IAS Program on High Energy Physics (HEP 2021)

Probing EWPT in 2HDM with Future Lepton Colliders

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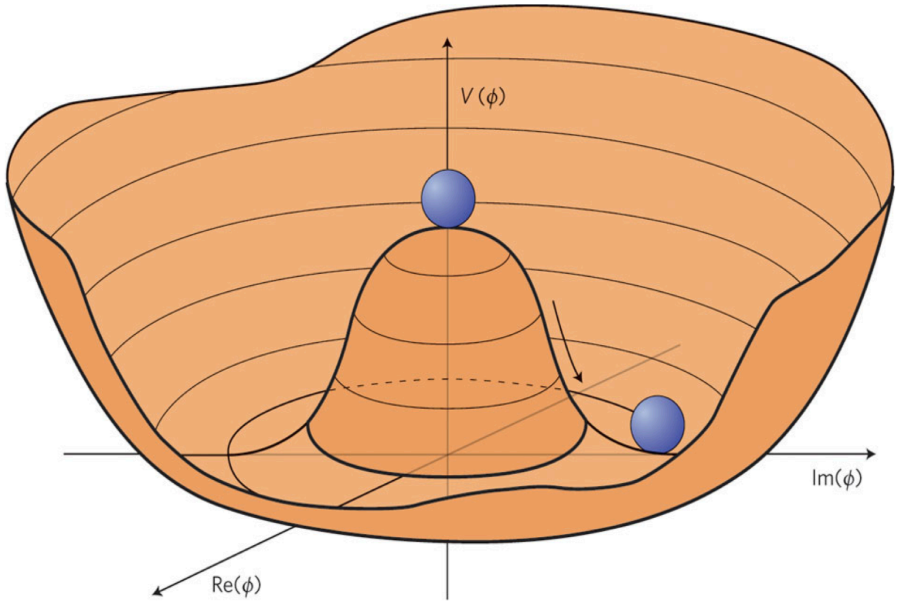
arXiv: 2011.04540 WS, A G. Williams, M. Zhang

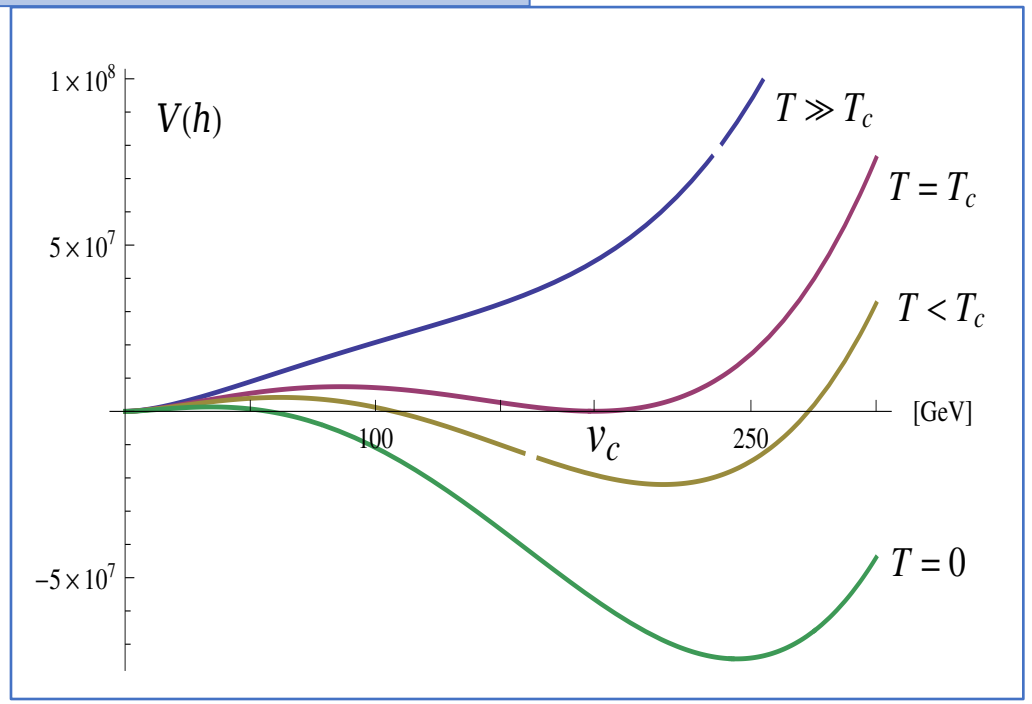
Outline

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

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)

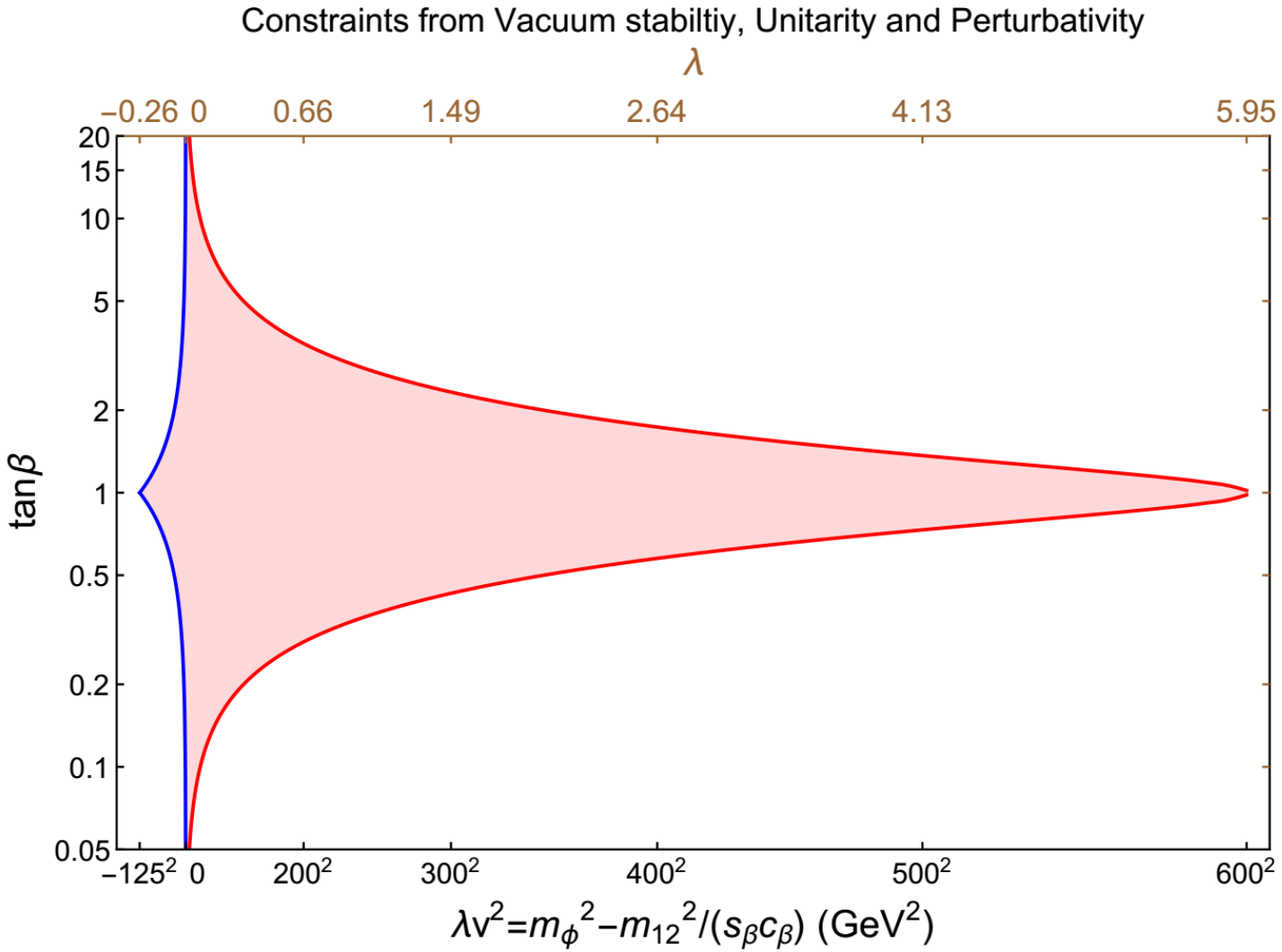
$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

Soft Z_2 symmetry breaking: m_{12}^2

246 GeV

125. GeV

2HDM:Theoretical constraints



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

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

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

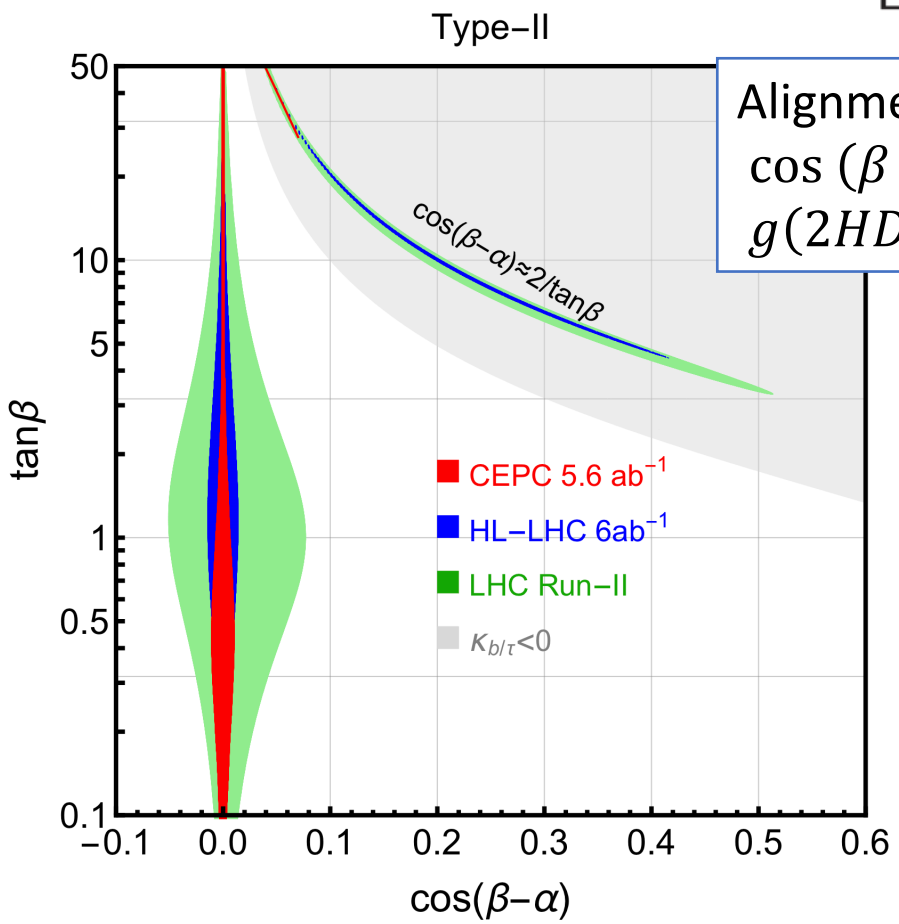
$$-125^2\,\mathrm{GeV}^2 < \lambda v^2 < 600^2\,\mathrm{GeV}^2$$

