Possibility of multi-step electroweak phase transition in the two Higgs doublet models

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Mayumi Aoki, Takatoshi Komatsu, H. S.　PTEP 2022 (2022) 6, 063B05
[arXiv:2106.03439]

Workshop on Multi-Higgs Models 2022

Introduction

Motivations of multi-step EW phase transitions (PTs):

EW baryogenesis (by achieving a first-order EWPT)

(Multi-peaked) gravitational waves (GWs)

Changing DM abundance (but irrelevant with this talk)

[HS, Toma ('22), arXiv:2207.14662]

Features of the multi-step PTs

With the appearance of a public code "CosmoTransitons," [Wainwright ('12)] studies of multi-step EWPTs have become much easier.

▼ However,

the number of articles that study features of multi-step PTs is small.

▼ Therefore,

we studied their features and causes in CP-conserving 2HDMs, and we would imply general features of multi-step PTs.

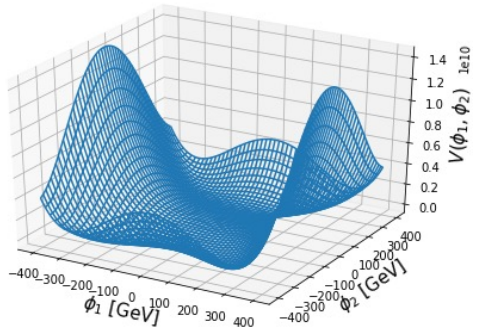
Two Higgs Doublet Model

2HDM is a model added one more SU(2) doublet to the SM.

$$V_0(\Phi_1,\Phi_2) = -m_1^2\Phi_1^\dagger\Phi_1 - m_2^2\Phi_2^\dagger\Phi_2 - m_3^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1) + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \frac{v_i+h_i+iz_i}{\sqrt{2}} \end{pmatrix} \quad (i=1,2), \quad \sqrt{v_1^2+v_2^2} = 246\ \text{GeV}$$

$$V_{eff} = V_0 + V_{1-\text{loop}} + V_{\text{daisy}}$$



Types of Yukawa interactions

To avoid FCNC processes, assume two doublets has different Yukawa couplings.

Type	u type	d type	lepton
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Type-X	Φ_2	Φ_2	Φ_1
Type-Y	Φ_2	Φ_1	Φ_2

Constraints

Input parameters) $m_{H^\pm},\ m_A,\ m_H,\ \tan\beta,\ \cos(\beta-\alpha),\ m_3$

Theoretical constraints

Bounded from below

Perturbative theory $|\lambda_i| < 4\pi$

Tree-level unitarity

Stability of EW vacuum (confirmed numerically in $|\phi_i| < 10$ TeV)
[Barroso, Ferreira, Ivanov, Santos ('13); Ivanov, Silva ('15)]

Experimental constraints

Electroweak precision data

$\rightarrow\ m_{H^\pm} = m_A$ or m_H [Haber, O'Neil ('11)]

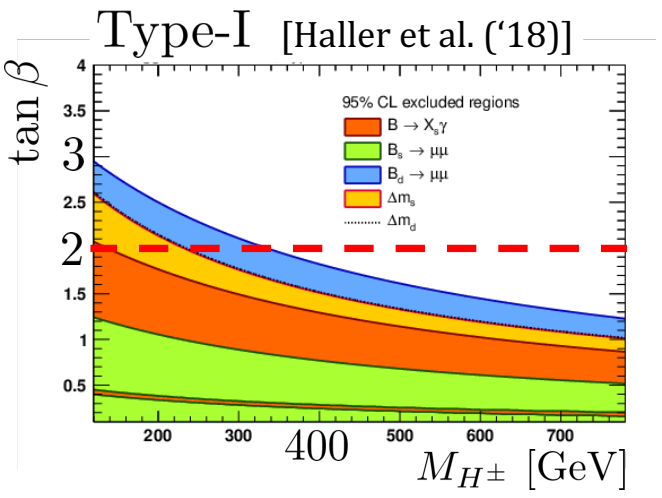
Flavor experiments

From $B_d \to \mu\mu,\ \tan\beta \gtrsim 2$ (Type-I)

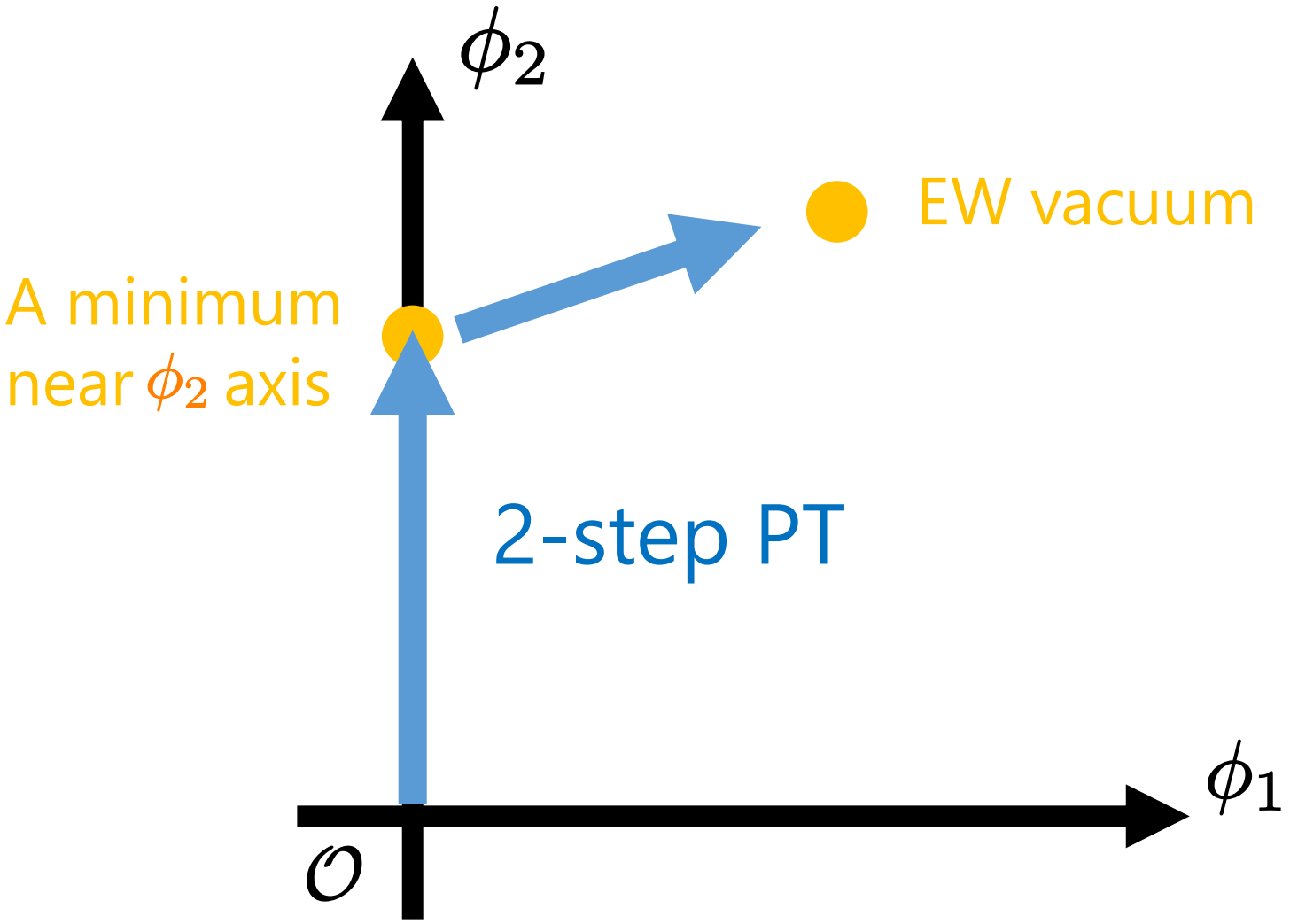
$m^\pm \to \tau\nu,\ m_H^\pm > 170$ GeV (Type-X)
[Arhrib, Moretti et al. ('18)]

Higgs couplings strength [ATLAS Collab. ('19)]

$\rightarrow\ |\cos(\beta-\alpha)| \lesssim 0.25$ (for $\tan\beta \gtrsim 2$, Type-I)



Typical Path of a 2-step PT



Numerical Results

M. Aoki, T. Komatsu, H. S.
[arXiv:2106.03439]

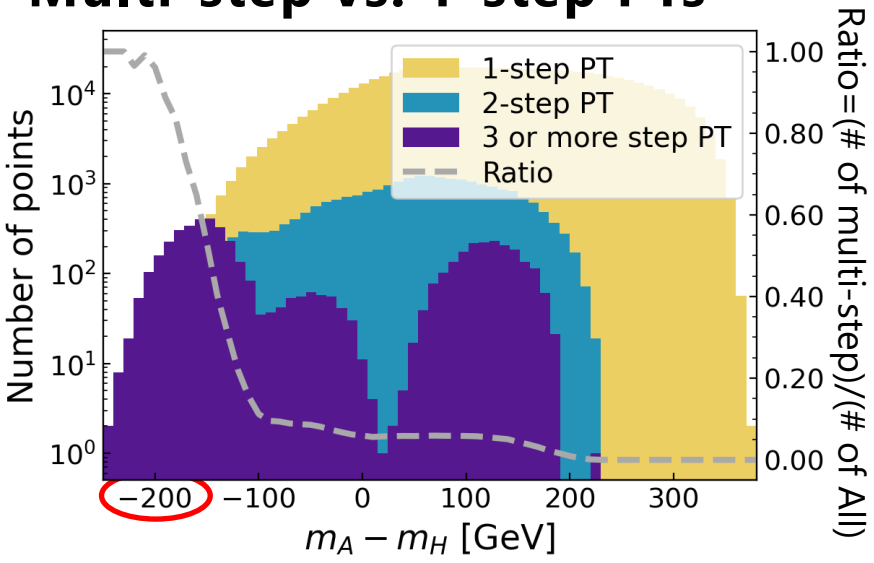
Searched parameter region (in Type-I)

$m_H^\pm = m_A$ [GeV]	m_H [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	m_3 [GeV]
180–1000 (/10)	180–1000 (/10)	2–10 (/0.5)	-0.25–0.25 (/0.05)	0–100 (/5)

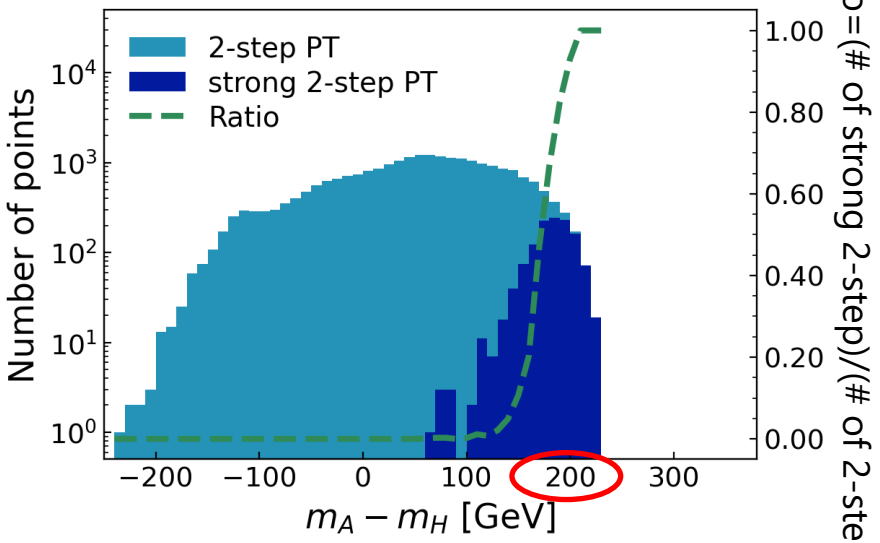
(You can see results for the other cases in our paper.)

Number Analyses

Multi-step vs. 1-step PTs



Strong 2-step PT: 2-step PT where the 1st step is strongly 1st order



Large $|m_A - m_H|$ is favored in both cases.

Features of multi-step PTs

We find multi-step PTs occur in wide parameter ranges.

Especially, **multi-step PTs favor ranges where:**

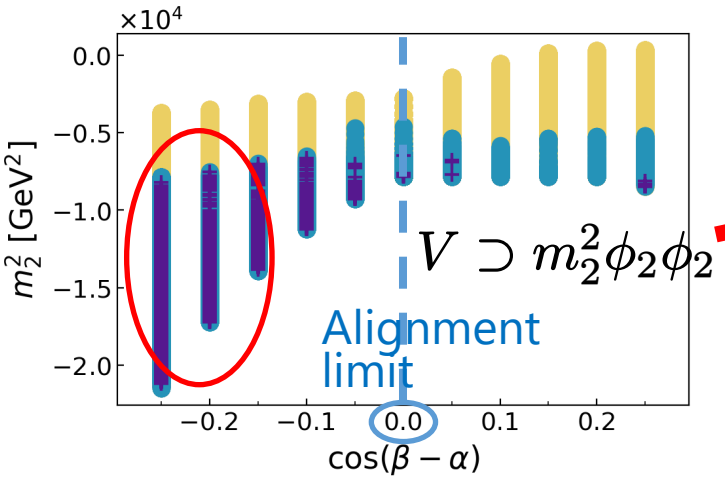
Large $|\mathbf{m_A - m_H}|$ Non-decoupling effects

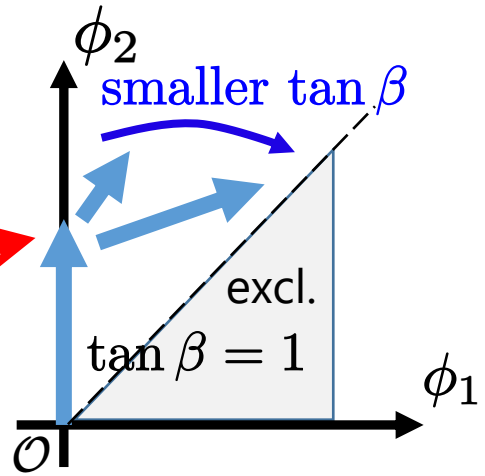
Negative and small $\cos(\beta-\alpha)$

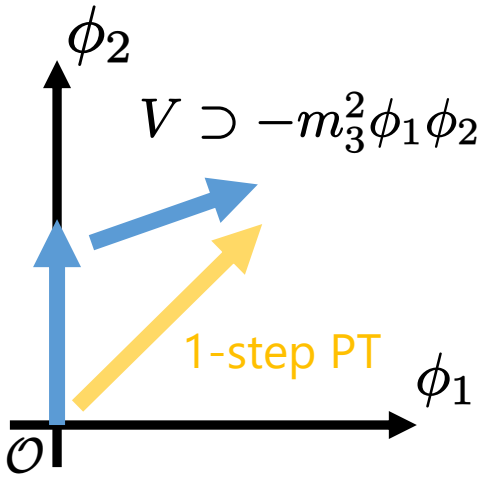
Small $\tan\beta$ (large distance between two minima)

Small m_2^2

Small $\mathbf{m_3^2}$ (approx. Z_2 sym. If it is large, the PT becomes 1-step PT)
(Non-decoupling effects & small m2^2)



