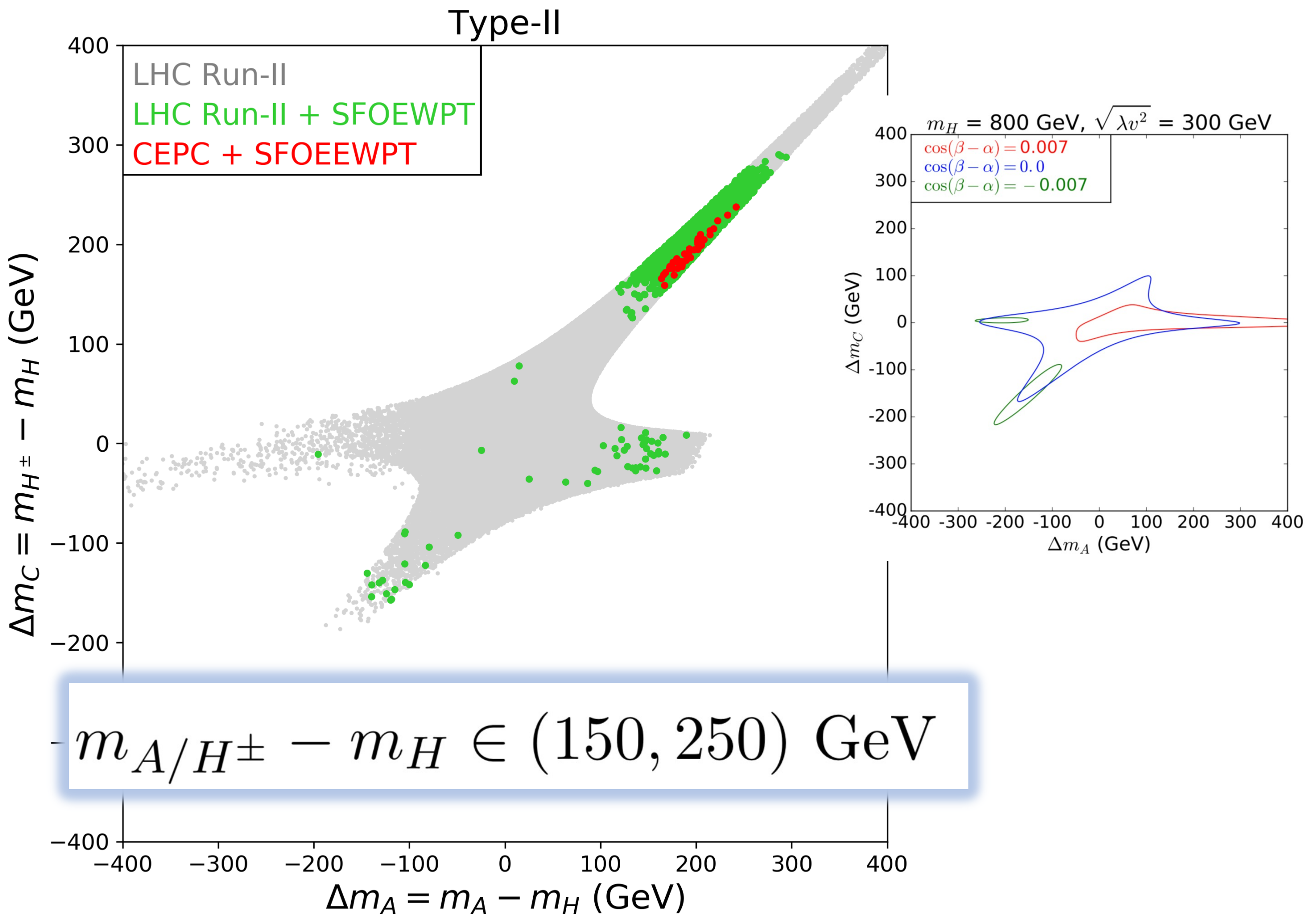
m_H=**700 GeV**



Too large masses or mass splitting can not generate SFOEWPT

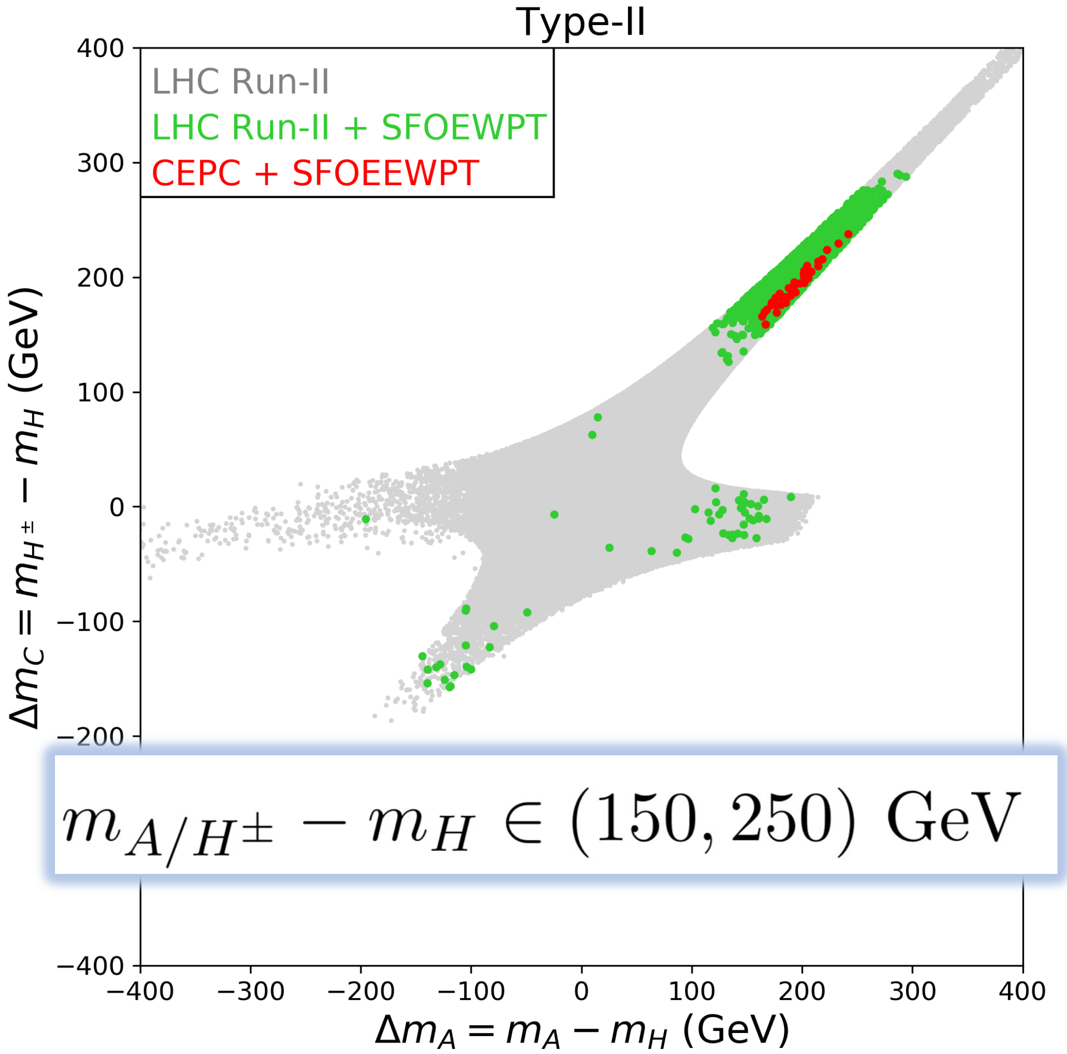