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

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

2HDM: precision

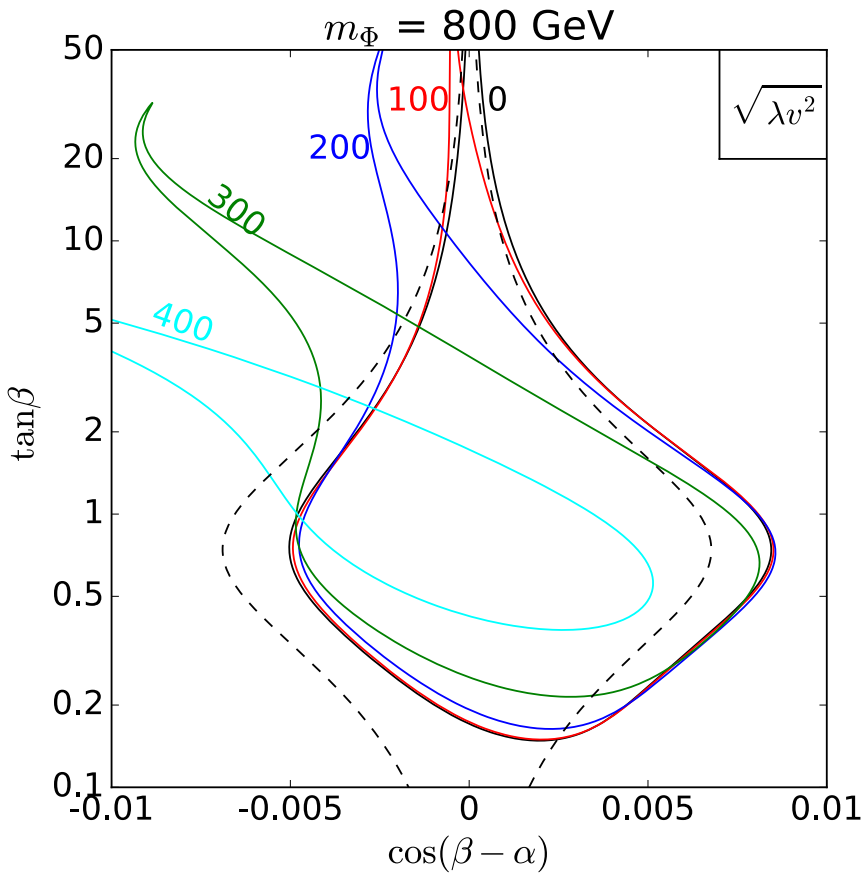
Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$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



Alignment limit :

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

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



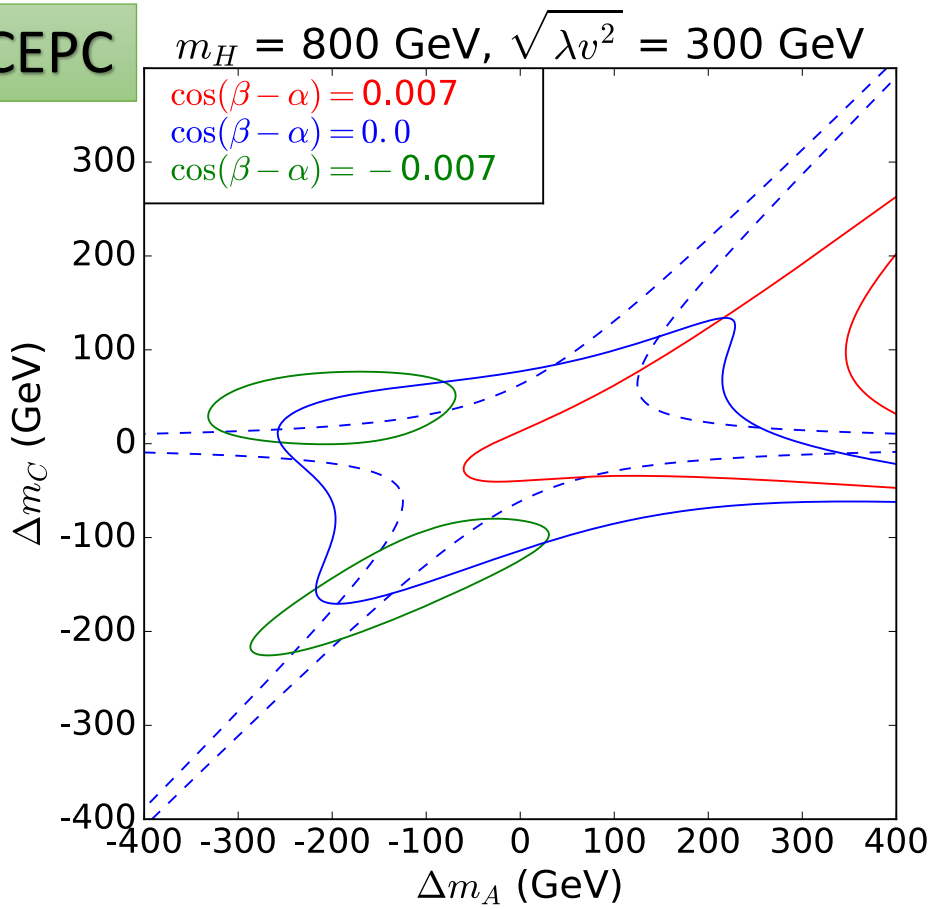
1910.06269 WS

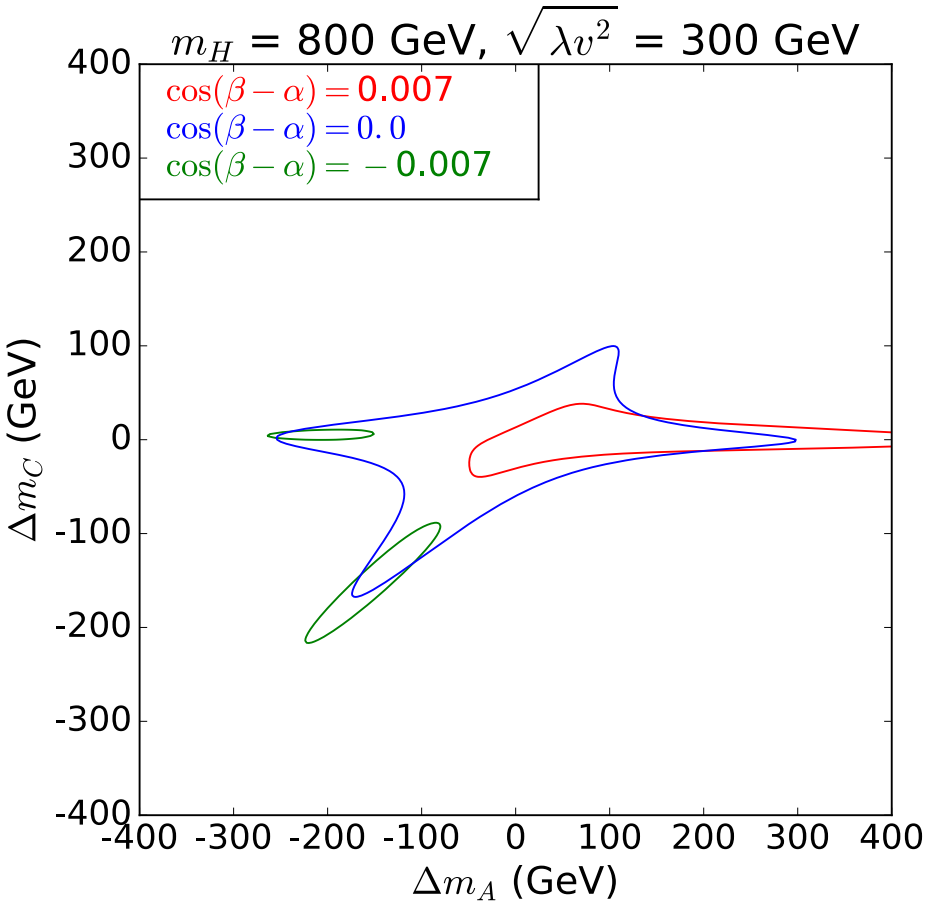
1808.02037 N. Chen, T. Han, S. Su, WS, Y. Wu