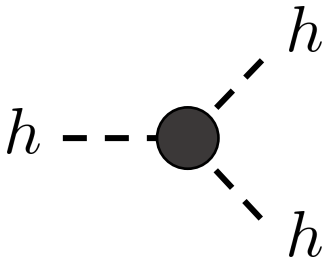


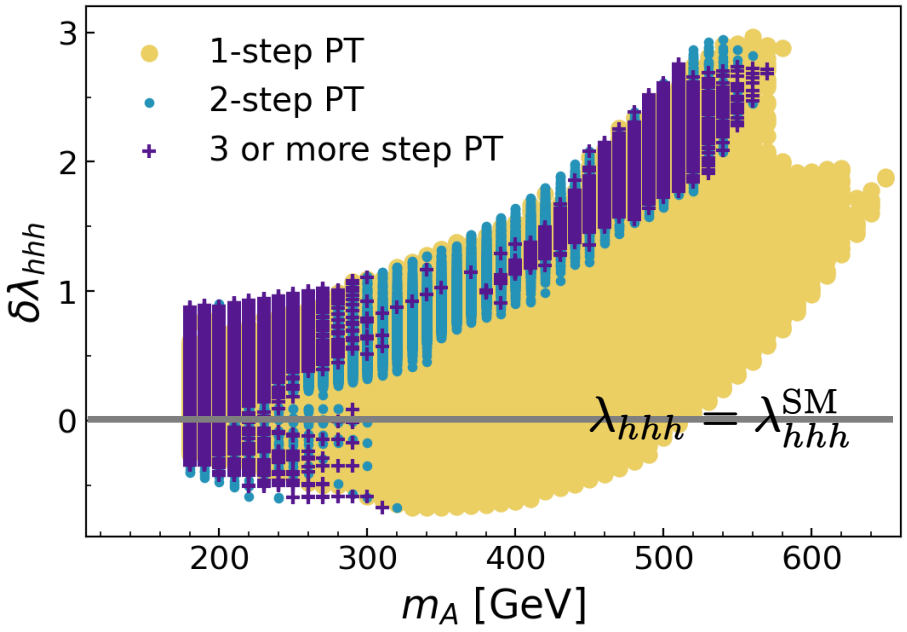


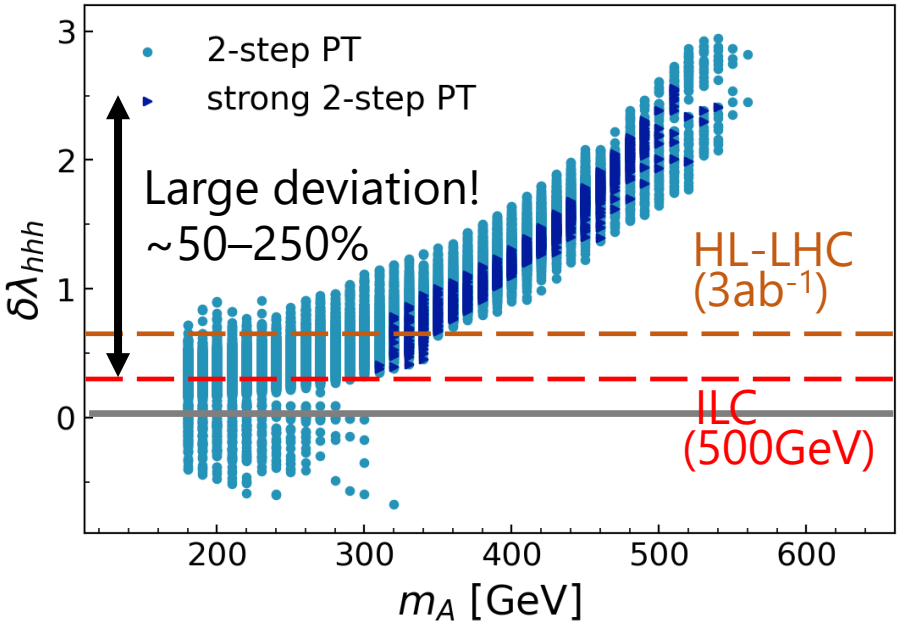
Higgs trilinear couplings

The deviation of the Higgs trilinear coupling from the SM

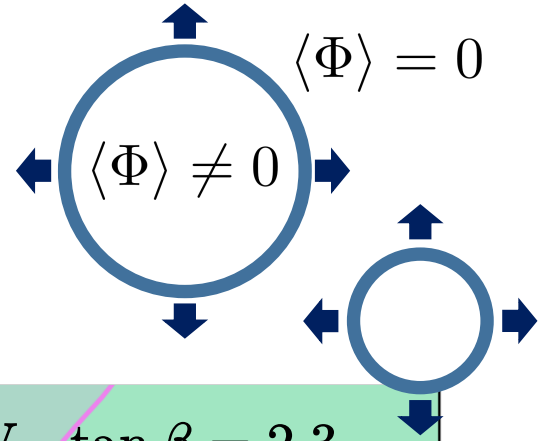
$$\lambda_{hhh} = \left.\frac{\partial^3 V_{\rm eff}}{\partial h^3}\right|_{\langle\phi\rangle}, \quad \delta\lambda_{hhh} \equiv \frac{\lambda_{hhh} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}}$$



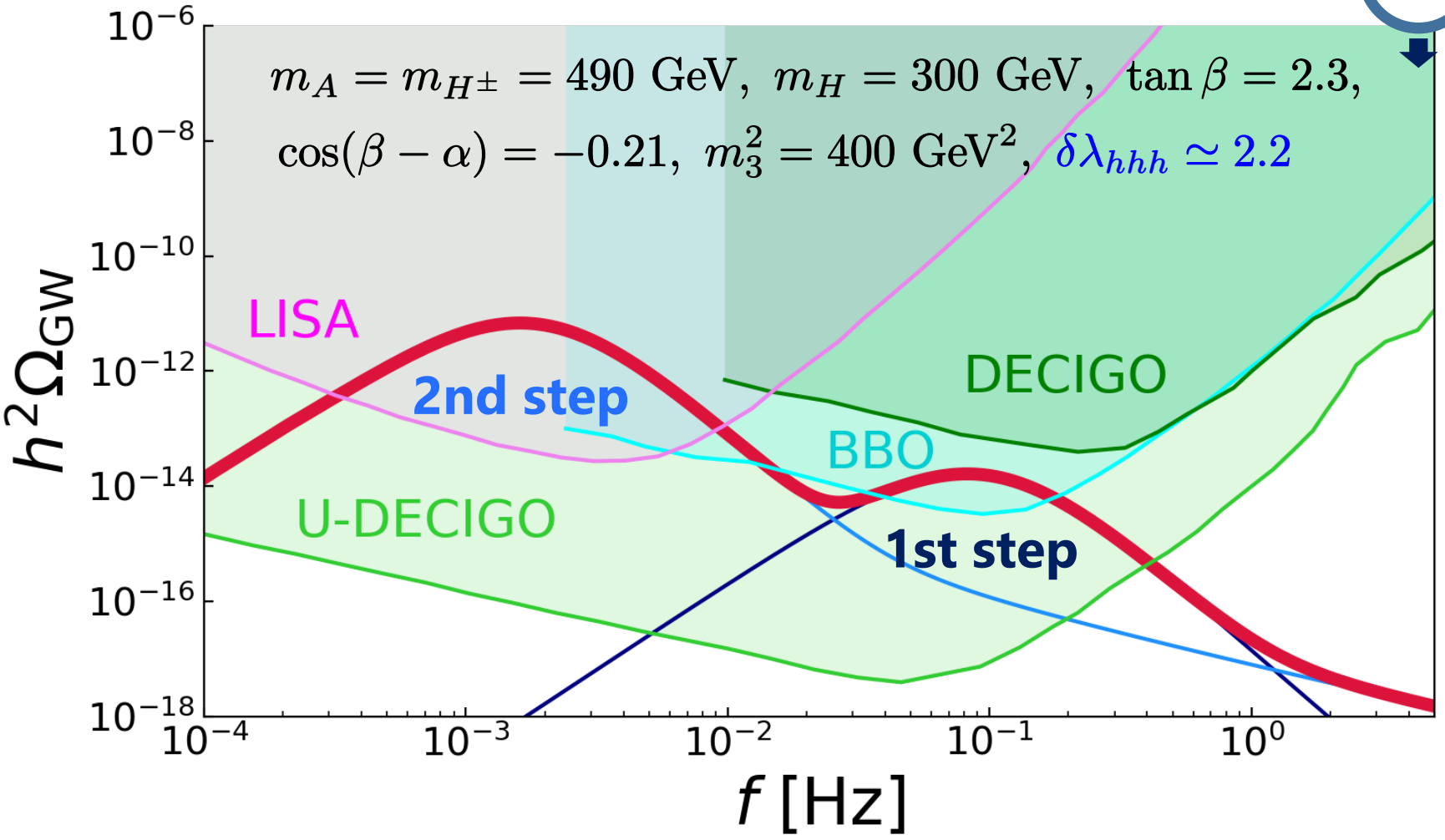




Gravitational Wave



GW spectrums from a 2-step PT



Summary

We find wide areas where multi-step PTs occur in the CP-conserving 2HDM.

We also reveal their features and causes, as the non-decoupling effect and the approx. Z2 sym. …

Multi-step PTs favor the deviations from the SM!

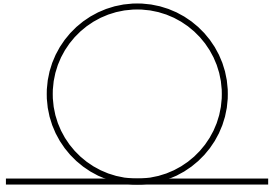
Future experiments especially for the **Higgs trilinear coupling** and **the GW spectrum** could verify the multi-step PTs.

Back Up

The Effective Potential

The one-loop corrected effective potential

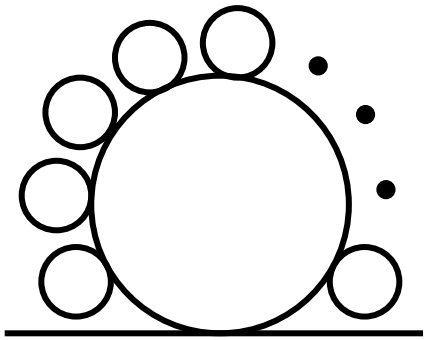
$$V^{\beta} = V_0 + V_1^0 + V_{\rm CT} + \underset{\sim}{\overline{V}_1^{\beta}}$$ Thermal effect



- V_1^0 the one-loop contributions at zero temperature
- $V_{\rm CT}$ the counter term for maintaining
  - the position of the minimum
  - the input parameters
- $\bar{V}_1^{\beta}$ the one-loop contributions at finite temperature

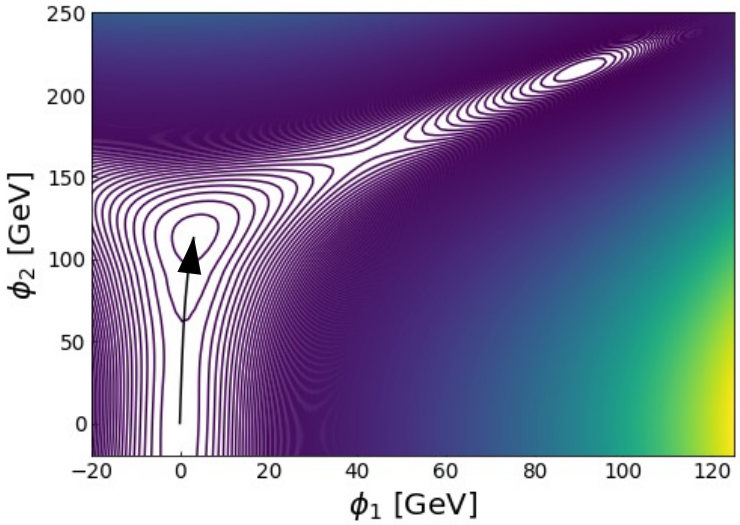
Resummation

We perform the numerical method for summing "Daisy diagram," called "Resummation." [Dolan, Jackiw ('74)] [Parwani ('92)]



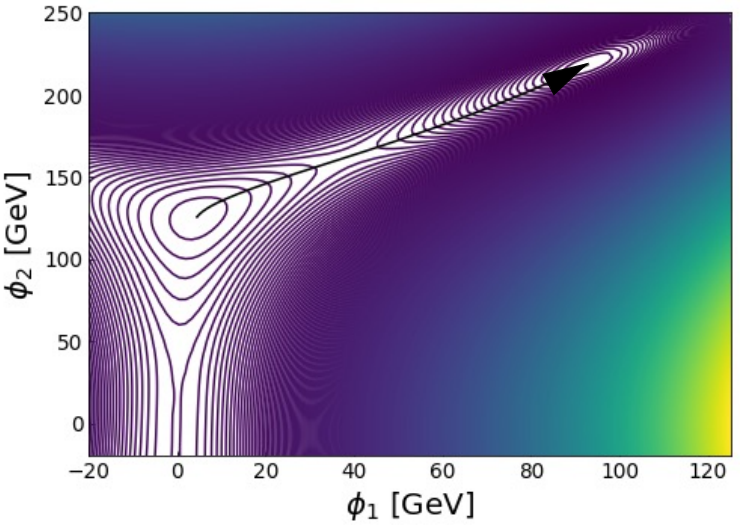
Pass of a multi-step EWPT

First step PT



From the origin to ϕ_2 axis,
(strong) 1st order PT occurs.

Second step PT



From ϕ_2 axis to EW vacuum,
1st or 2nd order PT occurs.

"Strong" means that the PT satisfies
the condition for suppressing the sphaleron processes $v(T_c)/T_c \geq 1$.

[Shaposhnikov ('86,'87,'88), Erratum(92)]

Numerical Results

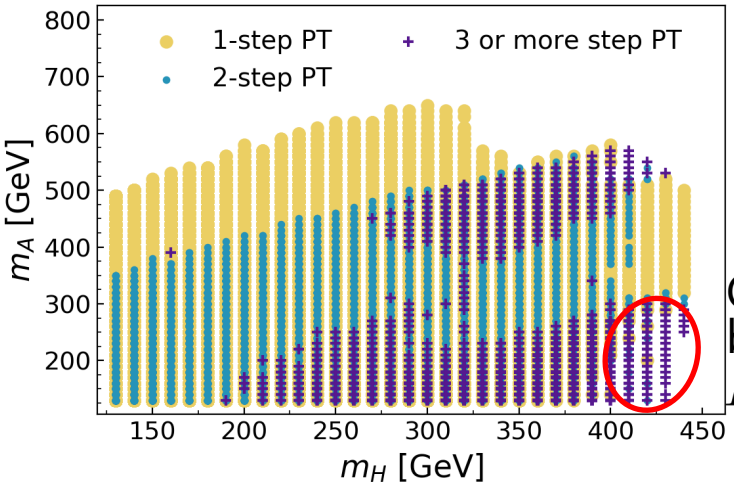
M. Aoki, T. Komatsu, H. S.
[arXiv:2106.03439]

Case of Type-I $(\mathbf{m_A = m_{H^\pm}})$ (we use CosmoTransitions)

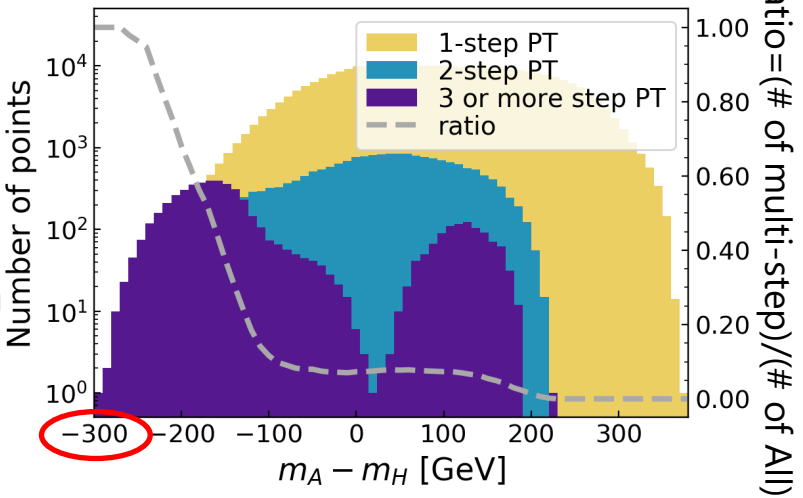
[Wainwright ('12)]

m_A [GeV]	m_H [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	m_3^2 [GeV^2]
130–1000	130–1000	2–10	−0.25–0.25	0–10^4

1-step PT vs. multi-step PT



Constrain by $B \to \mu\mu$



Multi-step PTs have tendency to occur with $m_A - m_H < 0$ and large $|m_A - m_H|$.