Results: Type-II



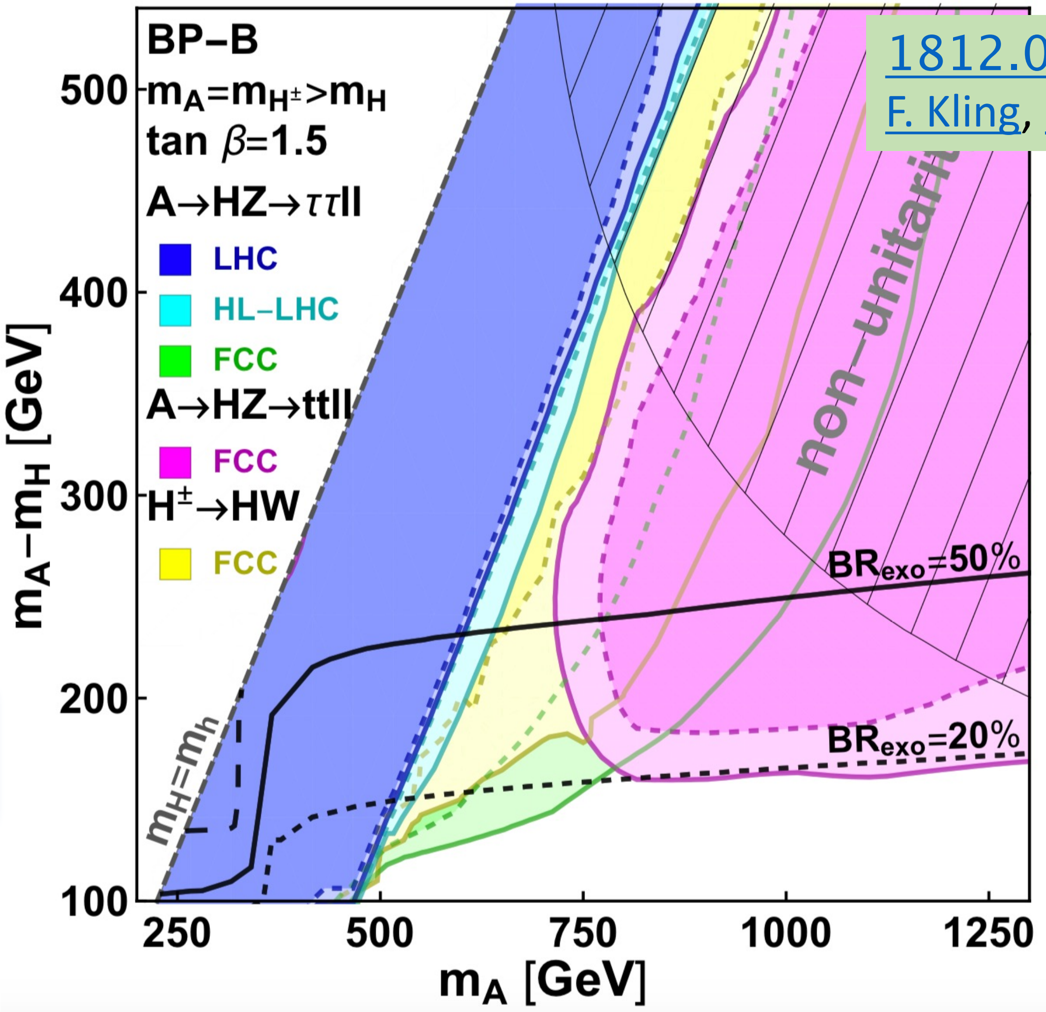


$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$

Future