2HDM: precision

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

Type-II, CEPC

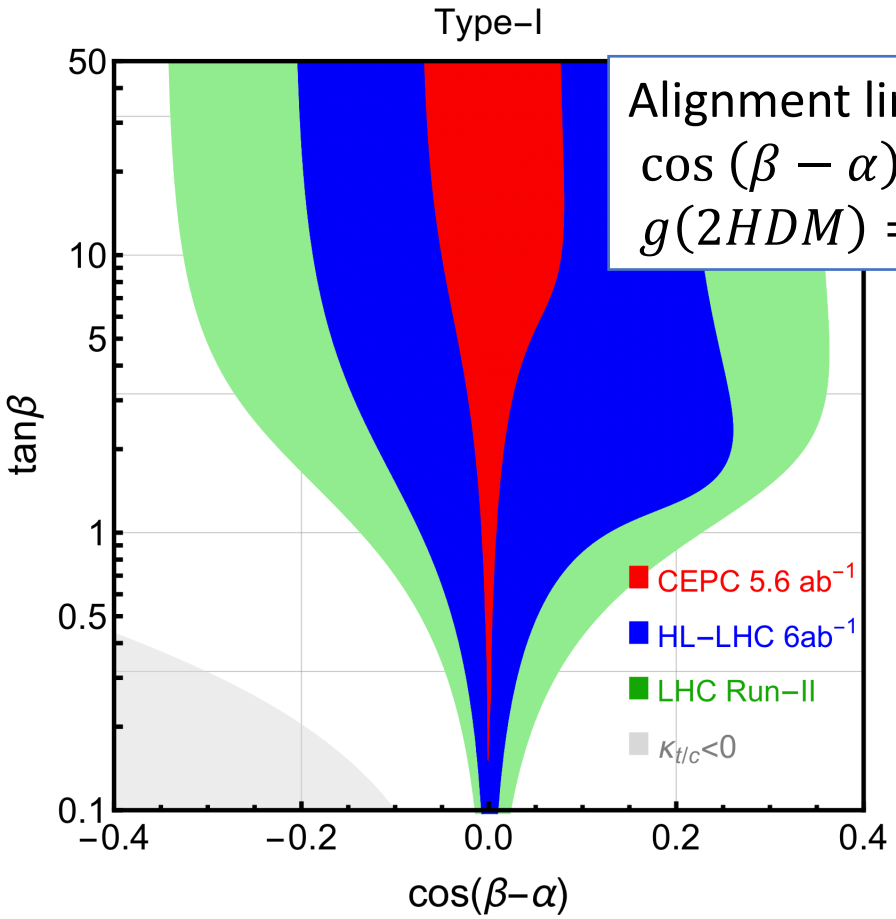




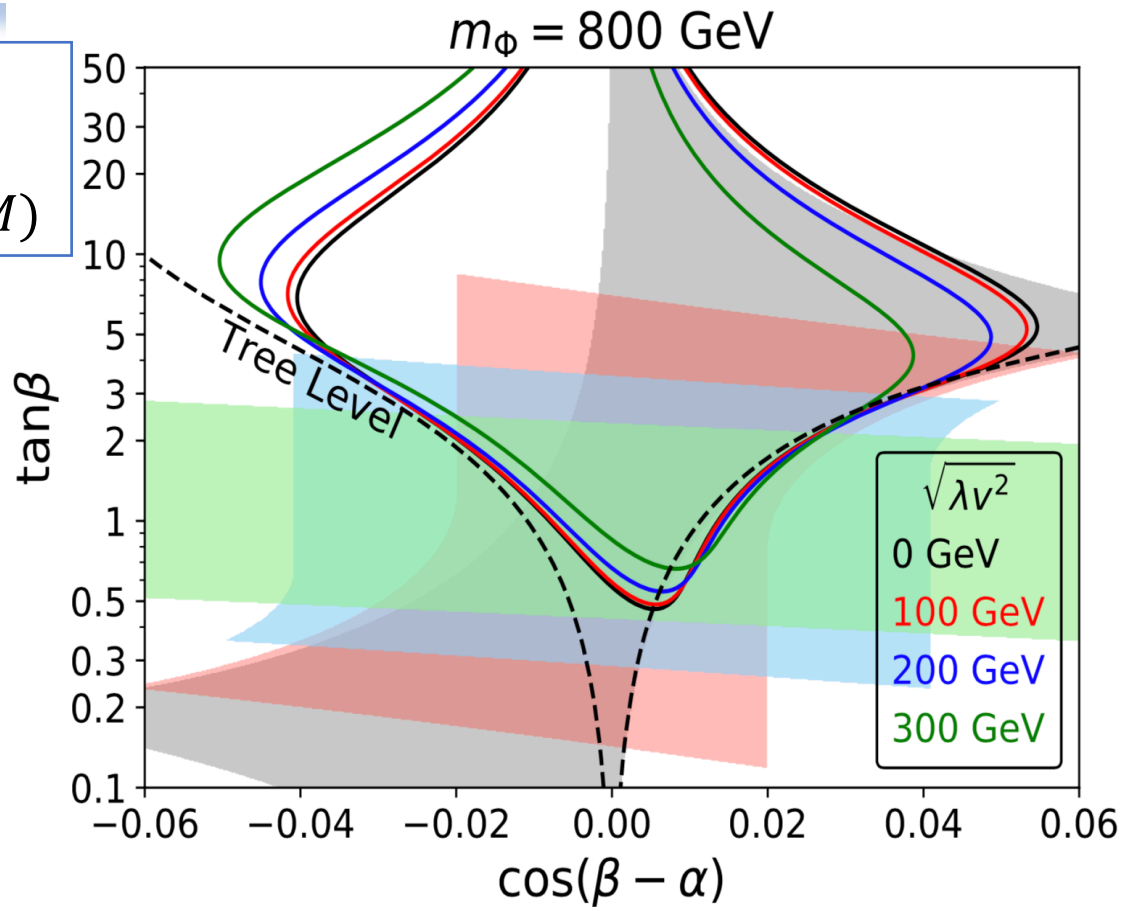
2HDM: precision

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

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



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

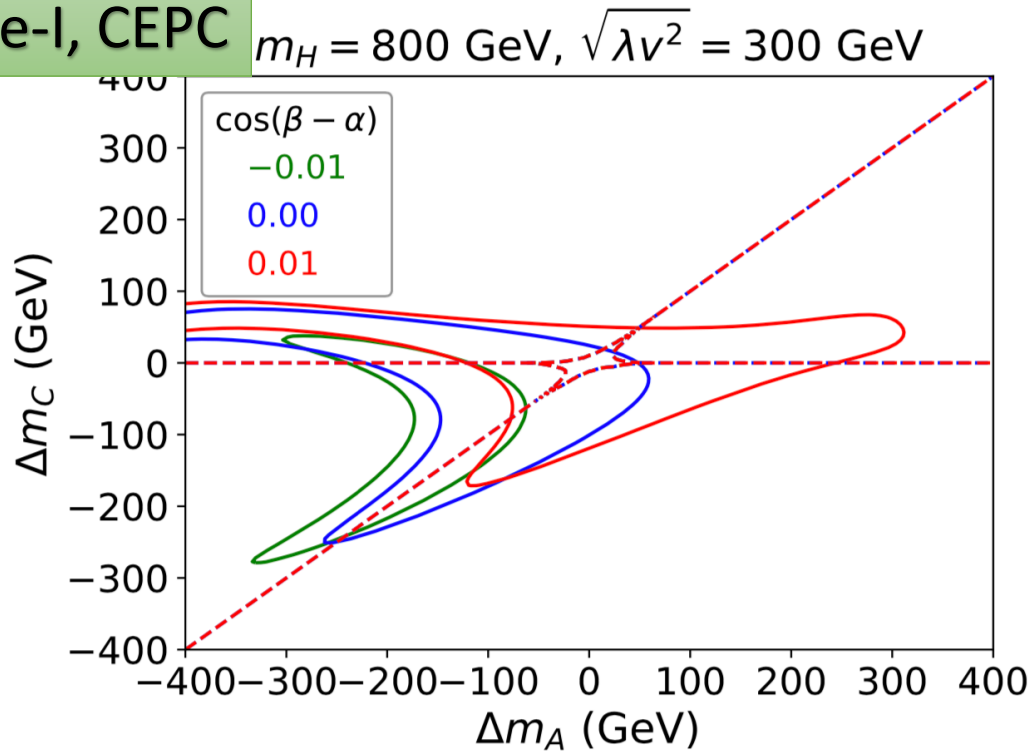


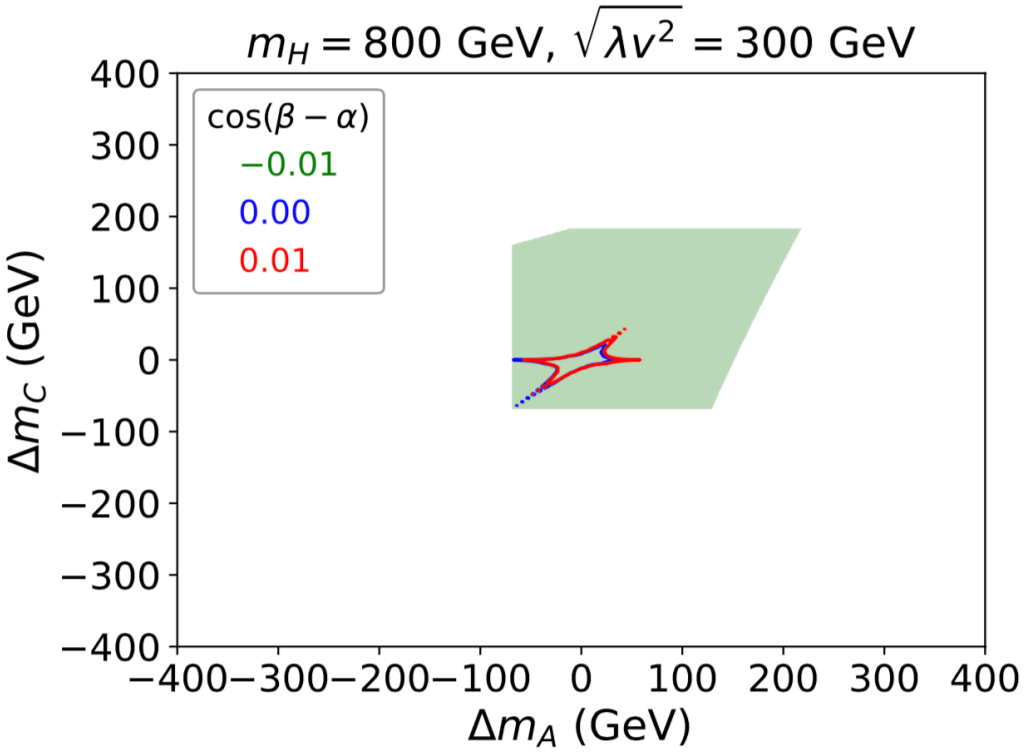
1910.06269 WS

2HDM: precision