Numerical Results

M. Aoki, T. Komatsu, H. S.
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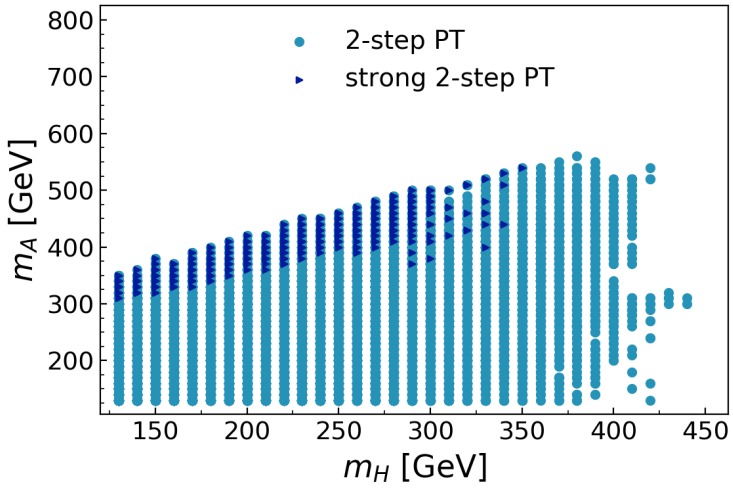
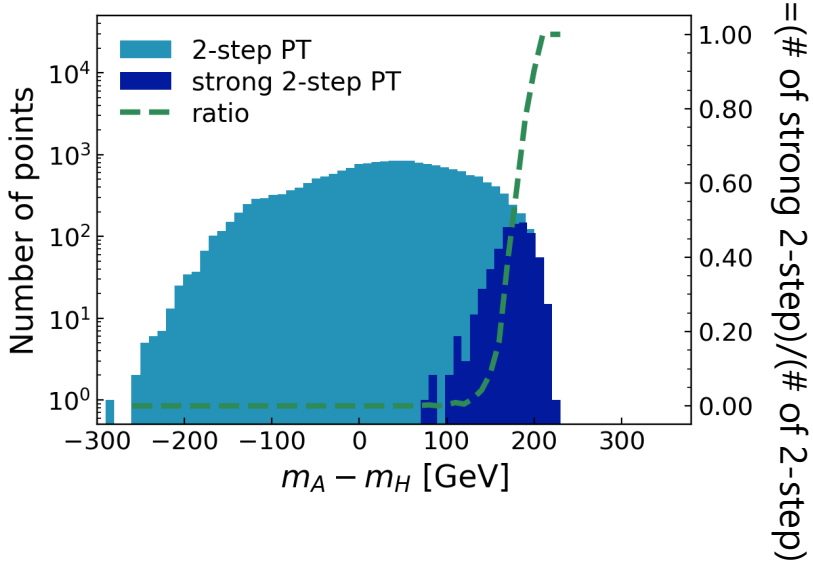
m_A [GeV]	m_H [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	m_3^2 [GeV^2]
130–1000	130–1000	2–10	−0.25–0.25	0–10^4

2-step PT vs. "strong 2-step" PT

2-step PT where 1st step is strongly 1st order





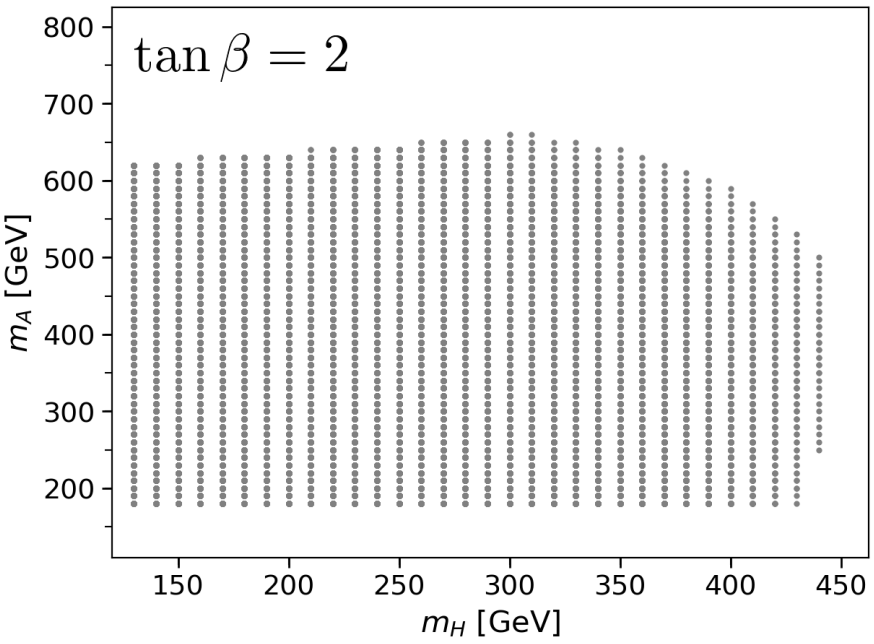
Strong 2-step PTs only occur with $m_A - m_H < 0$.

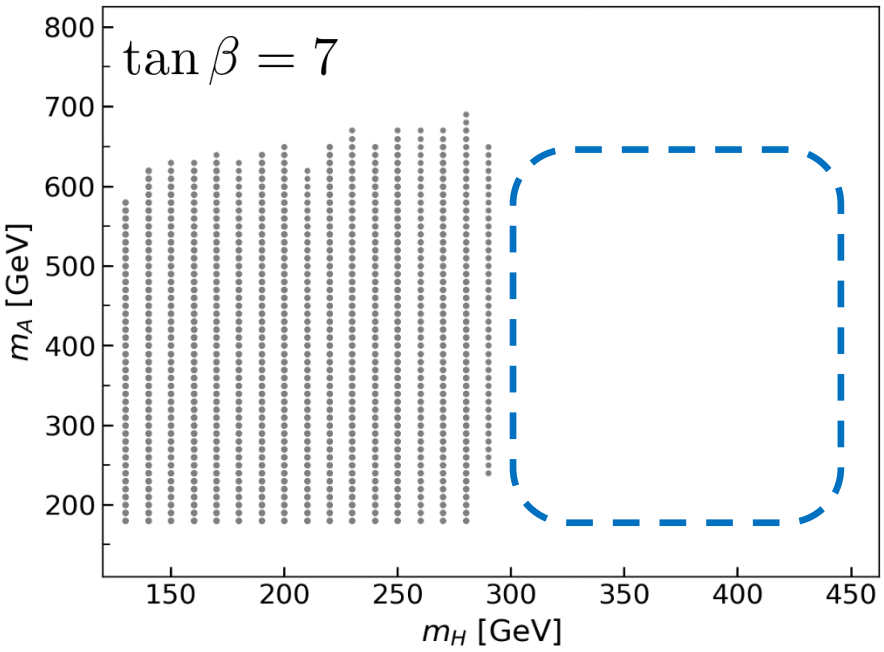
Opposite to the result of multi-step!

Back up (Constraints)

Theoretical Constraints

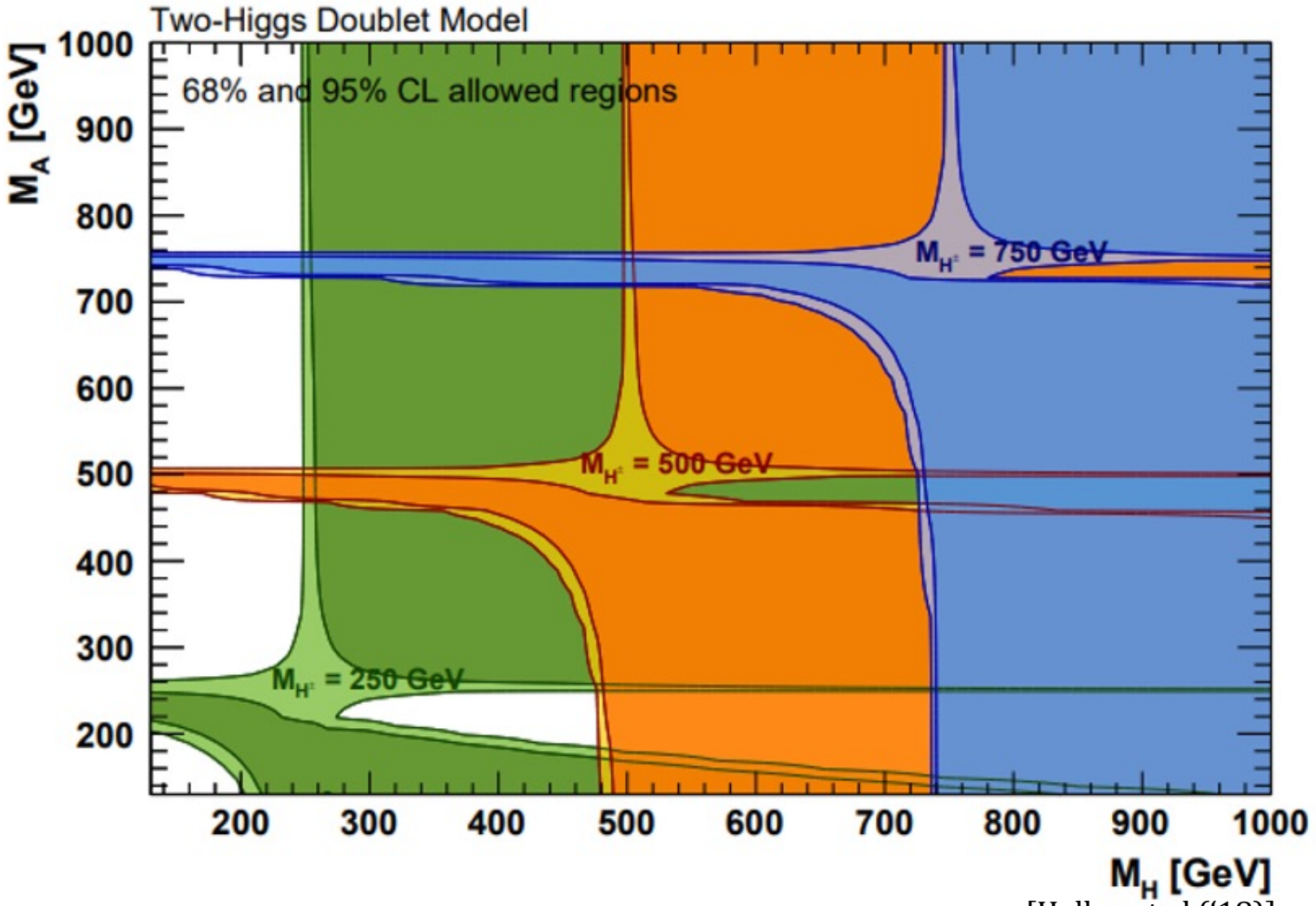
Allowed area by constraints from BFB, perturbative theory and tree-level unitarity in Type-I with $m_A = m_{H^\pm}$





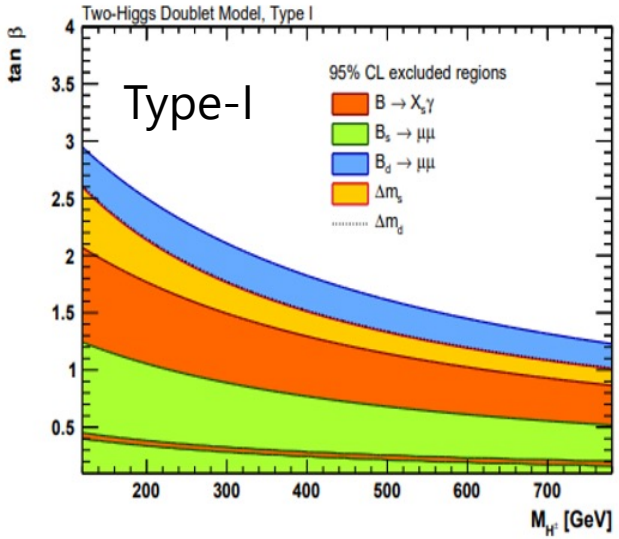
Even if in Type-I with $m_H = m_{H^\pm}$, large m_H is constrained at large $\tan\beta$.

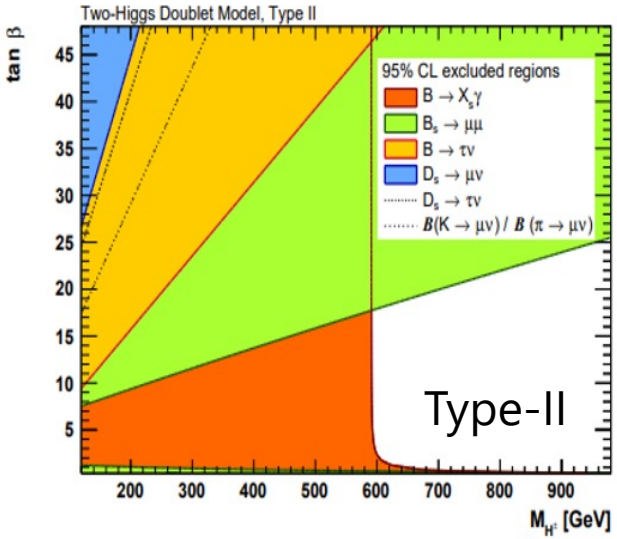
Electroweak Precision data

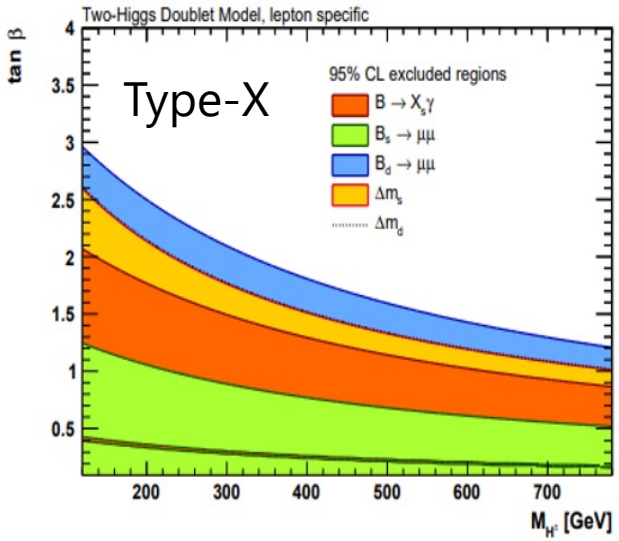


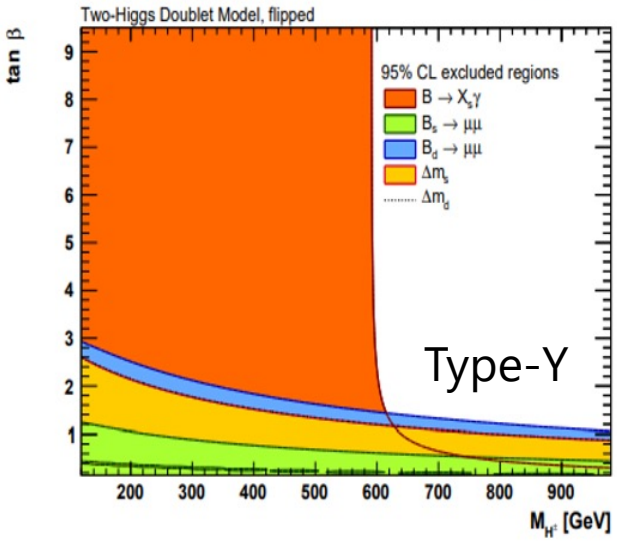
[Haller, et al.('18)]