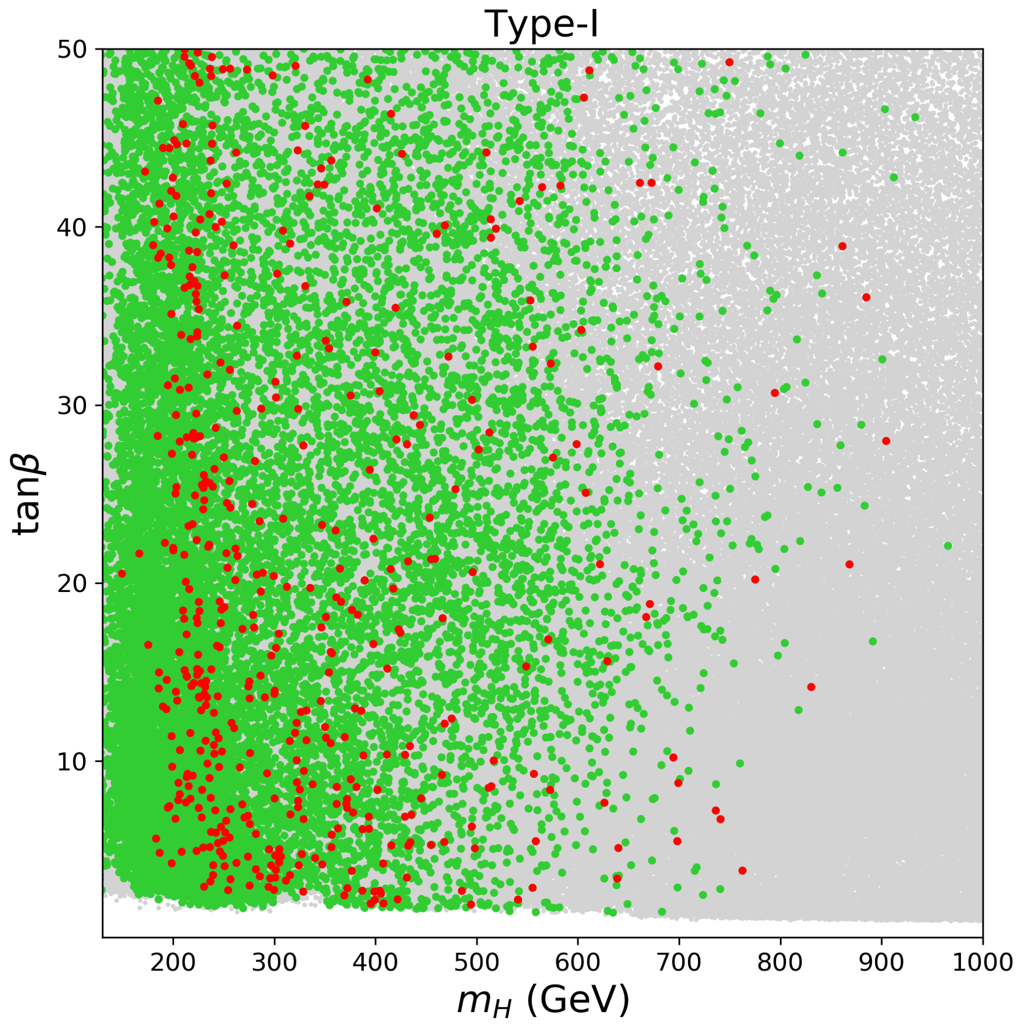


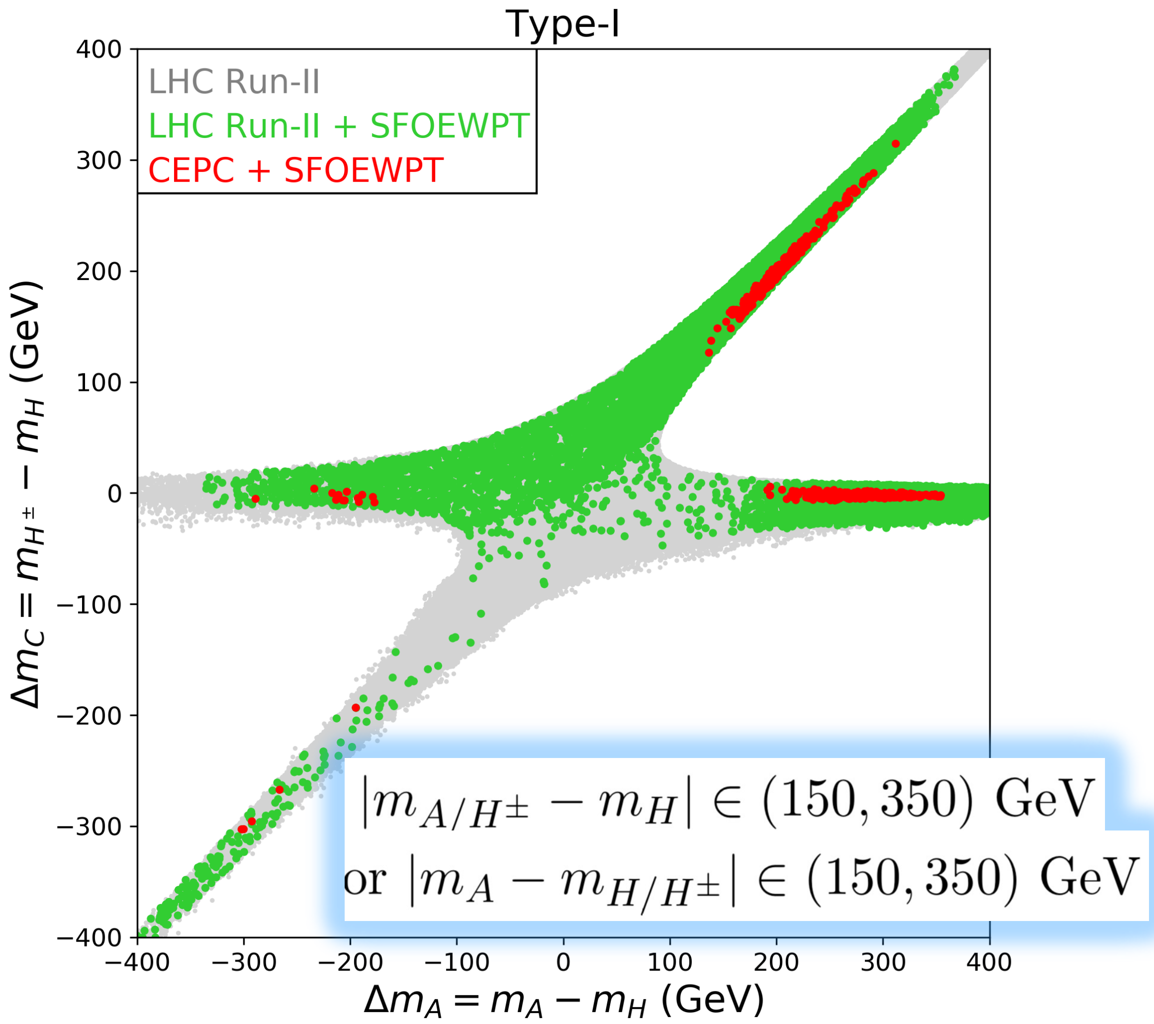
$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$