1912.01431 N. Chen, T. Han, S. Li, S. Su, WS, Y. Wu

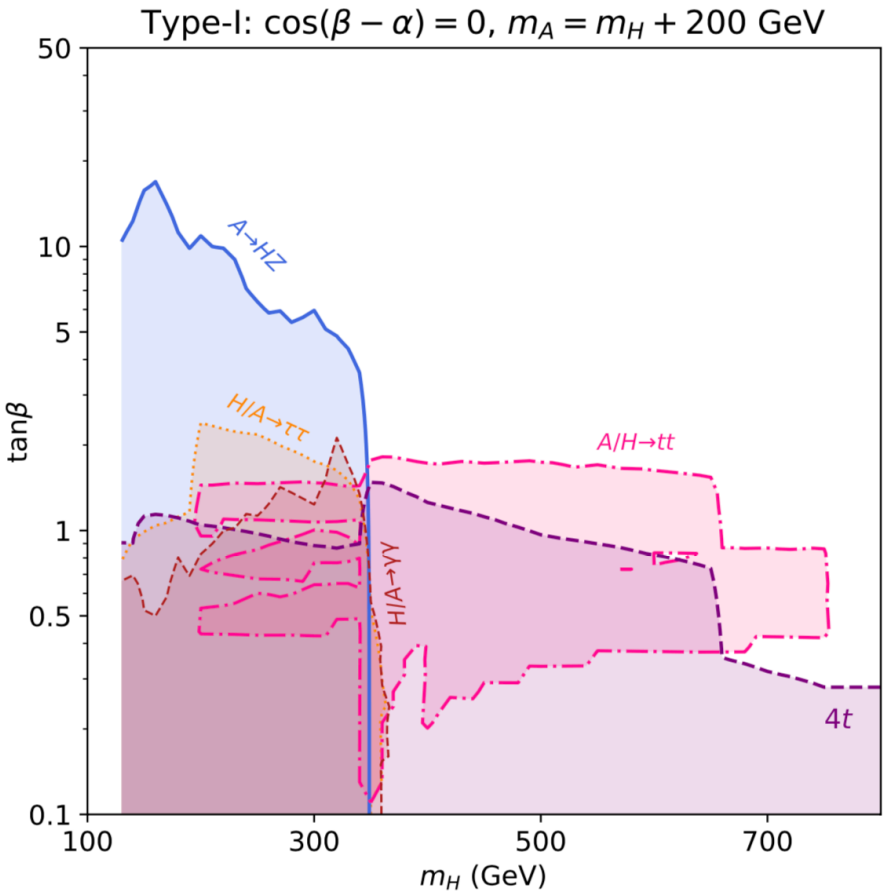
Type-I, CEPC

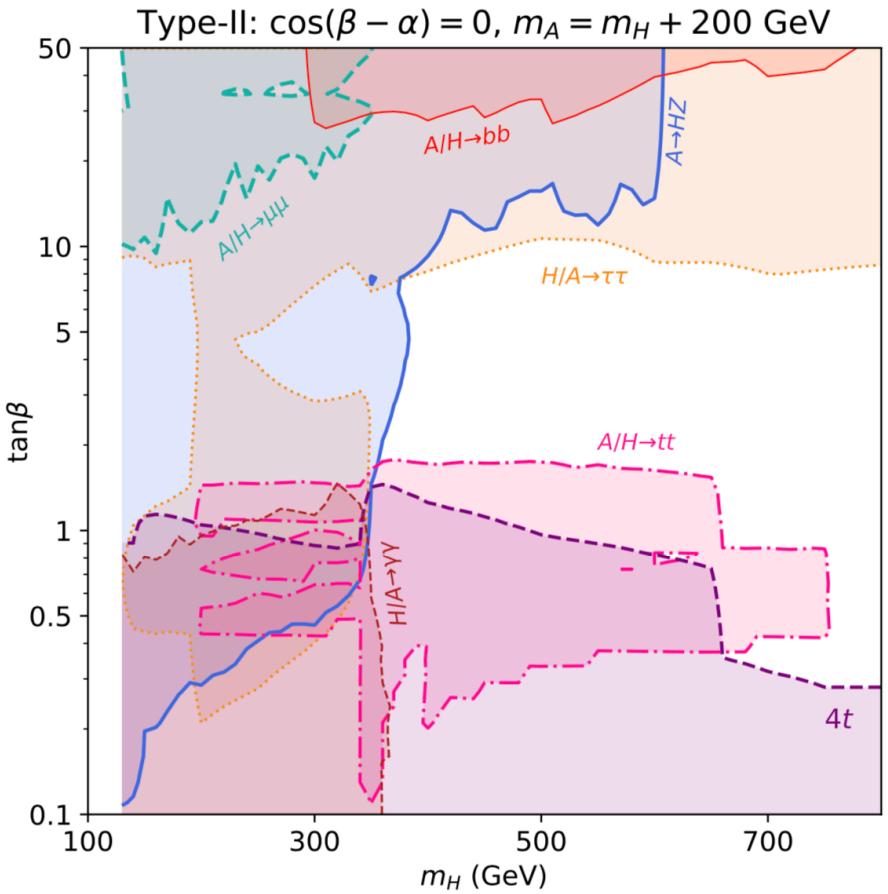




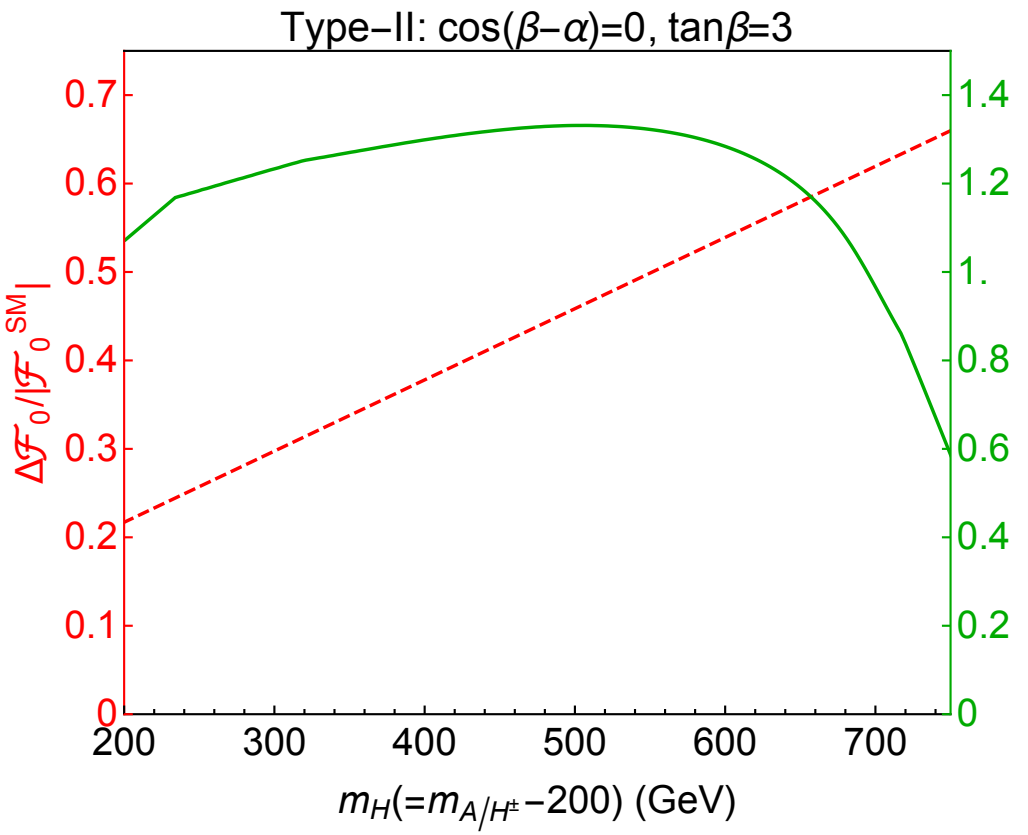
The precisions changed for Type-I and Type-II

2HDM: LHC direct search





PT vs. vacuum uplifting



Vacuum energy F

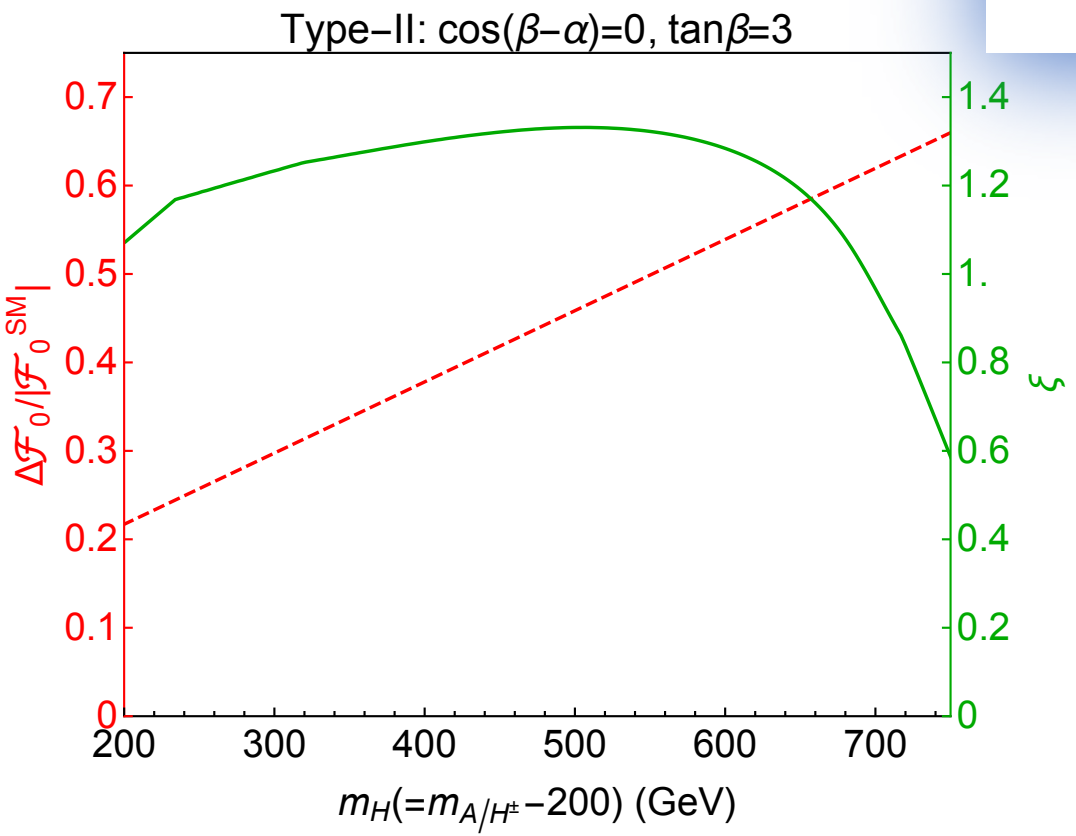
$$\mathcal{F}_0^{\rm SM} = -\frac{m_h^2 v^2}{8} + \frac{1}{64\pi^2}\left(3m_W^4 + \frac{3}{2}m_Z^4 - 6m_t^4\right) + \frac{m_h^4}{64\pi^2}(3+\log 2)$$