Flavor Experiments



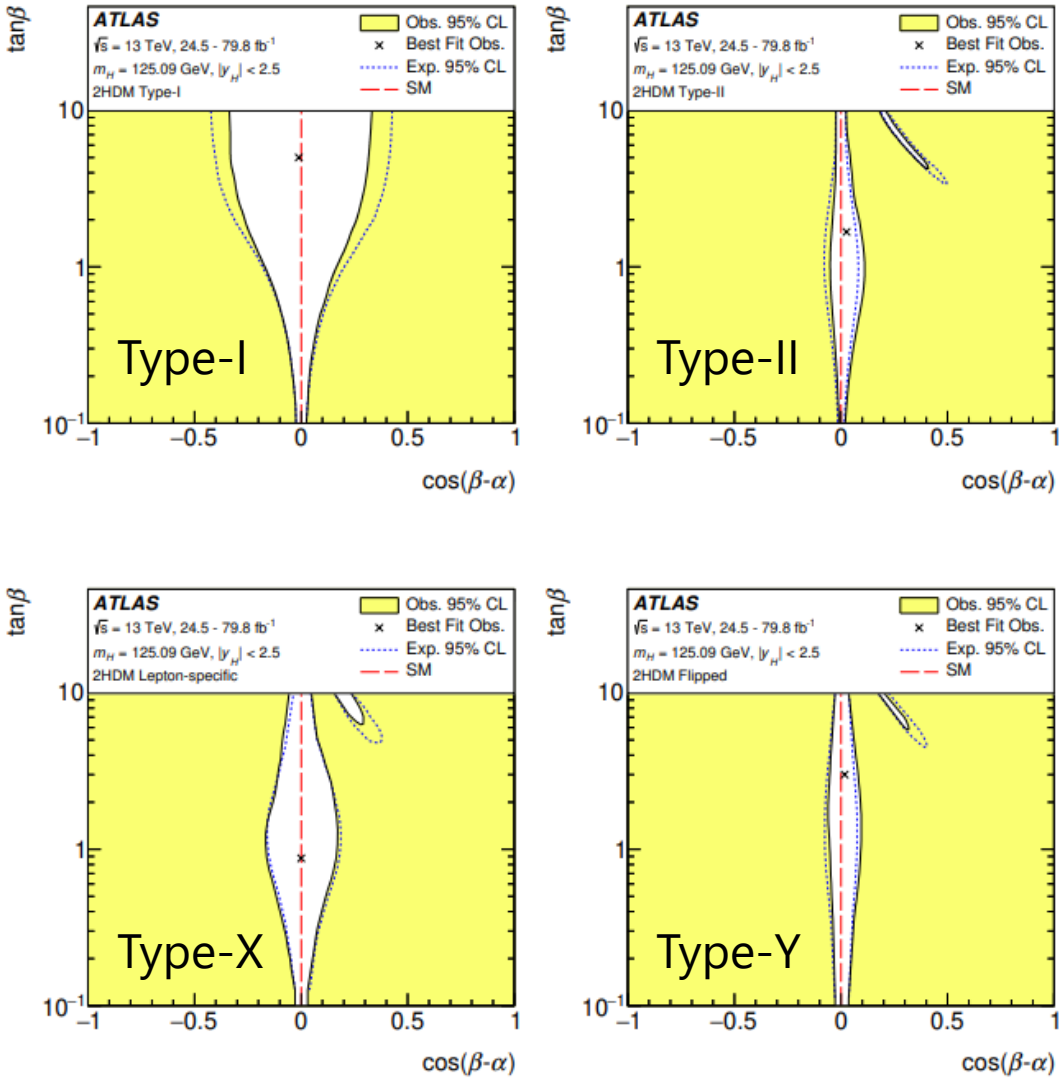






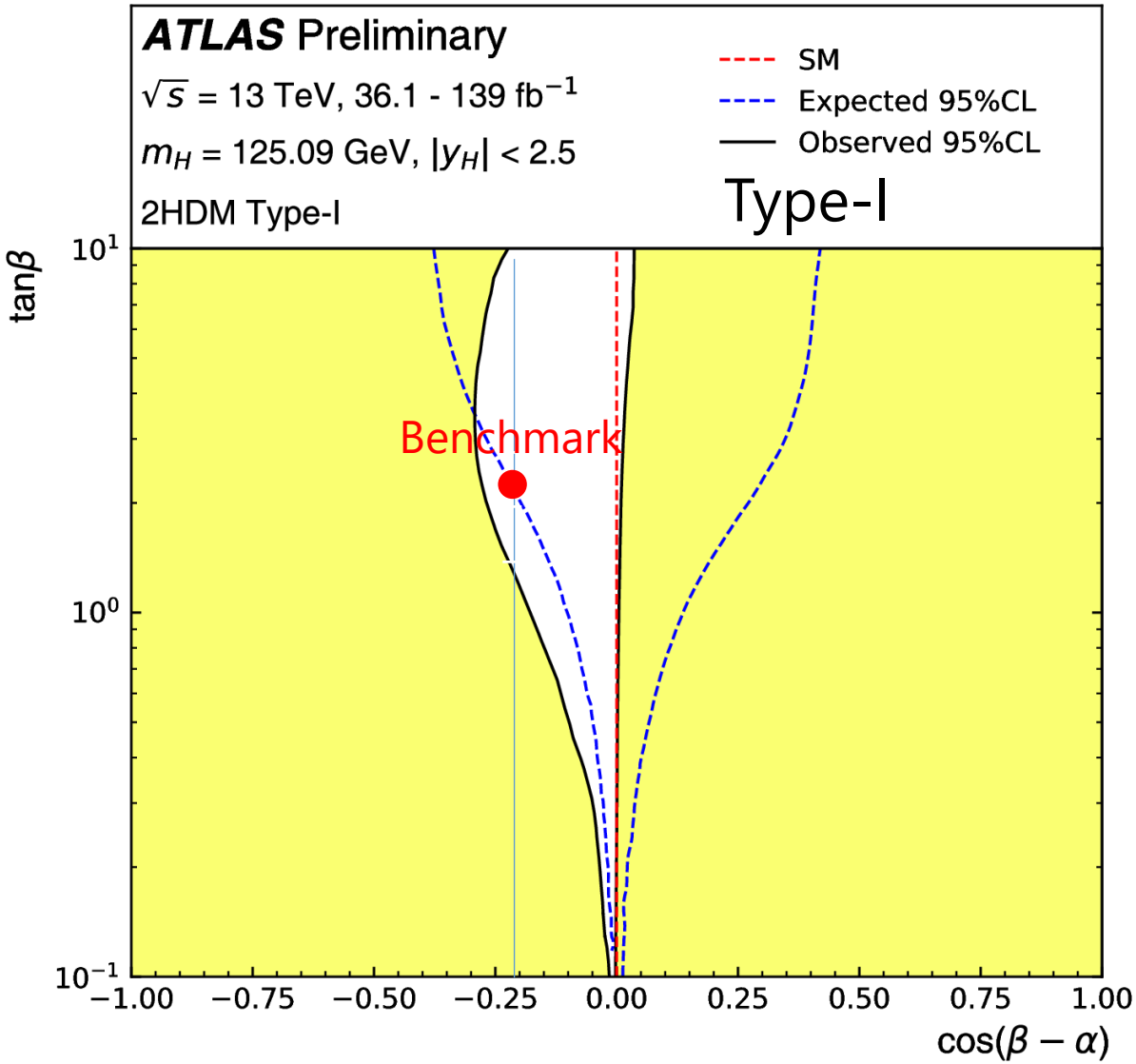
[Haller, et al.('18)]

Higgs couplings strength measurement



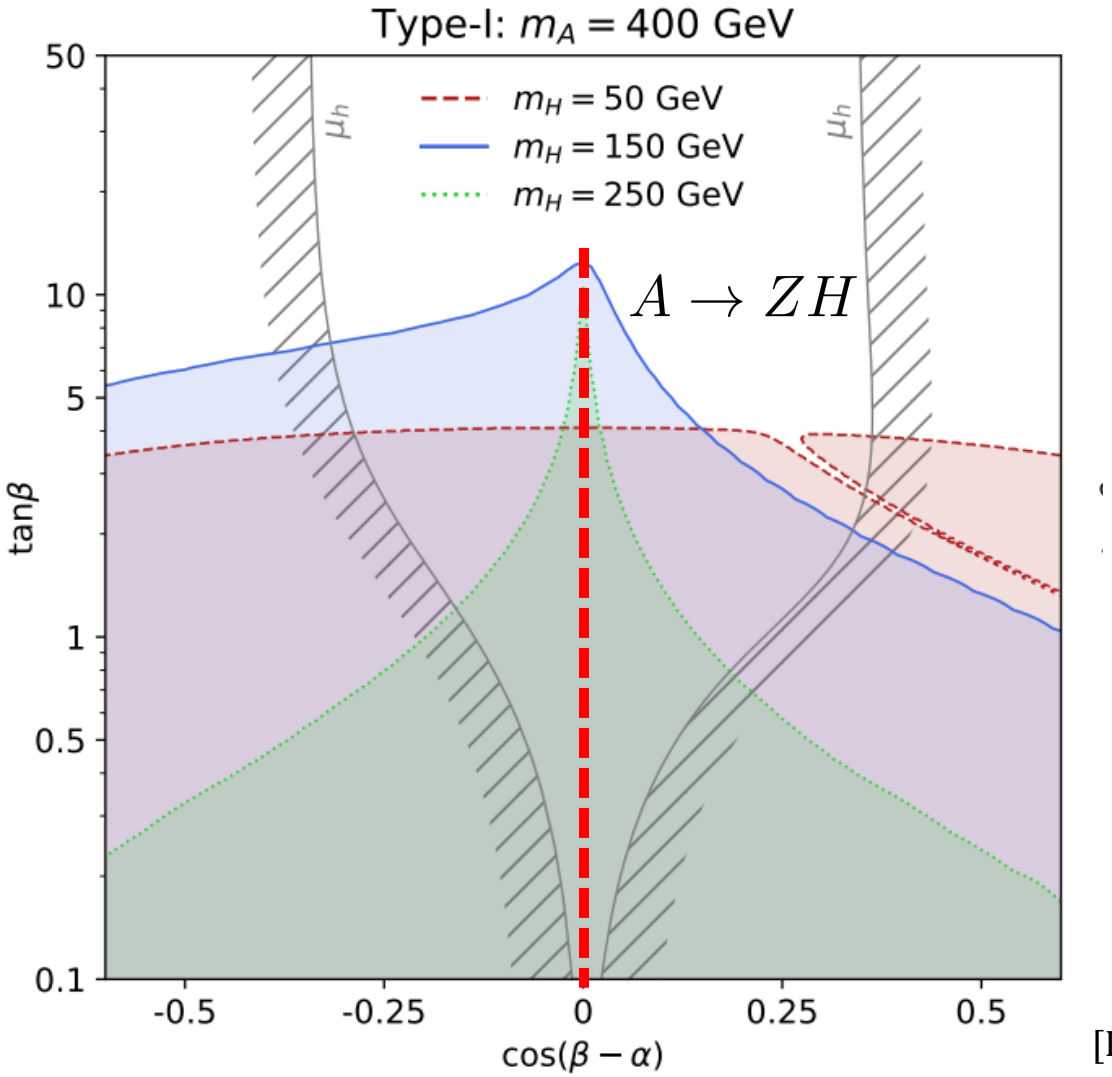
[ATLAS Collaboration ('19)]

Higgs couplings strength measurement



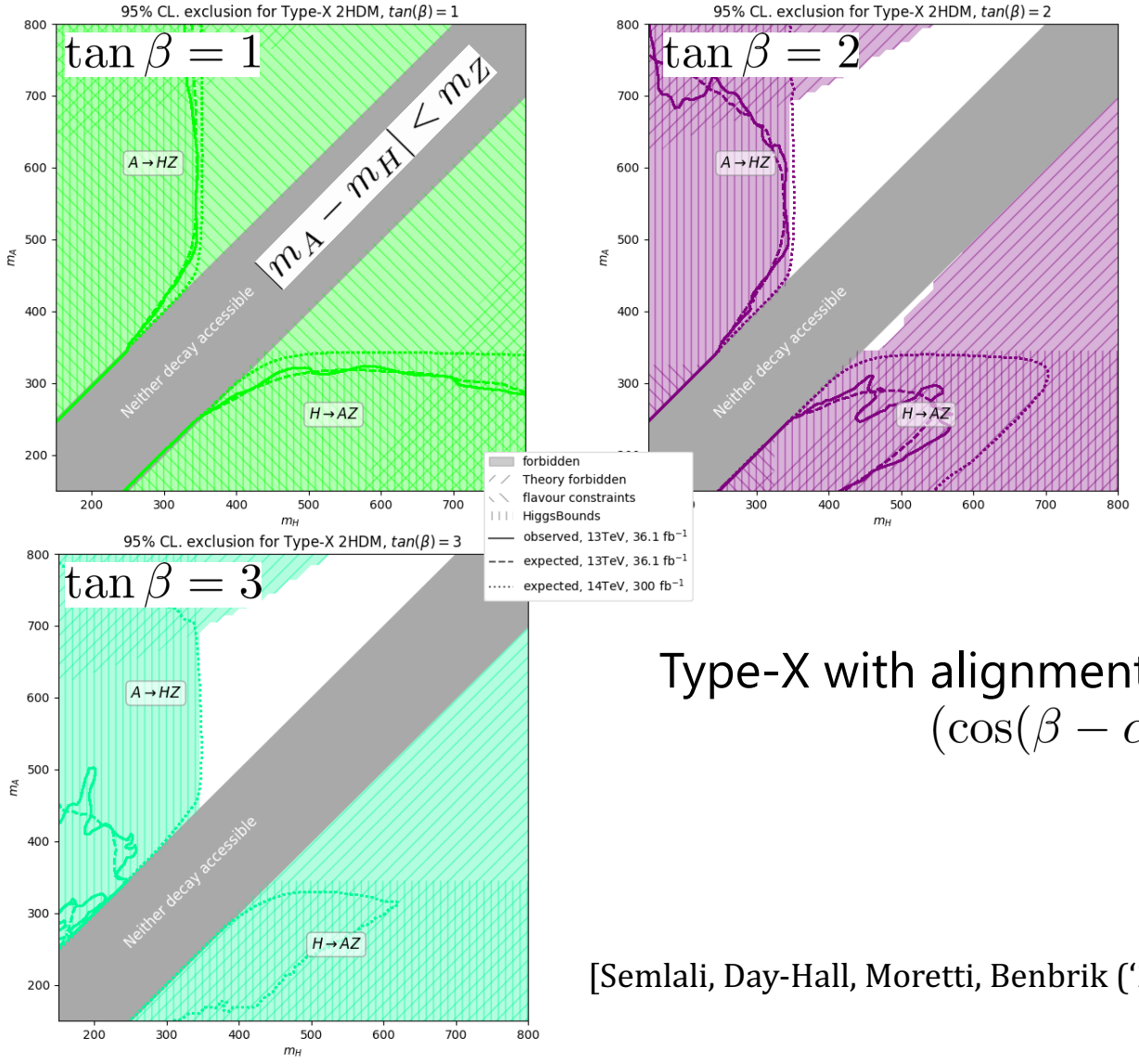
[ATLAS Collaboration ('21)]