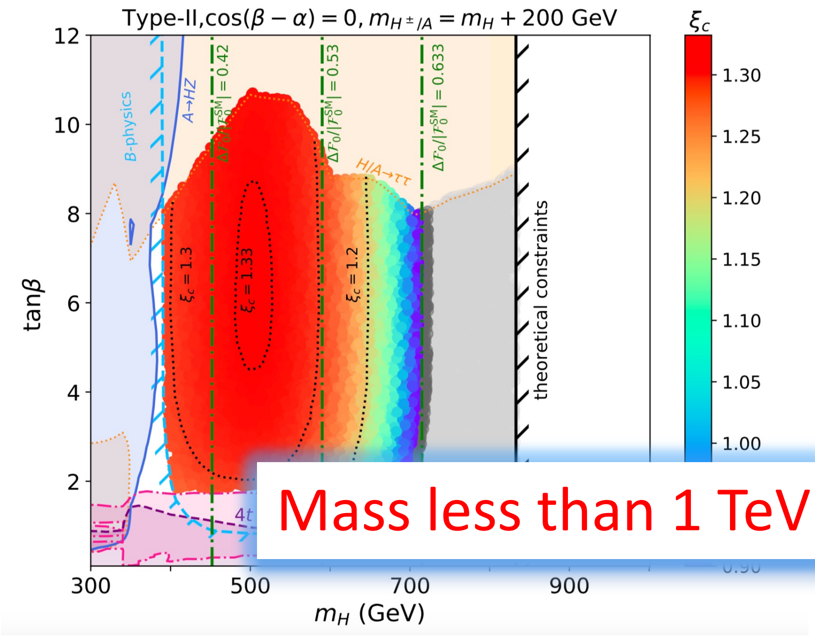
1812.01633
F. Kling, H. Li, etc

Results: Type-I

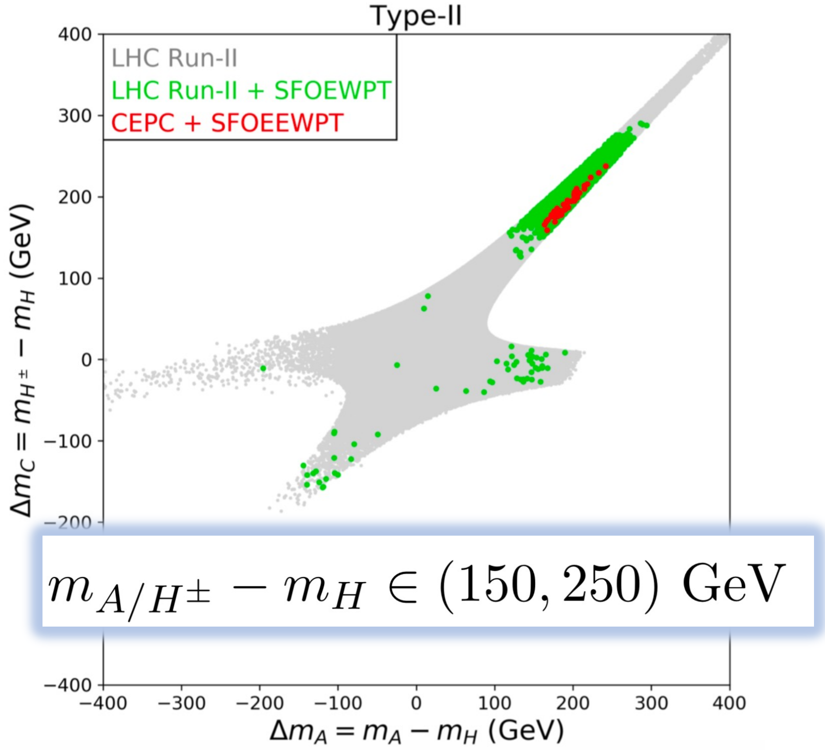