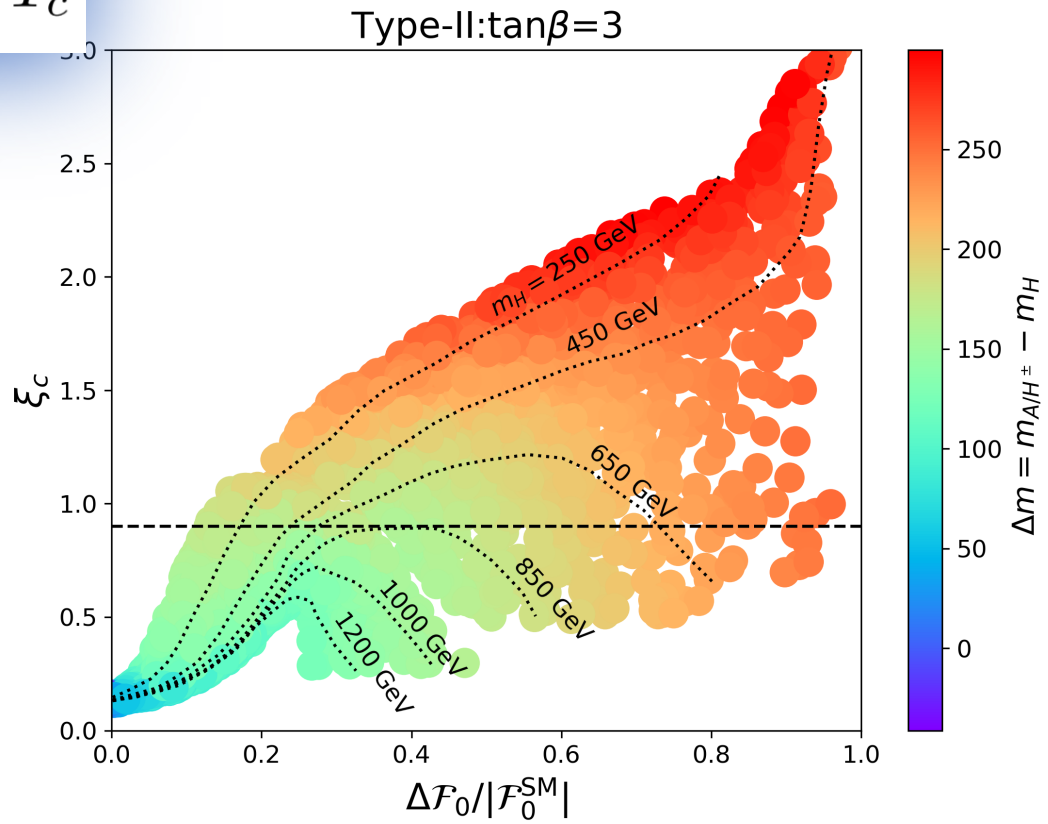
$$\xi_c \equiv \frac{v_c}{T_c}$$

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

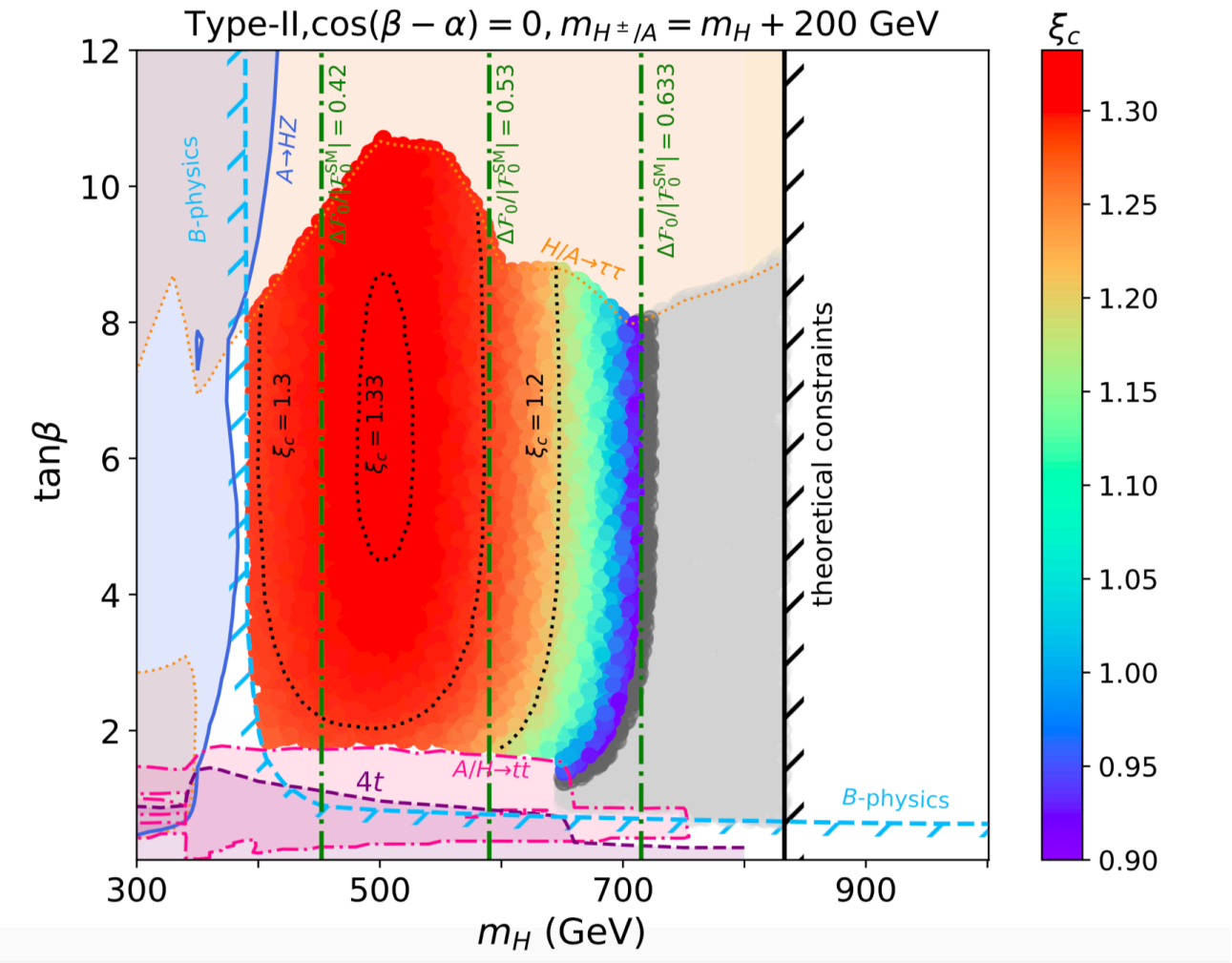
PT vs. vacuum uplifting

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





Results: Case-1

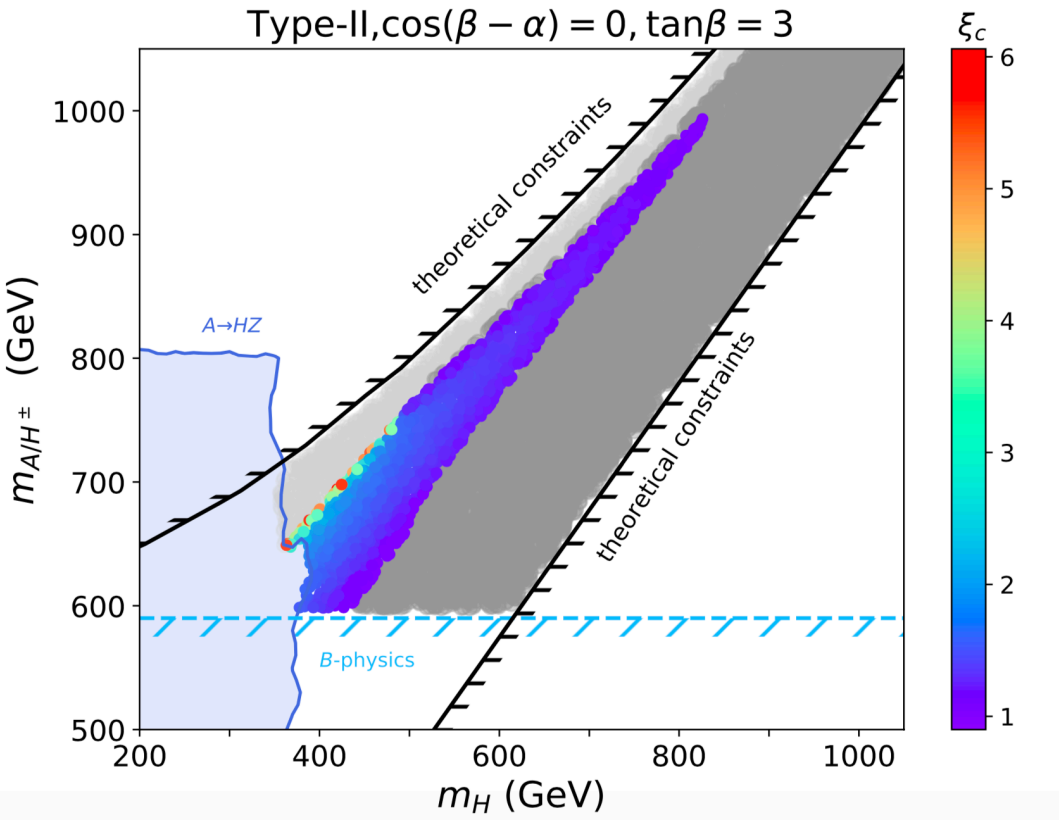


Type-II
fixed mass splitting 200 GeV

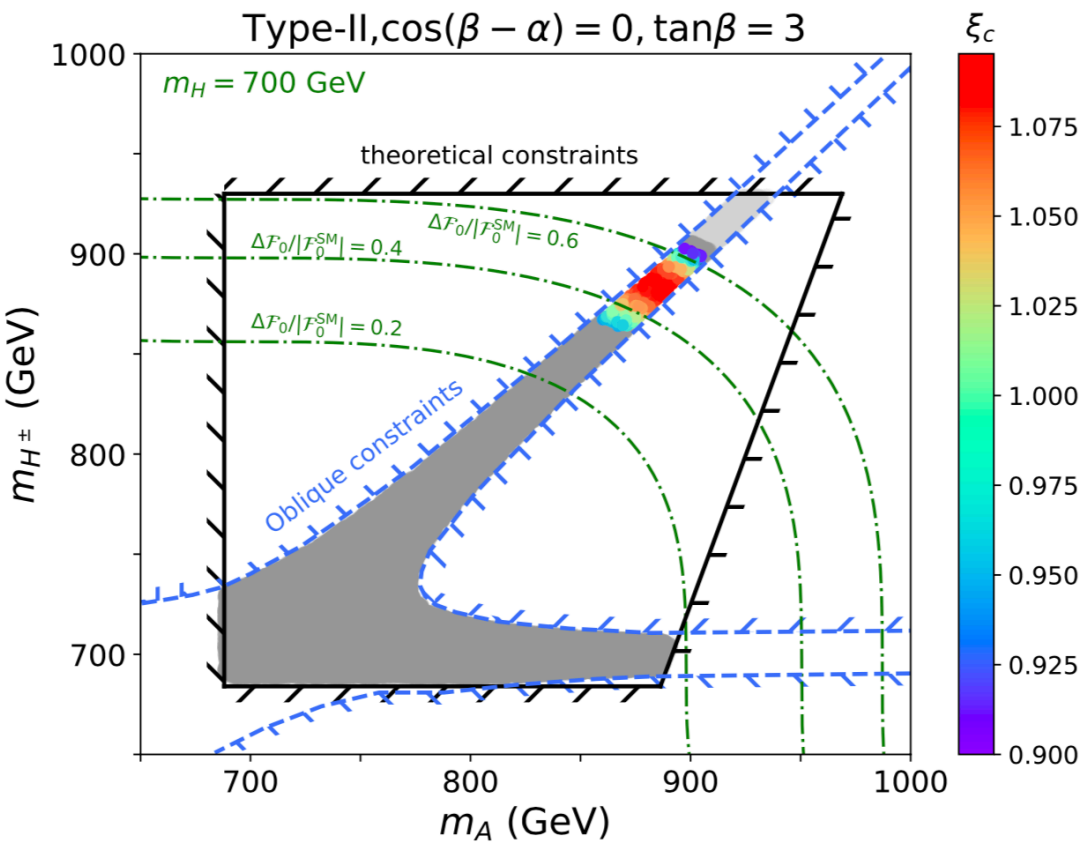
$m_H < 710$ GeV
$tan\beta\ \epsilon\ (1.8,10)$

Results: Case-2/3

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



m_H=700 GeV



Results:

High T approximation:

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

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

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