Exotic decay channels



[Kling et al. ('20)]

Exotic decay channels

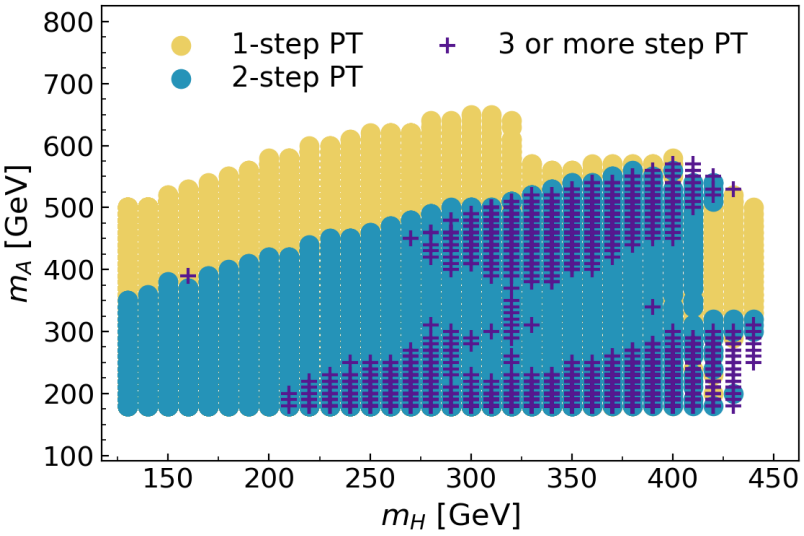


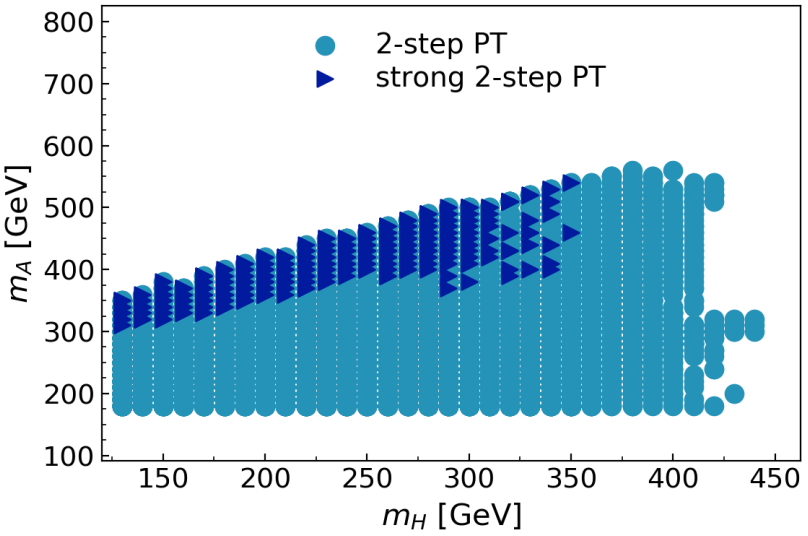
Type-X with alignment limit
$(\cos(\beta - \alpha) = 0)$

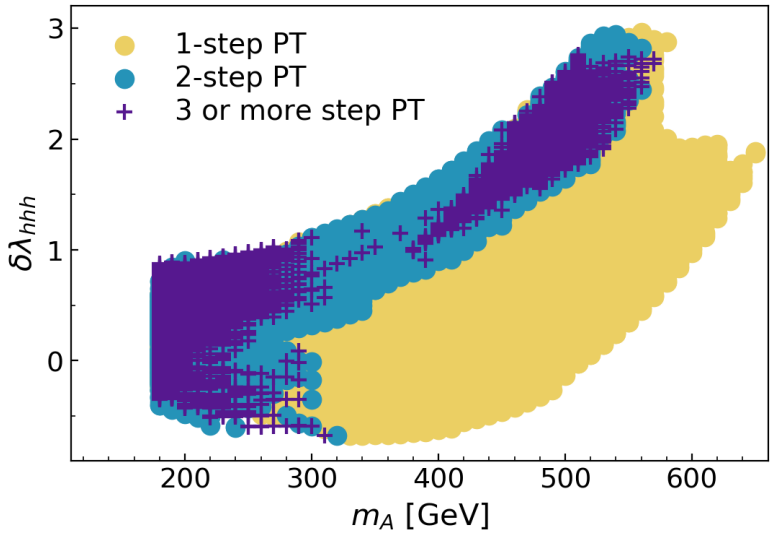
[Semlali, Day-Hall, Moretti, Benbrik ('20)]

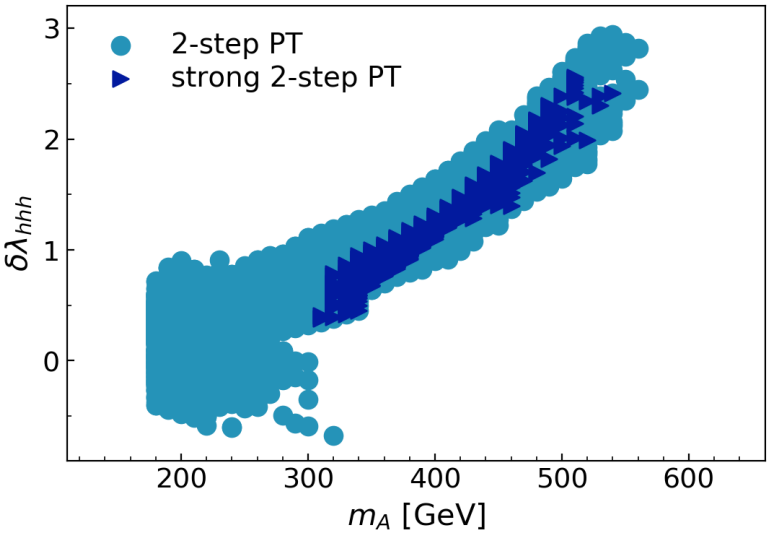
Back up (Results)

Type-I $(m_A = m_{H\pm})$







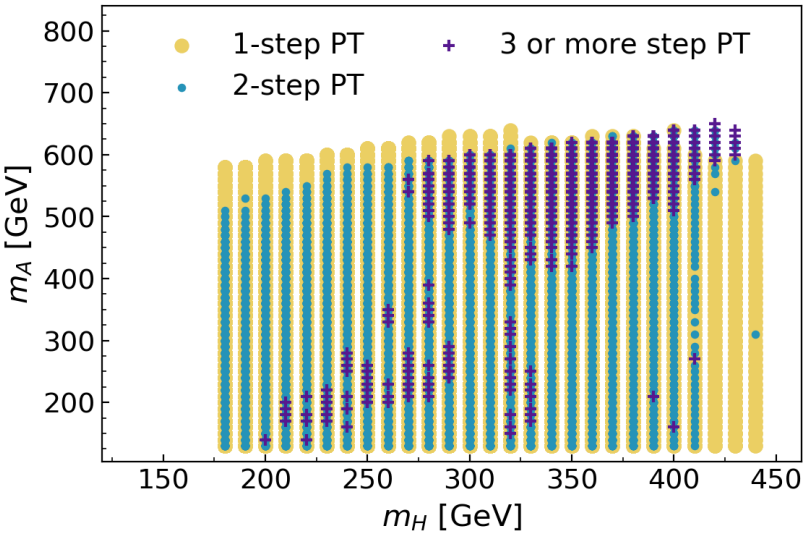


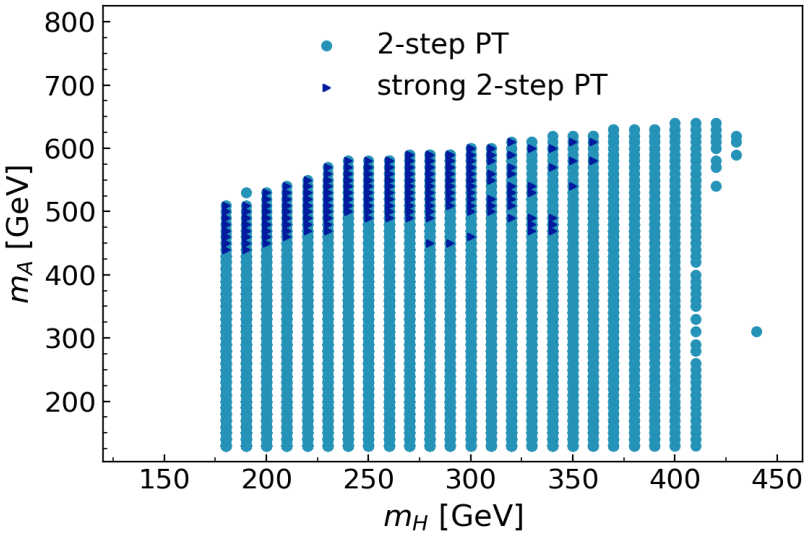
Parameter ranges for muti-step PTs

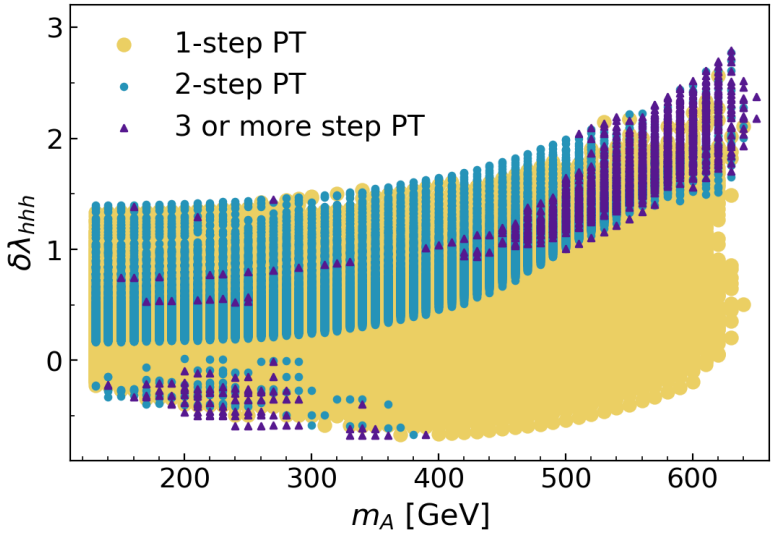
Type-I	$m_H^\pm = m_A$ [GeV]	m_H [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	m_3 [GeV]
searched	180–1000	130–1000	2–10	−0.25–0.25	0–100
1-step	180–650	130–440	2–10	−0.25–0.25	0–100
multi-step	180–570	130–440	2–10	−0.25–0.25	0–100