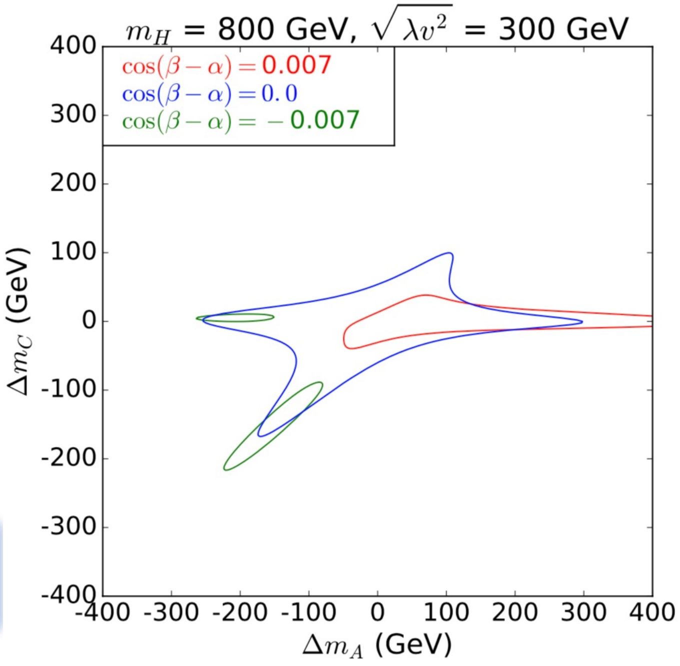
Conclusion



Mass less than 1 TeV



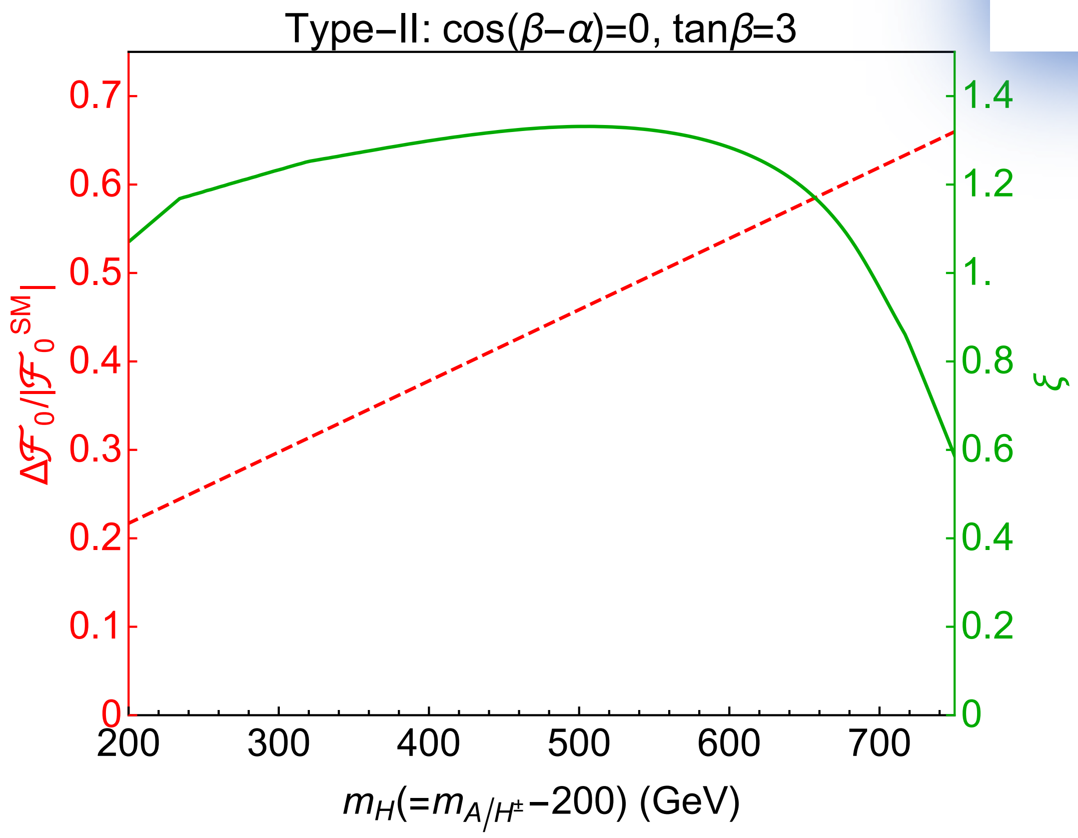
$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$