$$E_{(\alpha)} \approx \begin{cases} \frac{1}{12\pi}\lambda_\alpha^{3/2} = \frac{1}{12\pi}\frac{m_\alpha^3}{v^3}, & M^2 \ll \lambda_\alpha\phi_h^2 \\ 0, & M^2 \gg \lambda_\alpha\phi_h^2 \end{cases} \quad \lambda_{A/H^\pm}v^2 = (\Delta m)^2 + 2m_H\Delta m$$

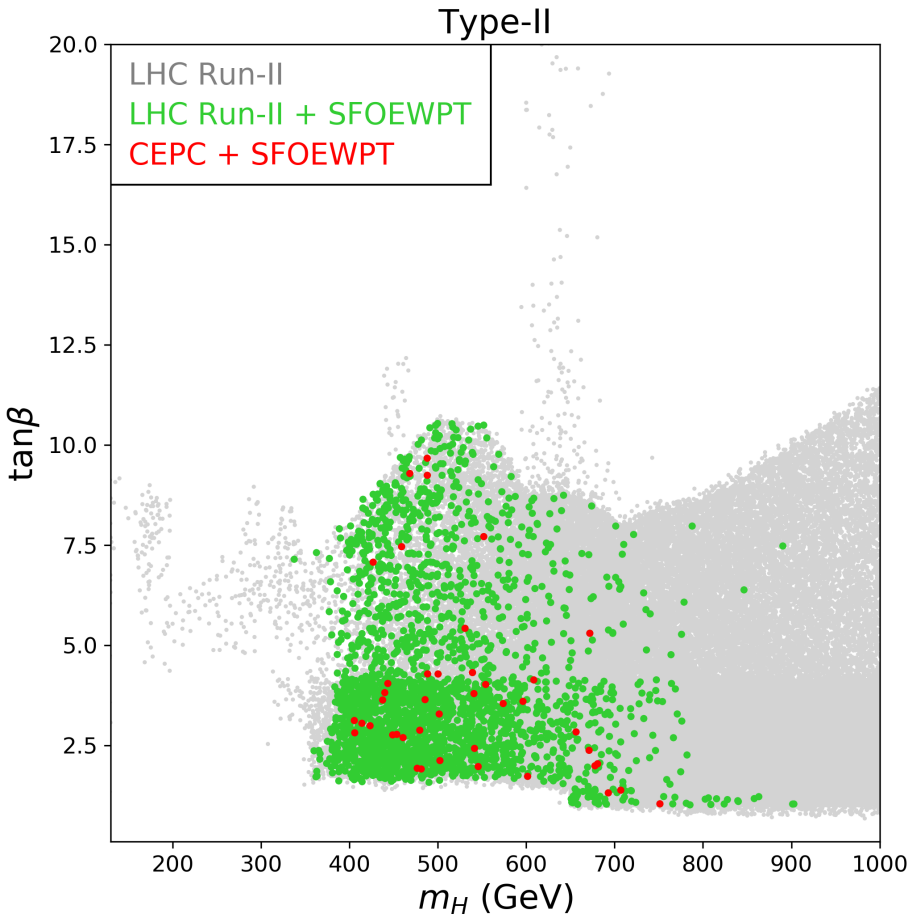
Vacuum uplifting:

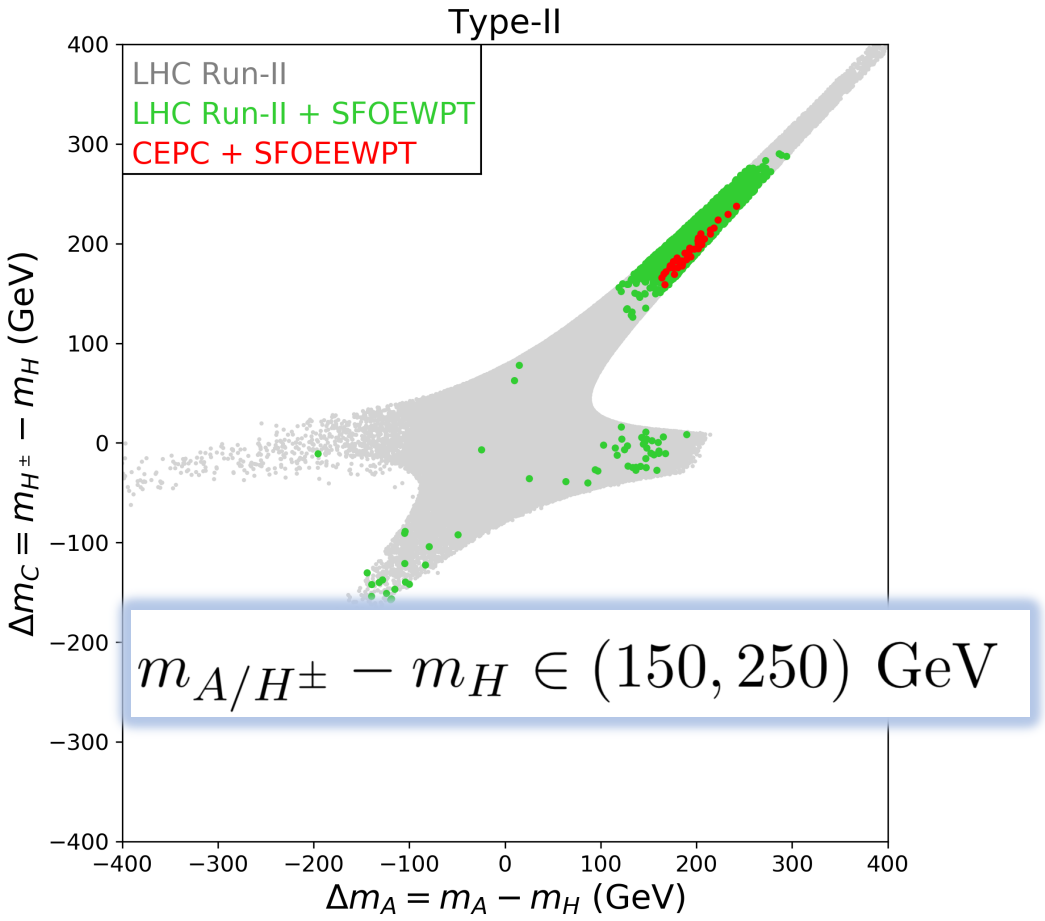
$$\Delta\mathcal{F}_0 = \frac{1}{64\pi^2}\left[\left(m_h^2 - 2M^2\right)^2\left(\frac{3}{2} + \frac{1}{2}\log\left[\frac{4m_A m_H m_{H^\pm}^2}{\left(m_h^2 - 2M^2\right)^2}\right]\right)\right.$$

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

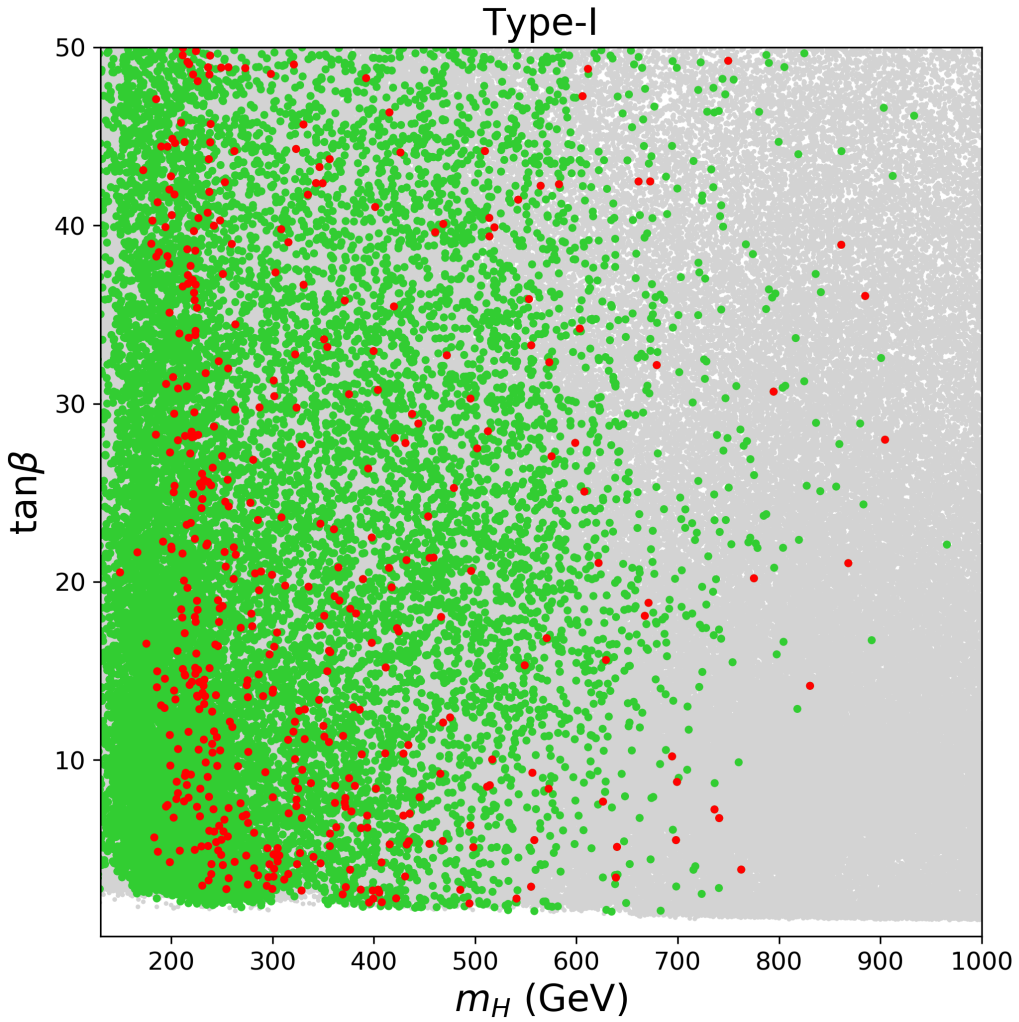
Too large masses or mass splitting can not generate SFOEWPT