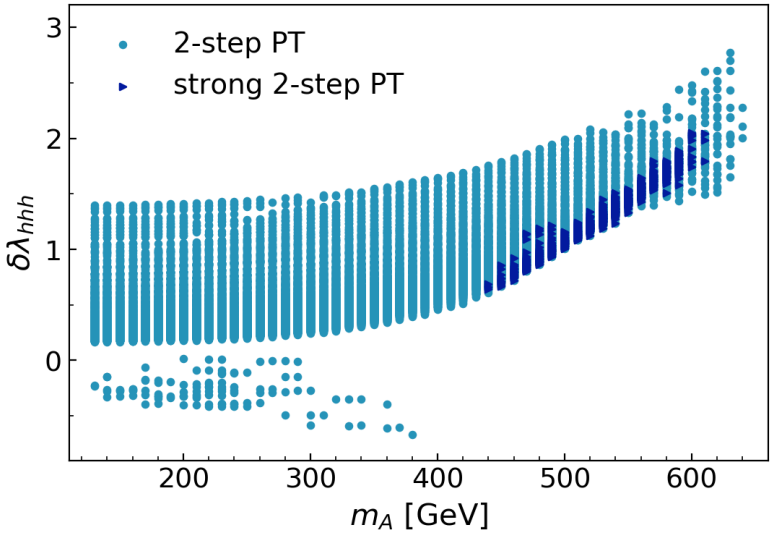
Same ranges

Type-I $(m_H = m_{H^\pm})$

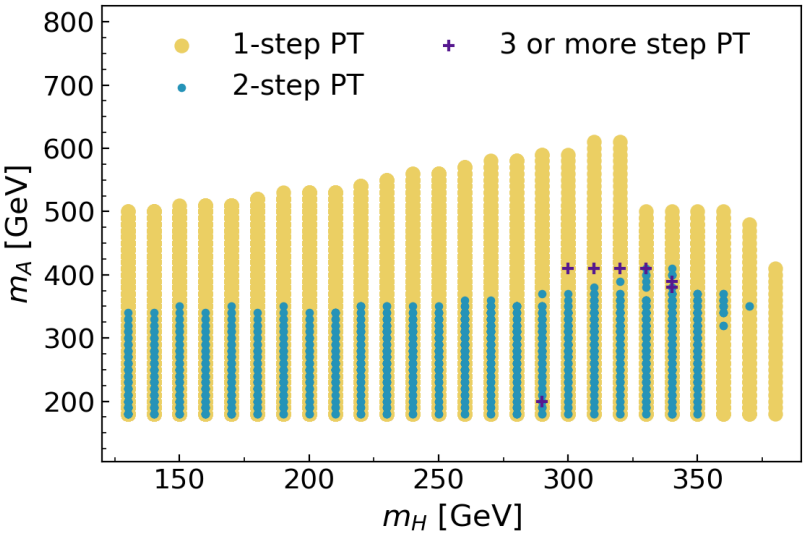


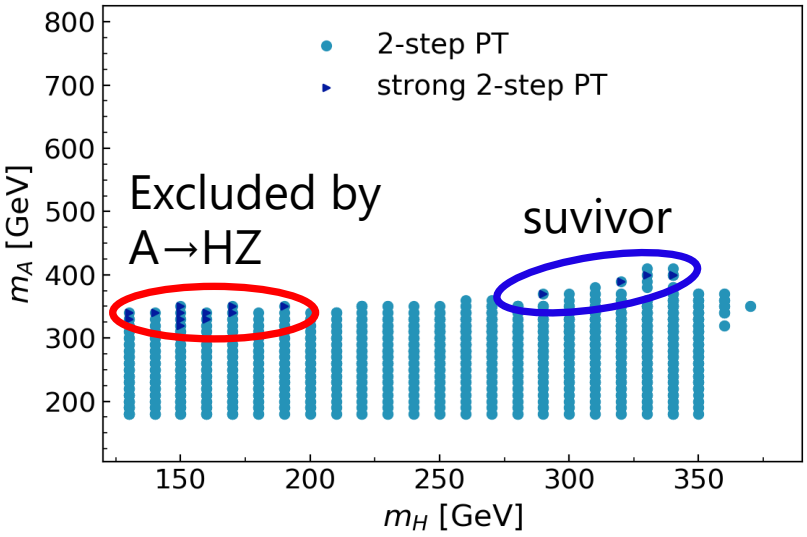


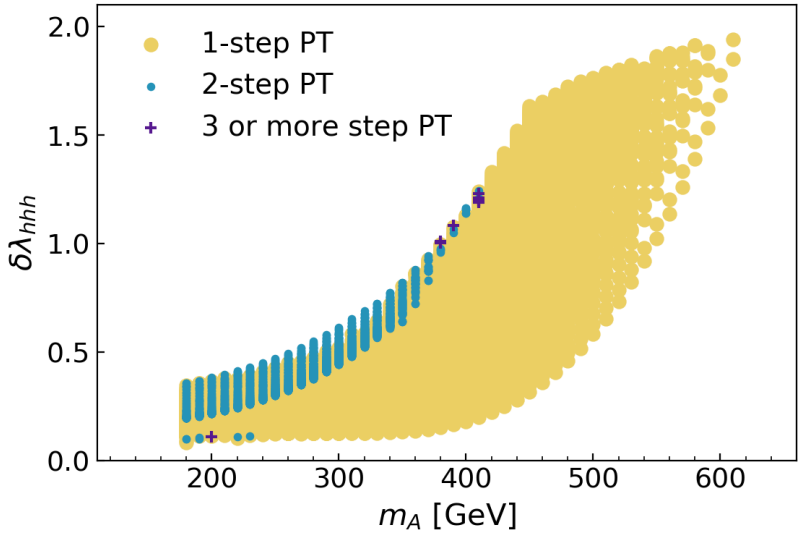


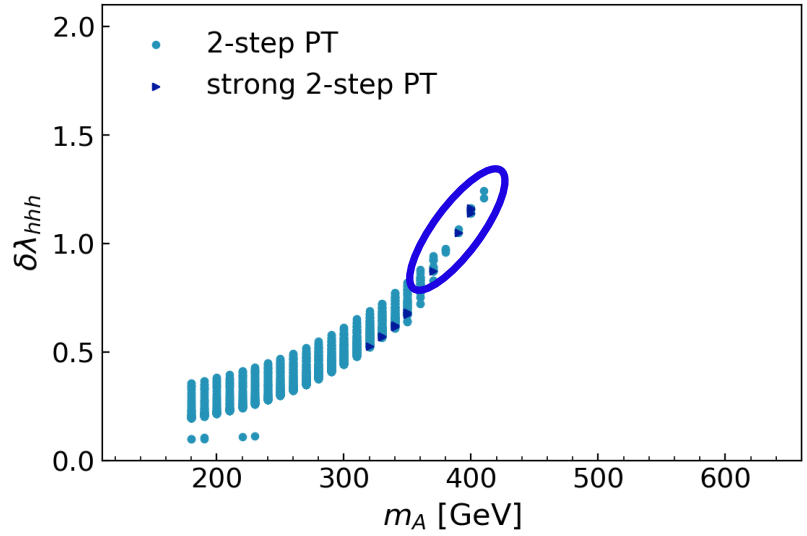


Type-X$(m_A = m_{H^\pm})$

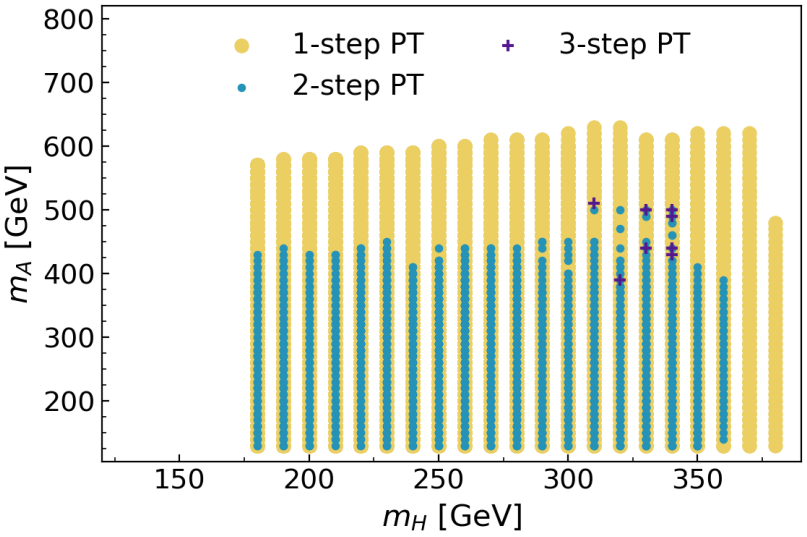


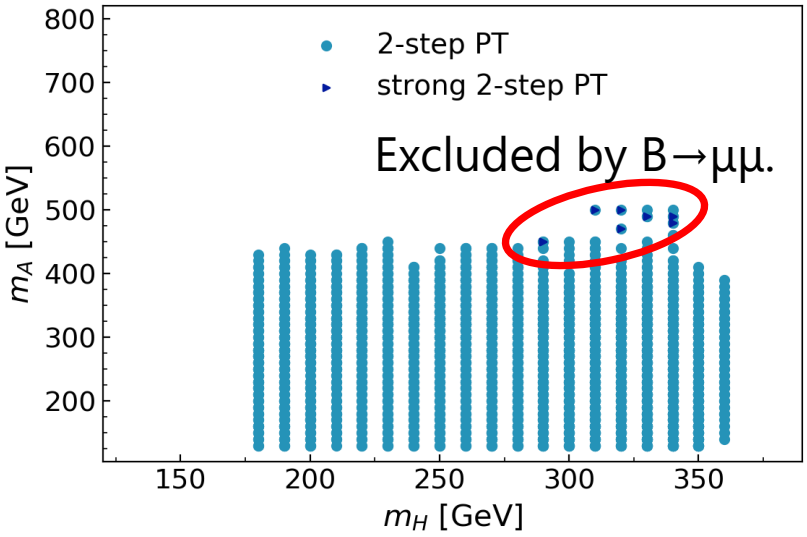


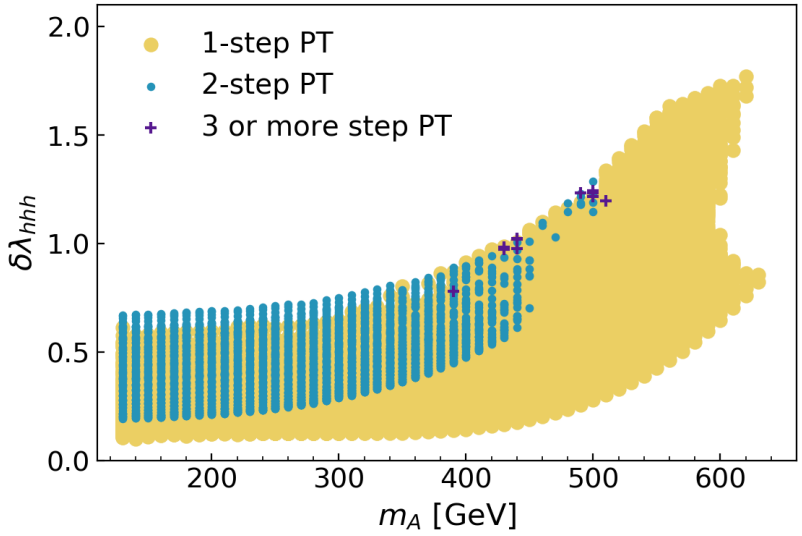


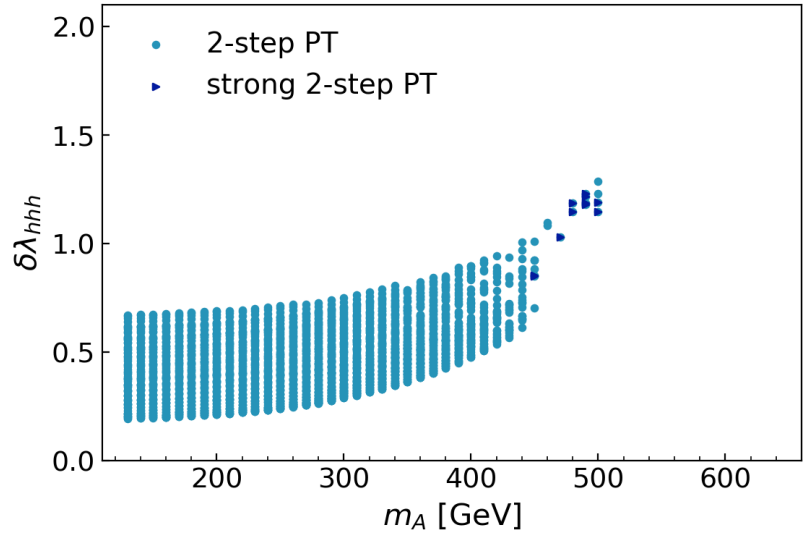


Type-X$(m_H = m_{H^\pm})$

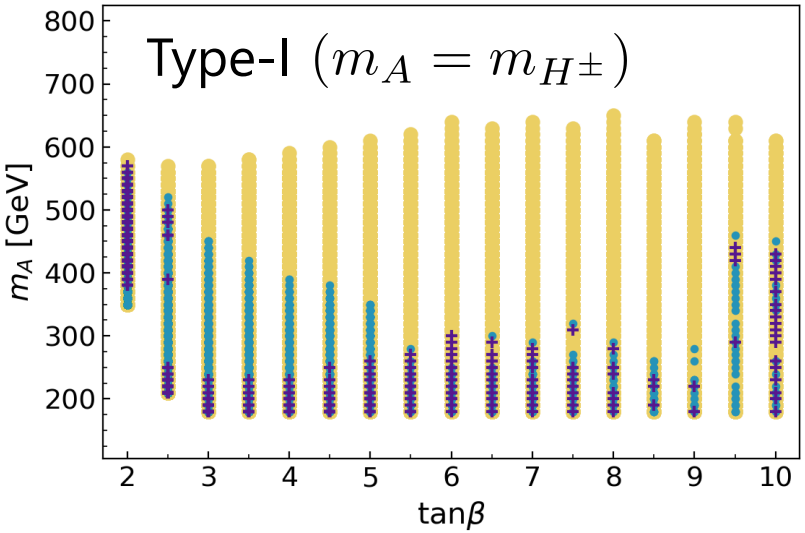


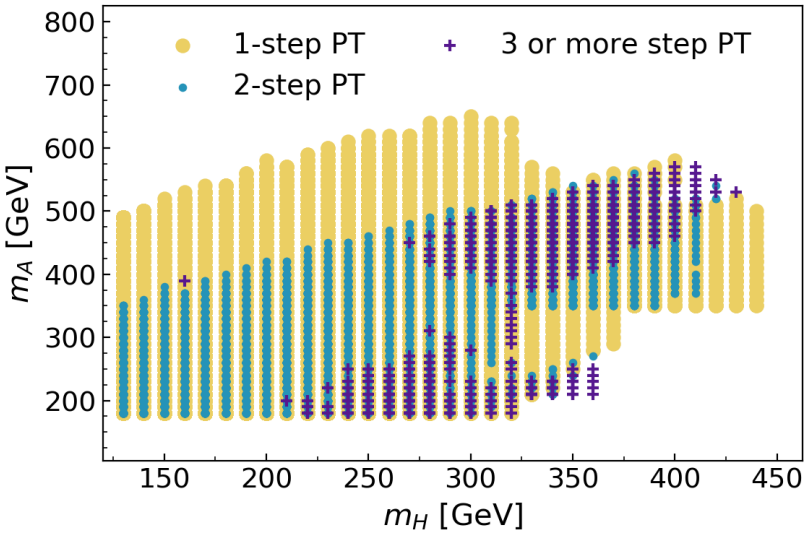


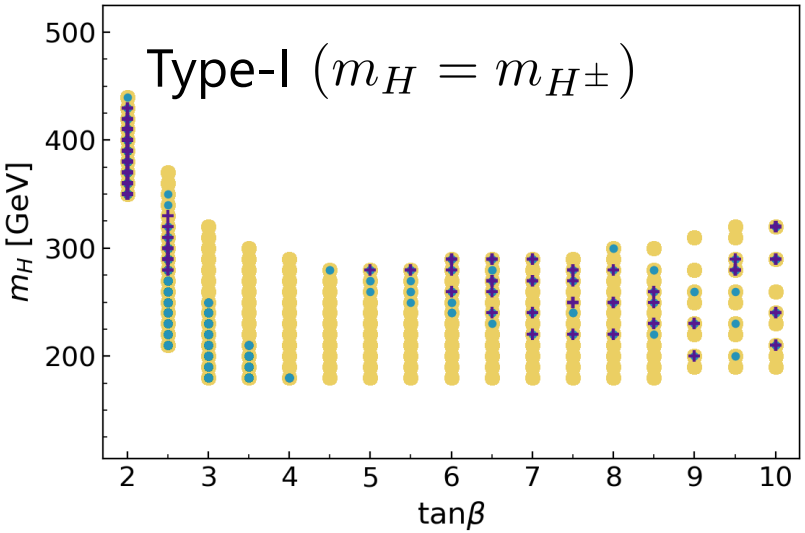


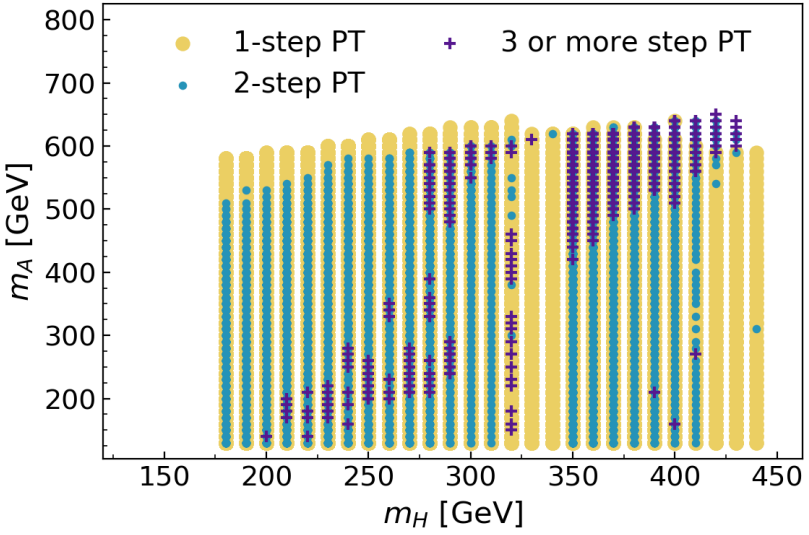


Considering constraint from B→μμ





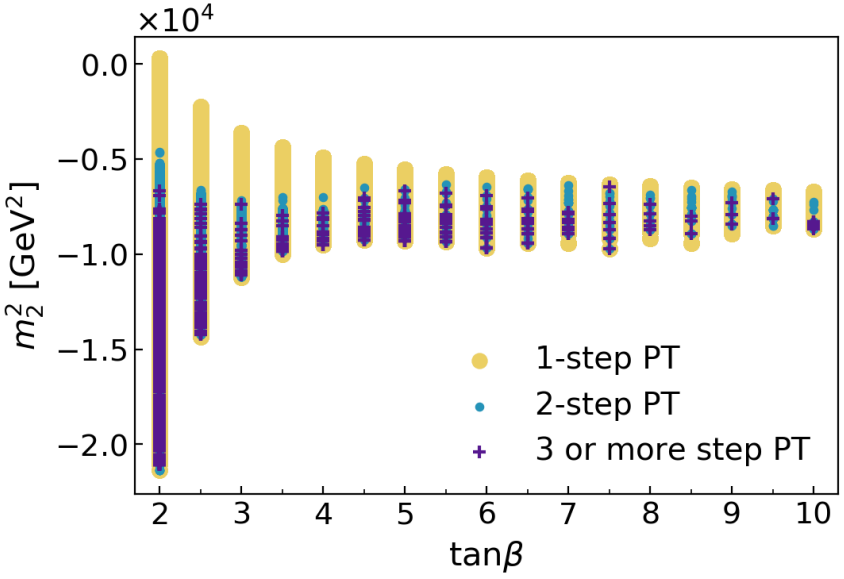