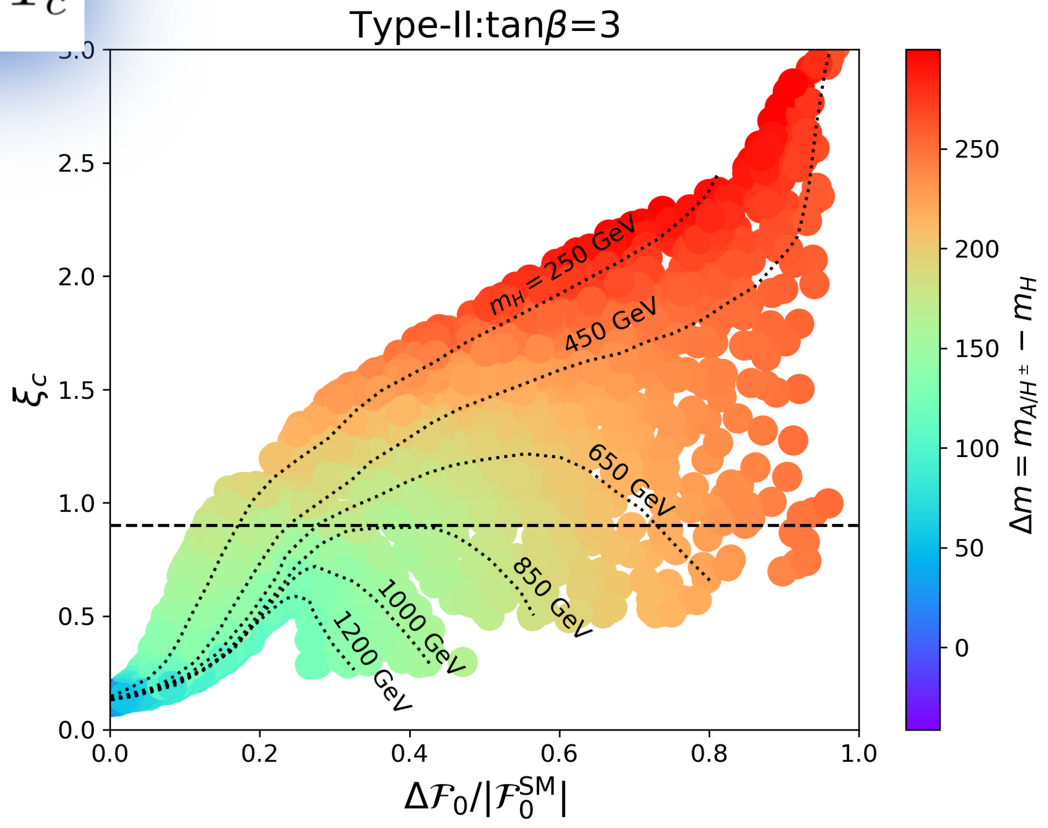


Thanks!