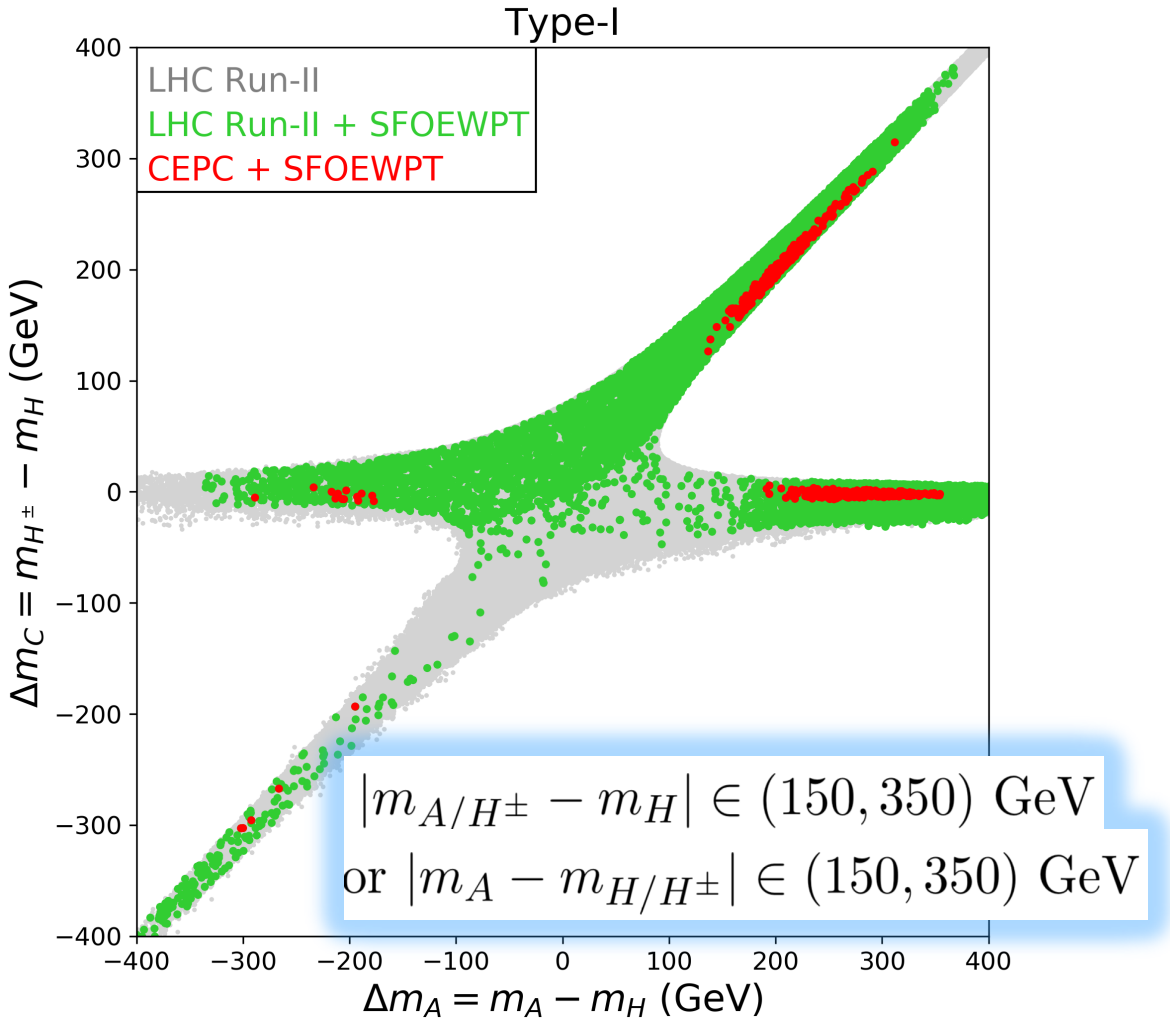
Results: Type-II



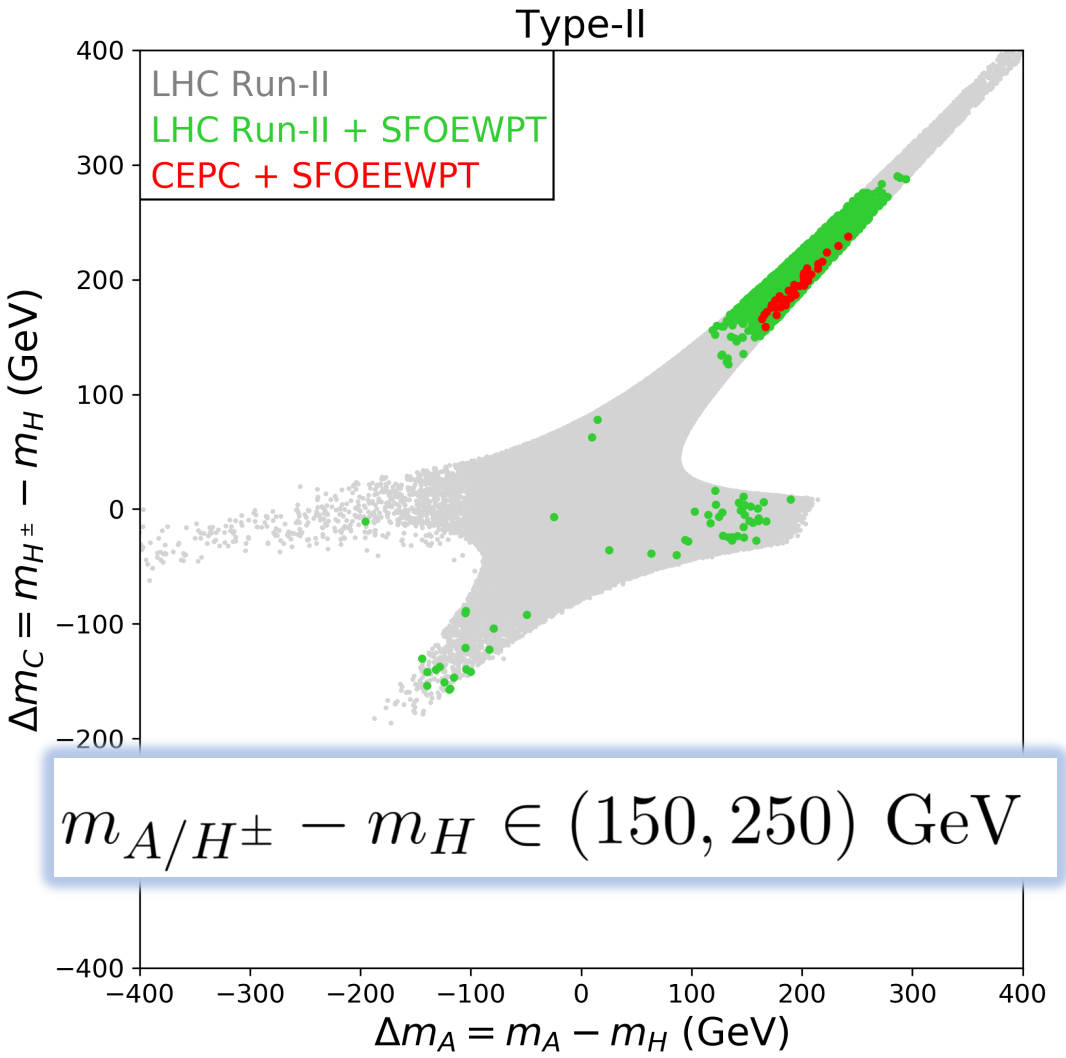


Results: Type-I

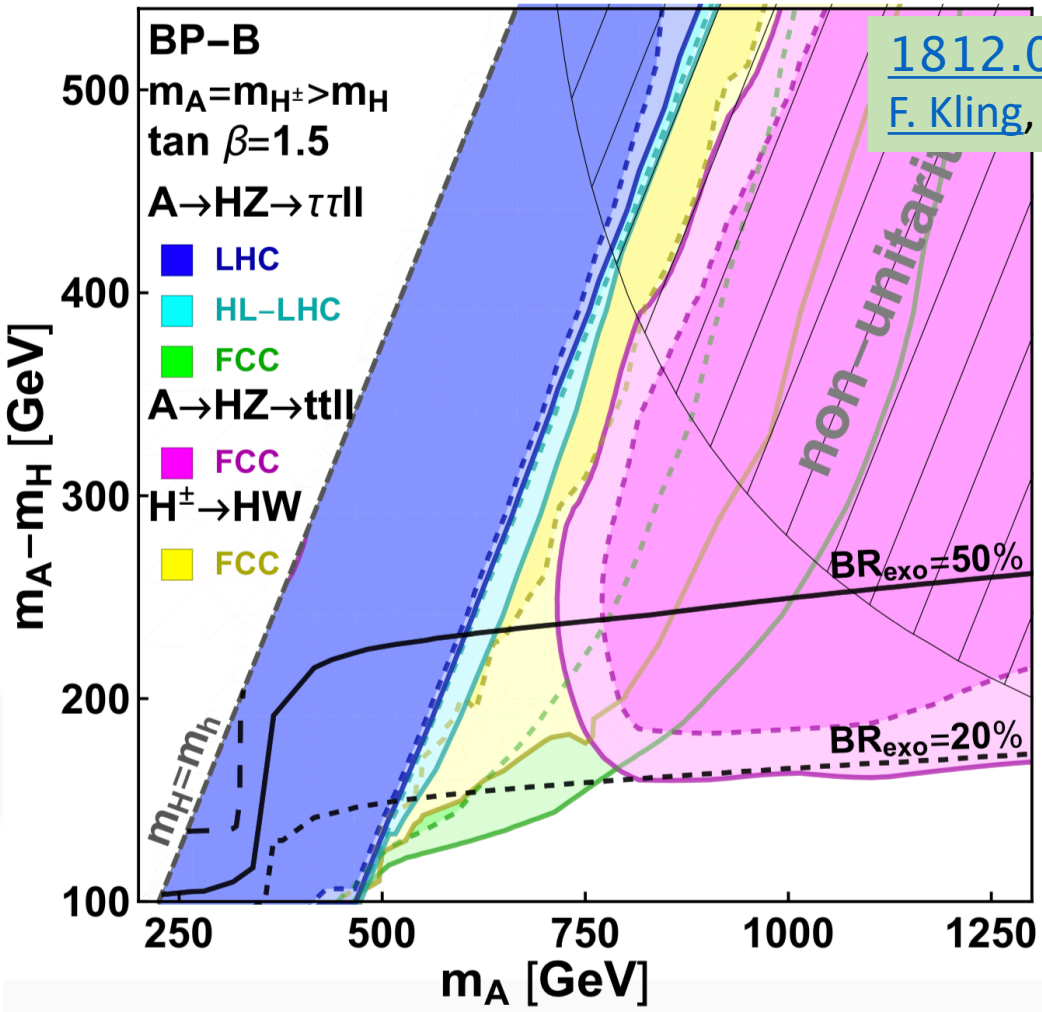




Future

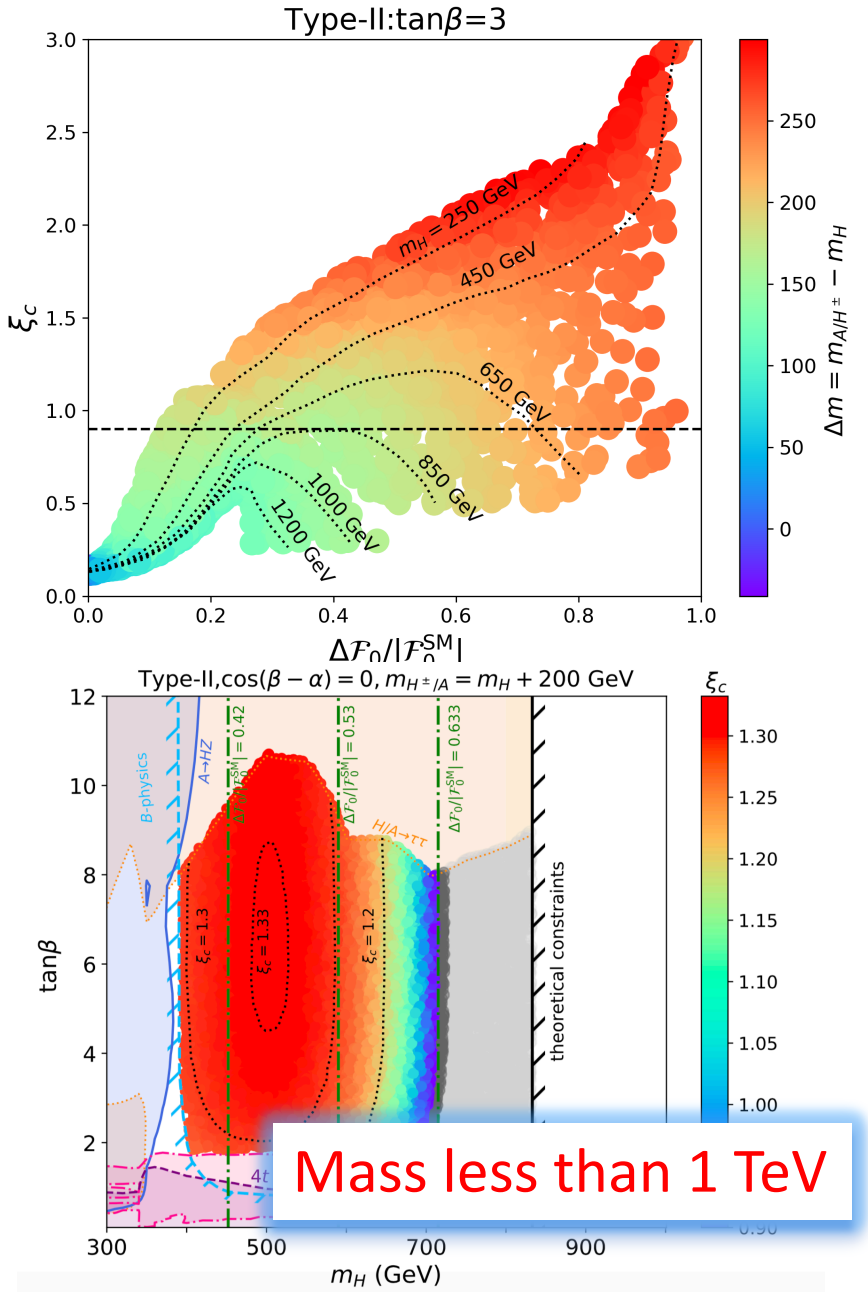


$$m_{A/H^\pm} - m_H \in (150, 250)\ \text{GeV}$$