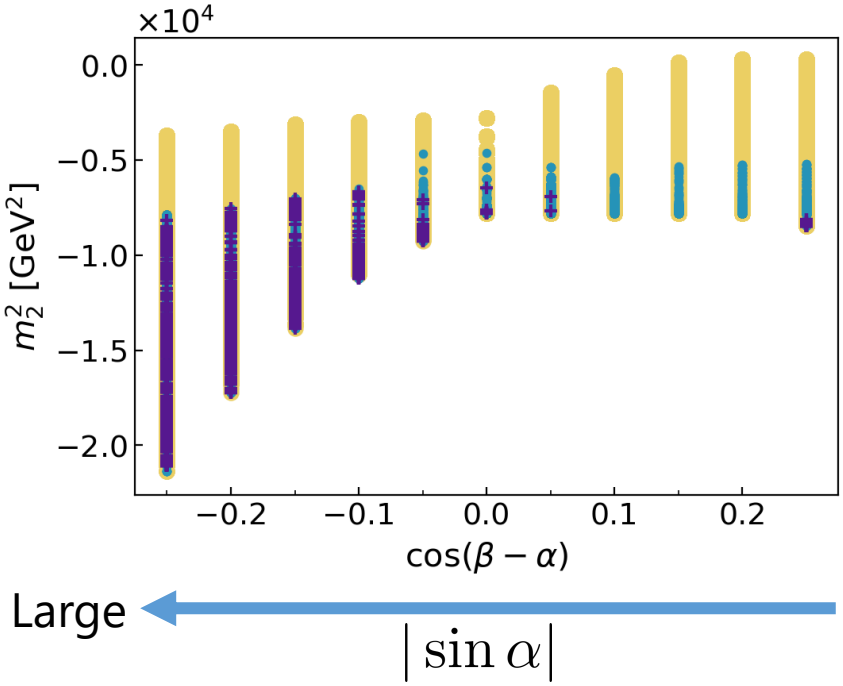


Parameters related to m_2^2

$$m_2^2 = \frac{1}{\tan\beta}\left[m_3^2 - \frac{1}{2}(m_H^2 - m_h^2)\cos\alpha\sin\alpha\right] - \frac{1}{2}(m_h^2\cos^2\alpha + m_H^2\sin^2\alpha)$$

Leading contribution except for near sinα=0

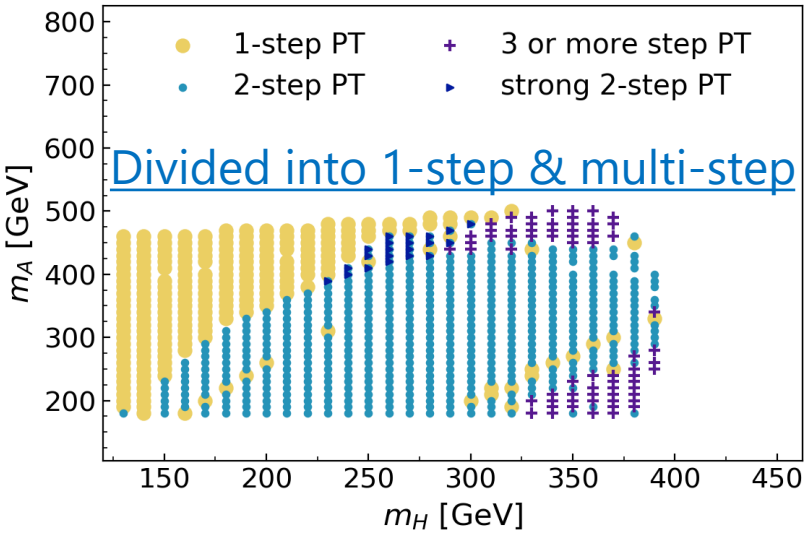


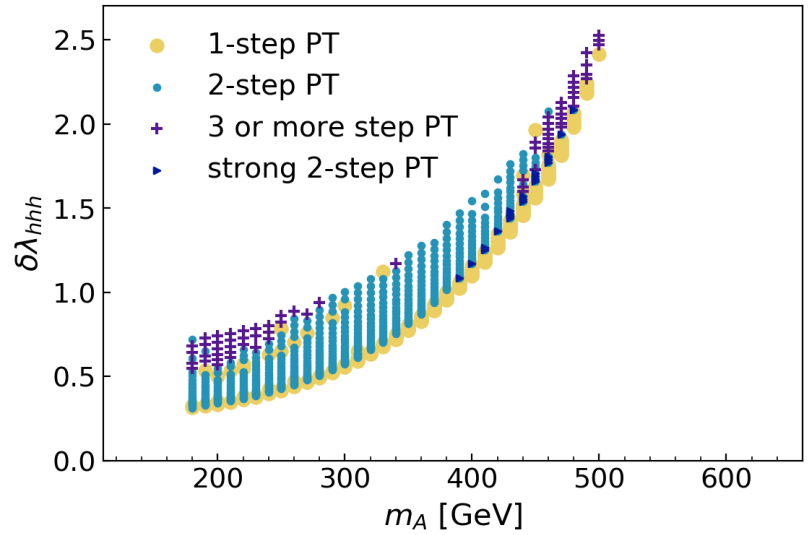


Large ← $|\sin\alpha|$

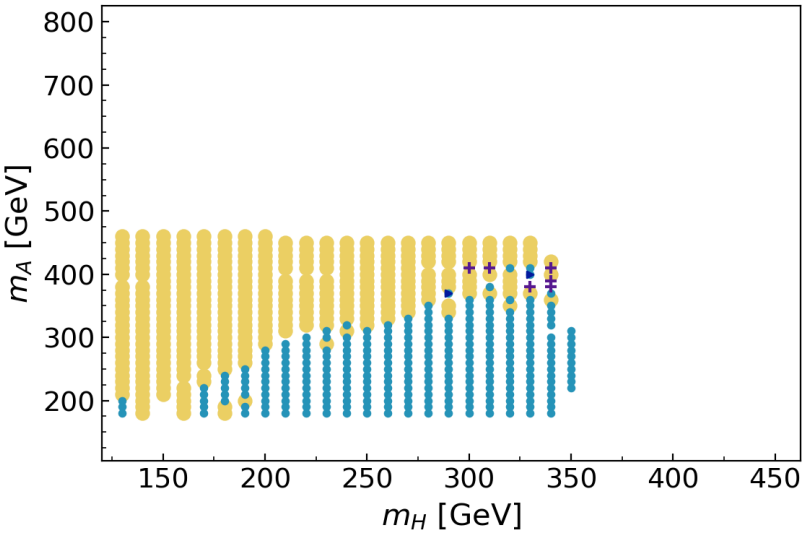
Cases of fixing parameters Type-I $(m_A = m_{H^\pm})$

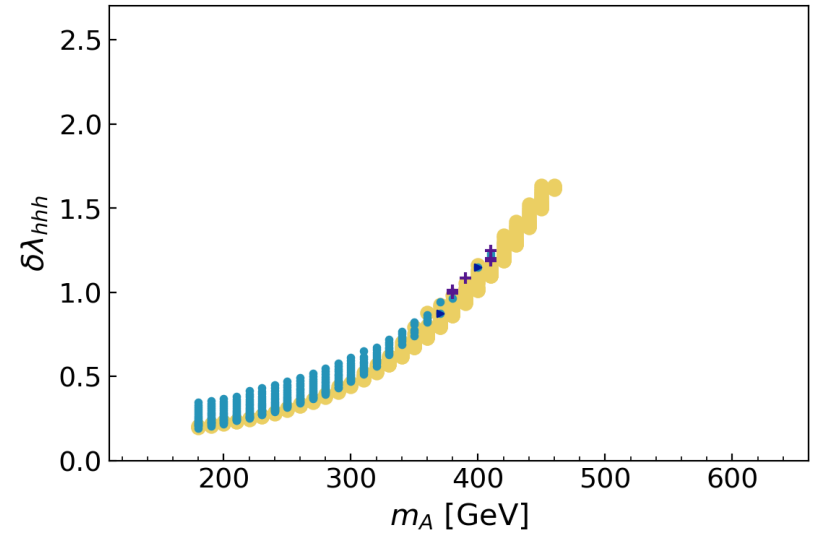
$\tan\beta = 2, \cos(\beta-\alpha) = -0.2, m_3^2 = 0\ \text{GeV}^2$





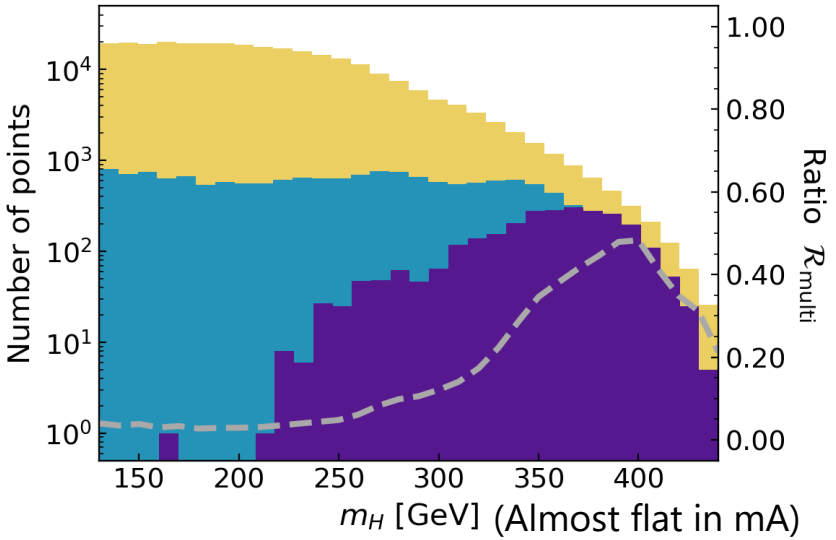
$\tan\beta = 2, \cos(\beta-\alpha) = 0, m_3^2 = 0\ \text{GeV}^2$