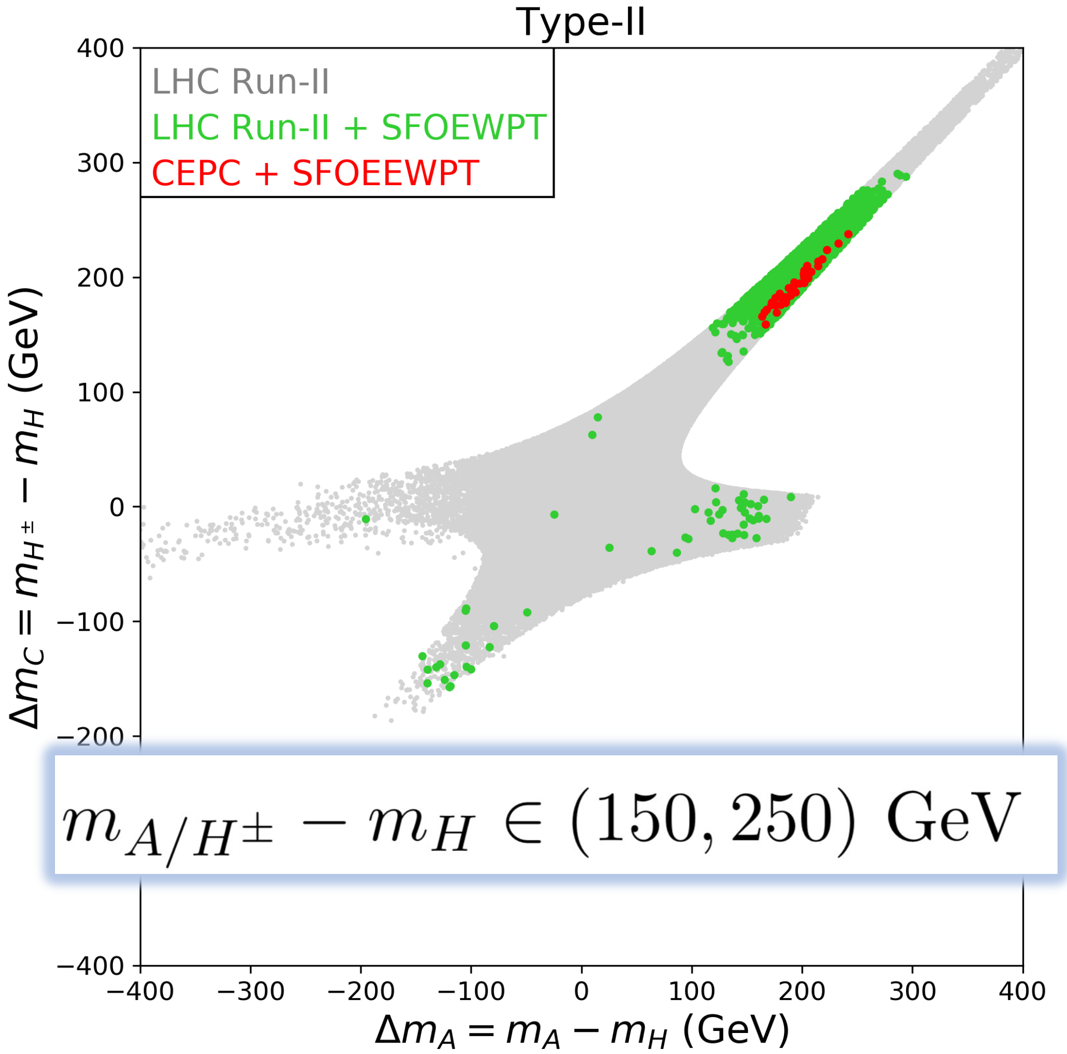
PT vs. vacuum uplifting

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

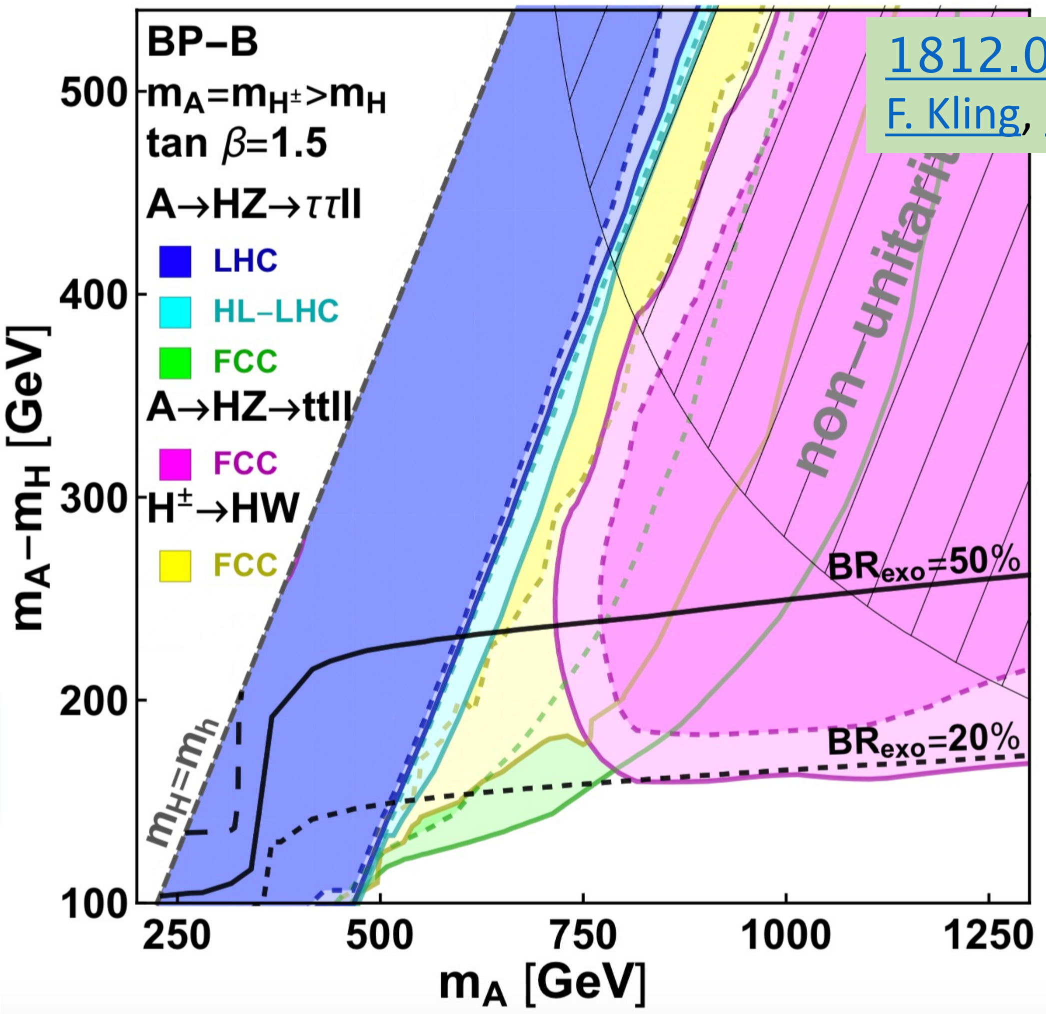




Future

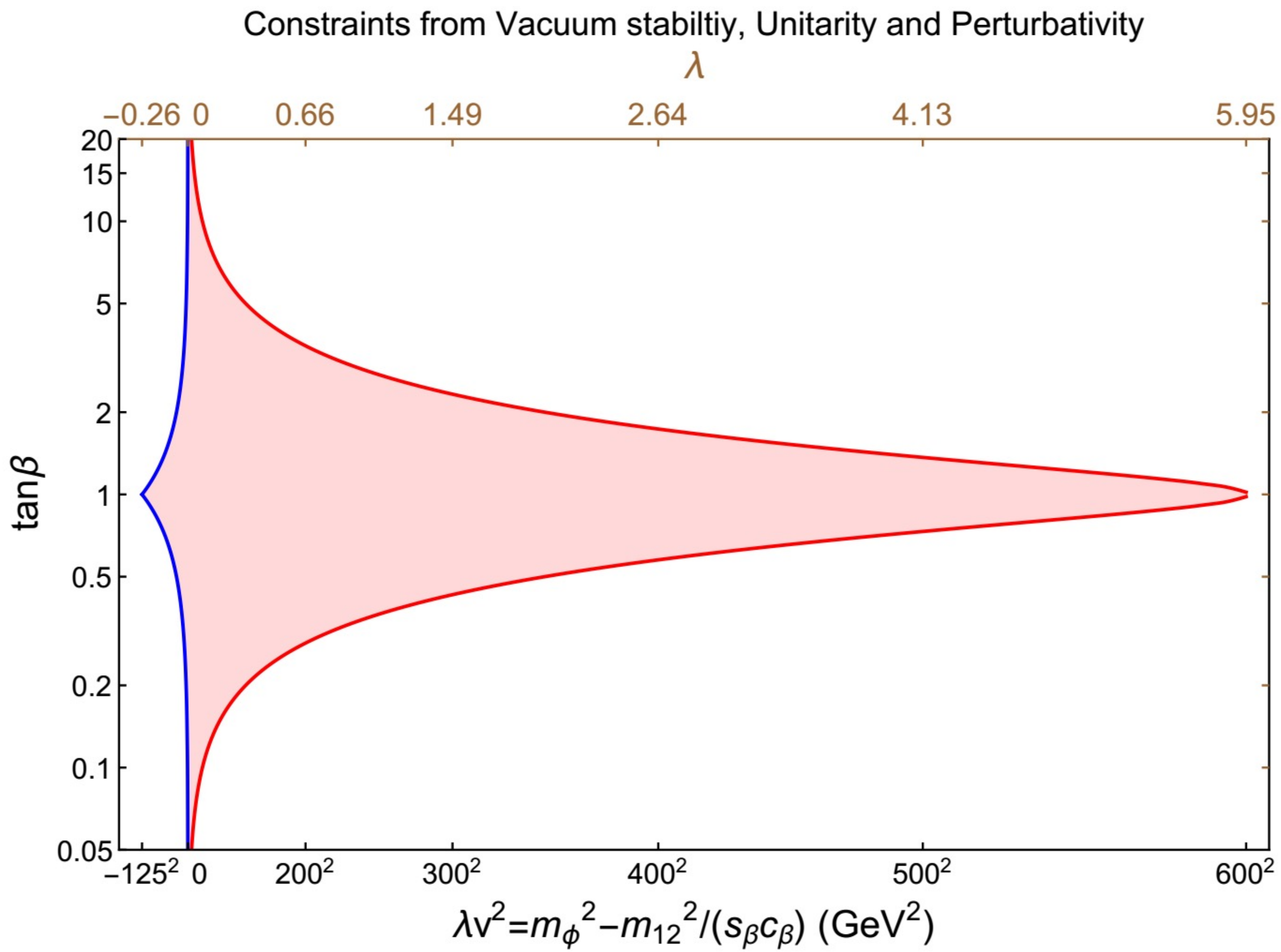


$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$



[1812.01633](1812.01633)
F. Kling, [H. Li](H. Li), etc

2HDM:Theoretical constraints



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

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

$$\lambda v^2 \equiv m_\Phi^2 - m_{12}^2/s_\beta c_\beta$$

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

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

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

Results: Case-2/3

High T approximation:

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

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

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

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

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

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 masses or mass splitting can not generate SFOEWPT