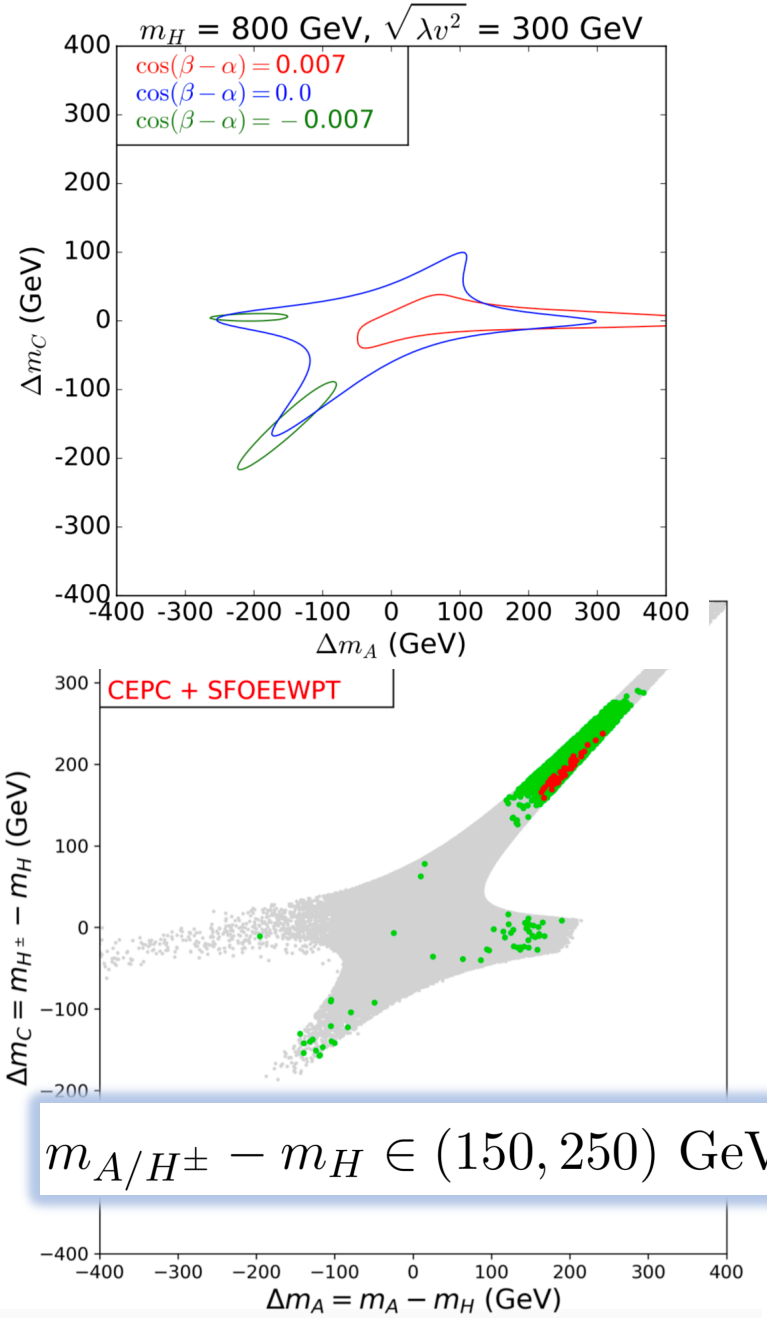


1812.01633
F. Kling, H. Li, etc

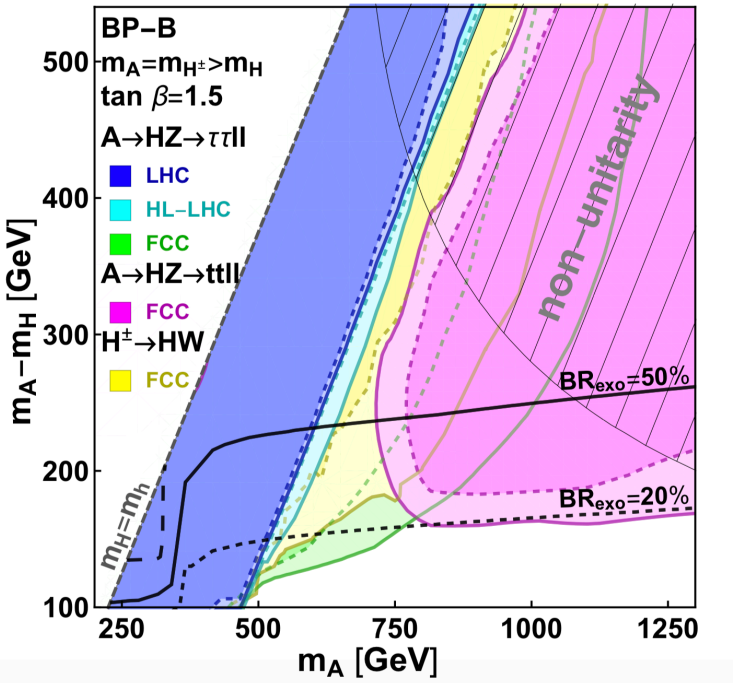
Conclusion



Mass less than 1 TeV



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



Thanks!

backup