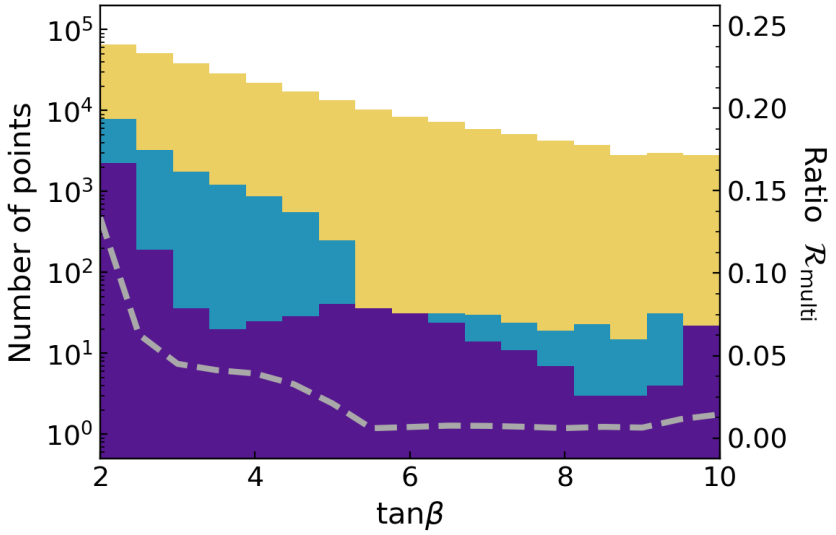


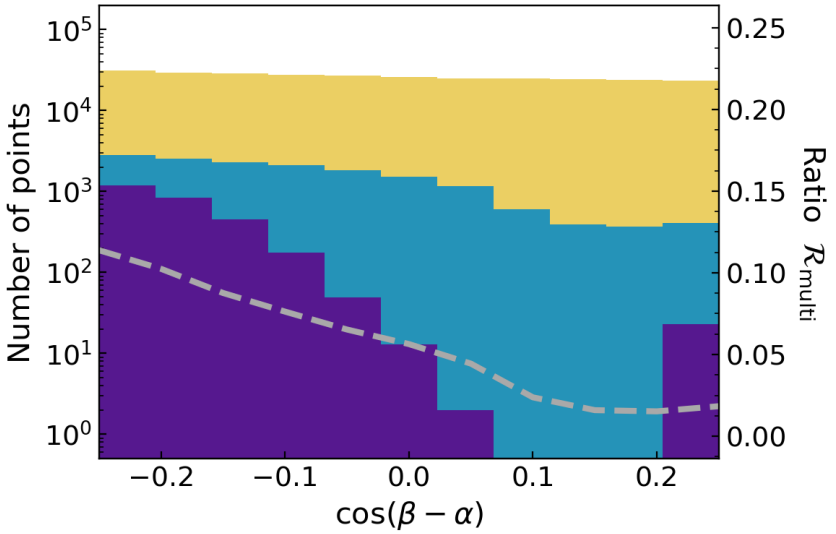


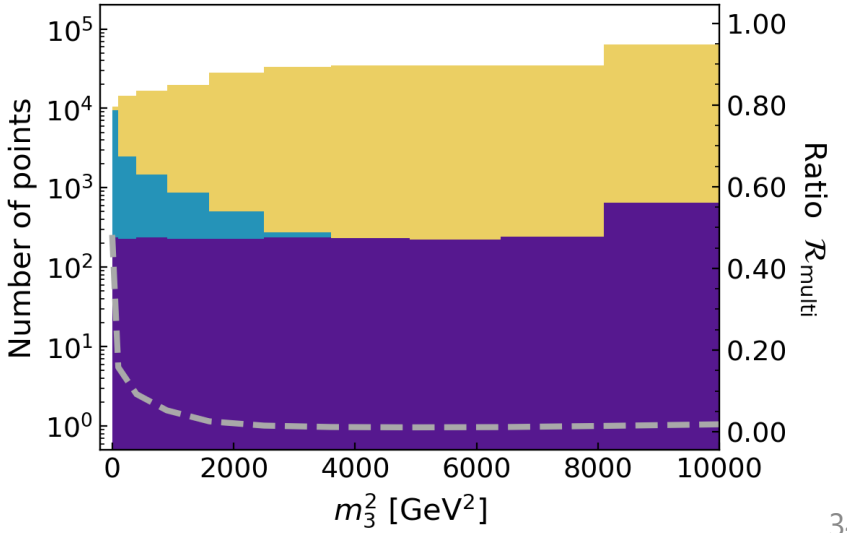
Number Analyses for multi-step PTs

Type-I $(m_A = m_{H^\pm})$



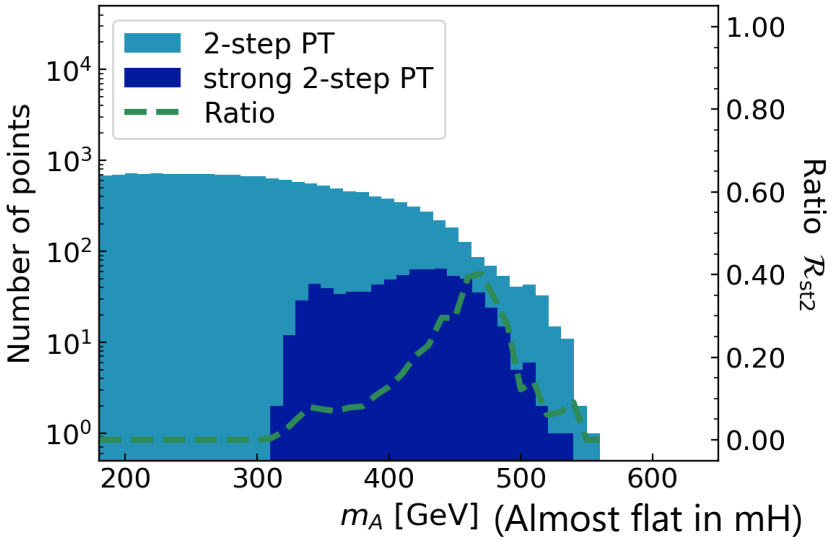


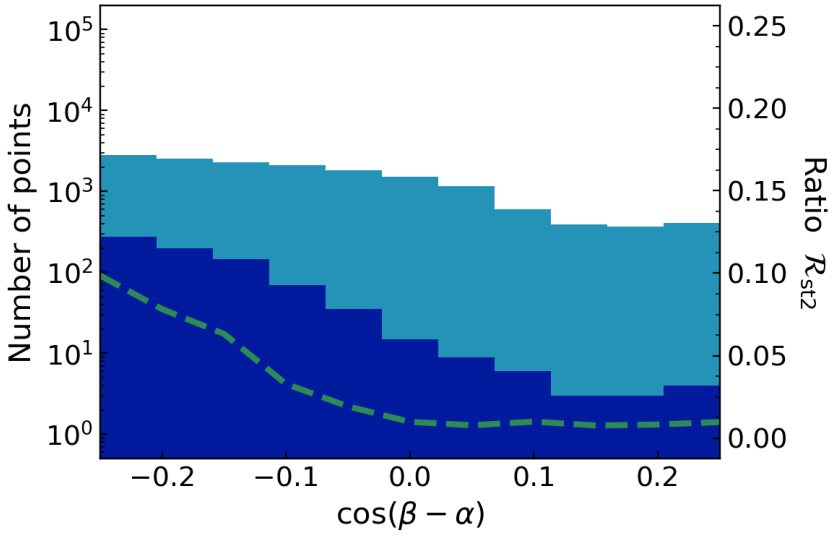


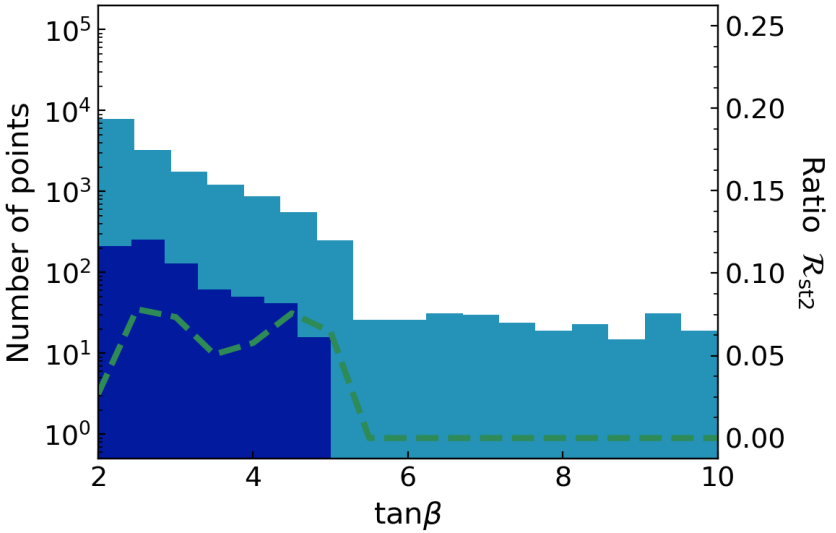


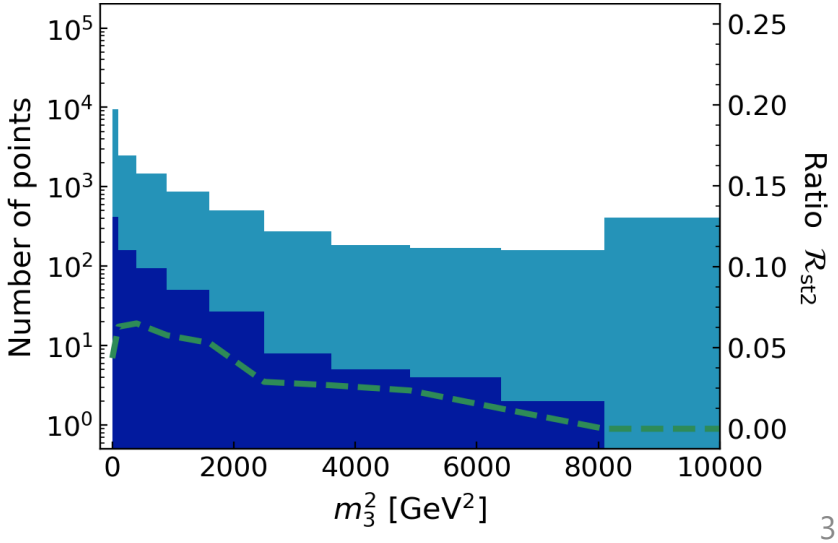
Number analyses for strong 2-step PTs

Type-I $(m_A = m_{H^\pm})$



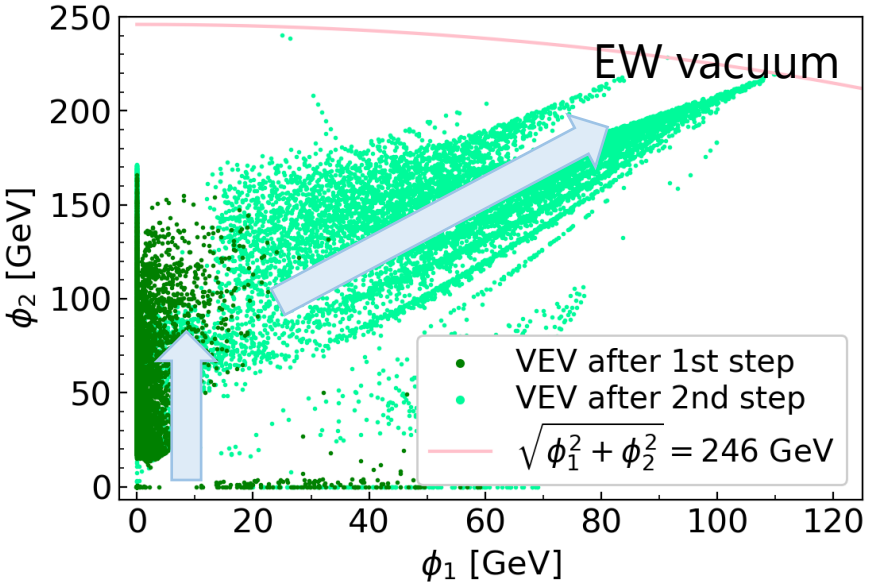




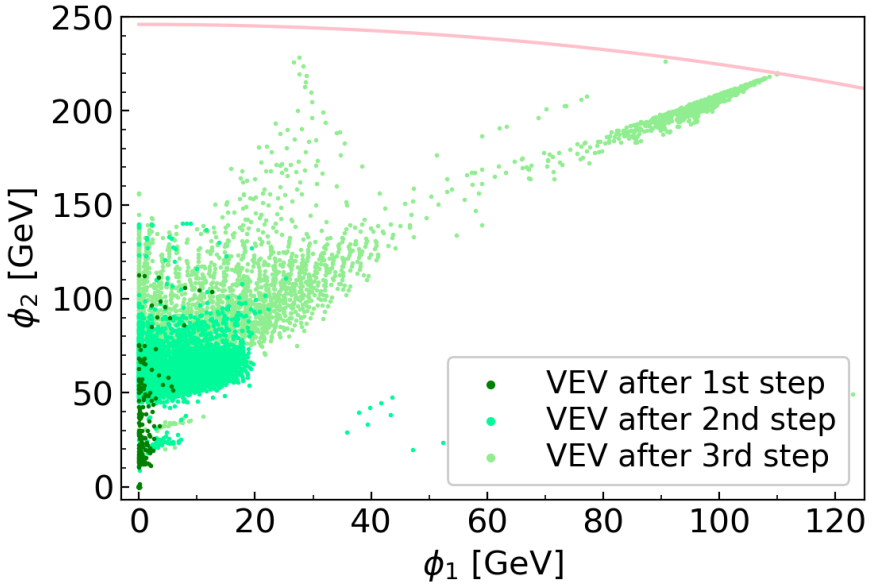


Passes of multi-step PTs

2-step PTs



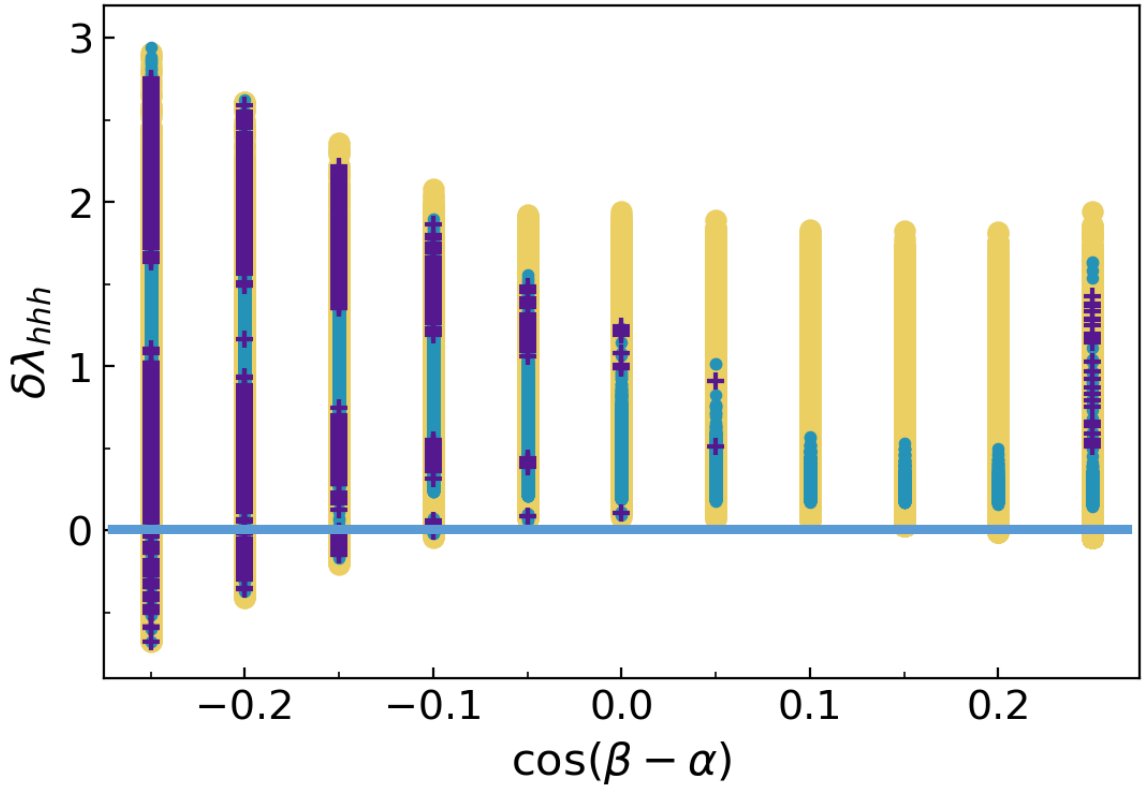
3-step PTs



In the first step, the PT occurs along an axis.
In the last step, the PT happens in the direction of the EW vacuum.

Higgs trilinear coupling & $\cos(\beta-\alpha)$

As $\cos(\beta-\alpha)$ is getting smaller,
the maximum deviations is larger.



Negative deviations yield when

$|\cos(\beta-\alpha)| \gtrsim 0.1$

$(m_3^2 \gtrsim 2500\ \mathrm{GeV}^2)$

Gravitational Waves

[Bian, Liu ('18)]

Bubble Collisions

$$h^2\Omega_{bc}(f) \simeq 1.67 \times 10^{-5} \tilde{\beta}^{-2} \left(\frac{\kappa_\phi \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_\star}\right)^{1/3} \frac{0.11 v_w^3}{0.42 + v_w^2} \frac{3.8 (f/f_{co})^{2.8}}{1 + 2.8 (f/f_{co})^{3.8}}$$

$$f_{bc} \simeq 1.65 \times 10^{-5} \text{Hz} \left(\frac{0.62}{1.8 - 0.1 v_w + v_w^2}\right) \tilde{\beta} \left(\frac{T_n}{100 \text{ GeV}}\right) \left(\frac{g_\star}{100}\right)^{1/6}$$

Sound Waves

$$h^2\Omega_{sw}(f) \simeq 2.65 \times 10^{-6} \tilde{\beta}^{-1} \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_\star}\right)^{1/3} v_w (f/f_{sw})^3 \left(\frac{7}{4 + 3(f/f_{sw})^2}\right)^{7/2}$$

$$f_{sw} \simeq 1.9 \times 10^{-5} \text{Hz} \frac{1}{v_w} \tilde{\beta} \left(\frac{T_n}{100 \text{ GeV}}\right) \left(\frac{g_\star}{100}\right)^{1/6}$$

Magentohydodynamic Turbulence

$$h^2\Omega_{turb}(f) \simeq 3.35 \times 10^{-4} \tilde{\beta}^{-1} \left(\frac{\kappa_{turb} \alpha}{1+\alpha}\right)^{3/2} \left(\frac{100}{g_\star}\right)^{1/3} v_w \frac{(f/f_{turb})^3}{(1 + f/f_{turb})^{11/3} (1 + 8\pi f/h_\star)}$$

$$f_{turb} \simeq 2.7 \times 10^{-5} \text{Hz} \frac{1}{v_w} \tilde{\beta} \left(\frac{T_n}{100 \text{ GeV}}\right) \left(\frac{g_\star}{100}\right)^{1/6}$$

Gravitational Waves

$$v_w = 1$$

$$h_* = 1.65 \times 10^{-5}\mathrm{Hz} \left(\frac{T_n}{100\ \mathrm{GeV}} \right) \left(\frac{g_\star}{100} \right)^{1/6}$$

$$\kappa_\phi = \frac{1}{1 + A\alpha} \left[A\alpha + \frac{4}{27} \sqrt{\frac{3\alpha}{2}} \right] \qquad (A = 0.715)$$

$$\kappa_v = \frac{\alpha}{0.73 + 0.083\sqrt{\alpha} + \alpha}$$

$$k_{\mathrm{turb}} \simeq 0.1 \kappa_v$$

Gravitational Waves

$$\alpha = \frac{\epsilon(T_n)}{\rho_{\rm rad}(T_n)}$$

$$\epsilon(T_n) = \left[-\Delta V + T\frac{\partial \Delta V}{\partial T}\right]\Bigg|_{T=T_n}$$

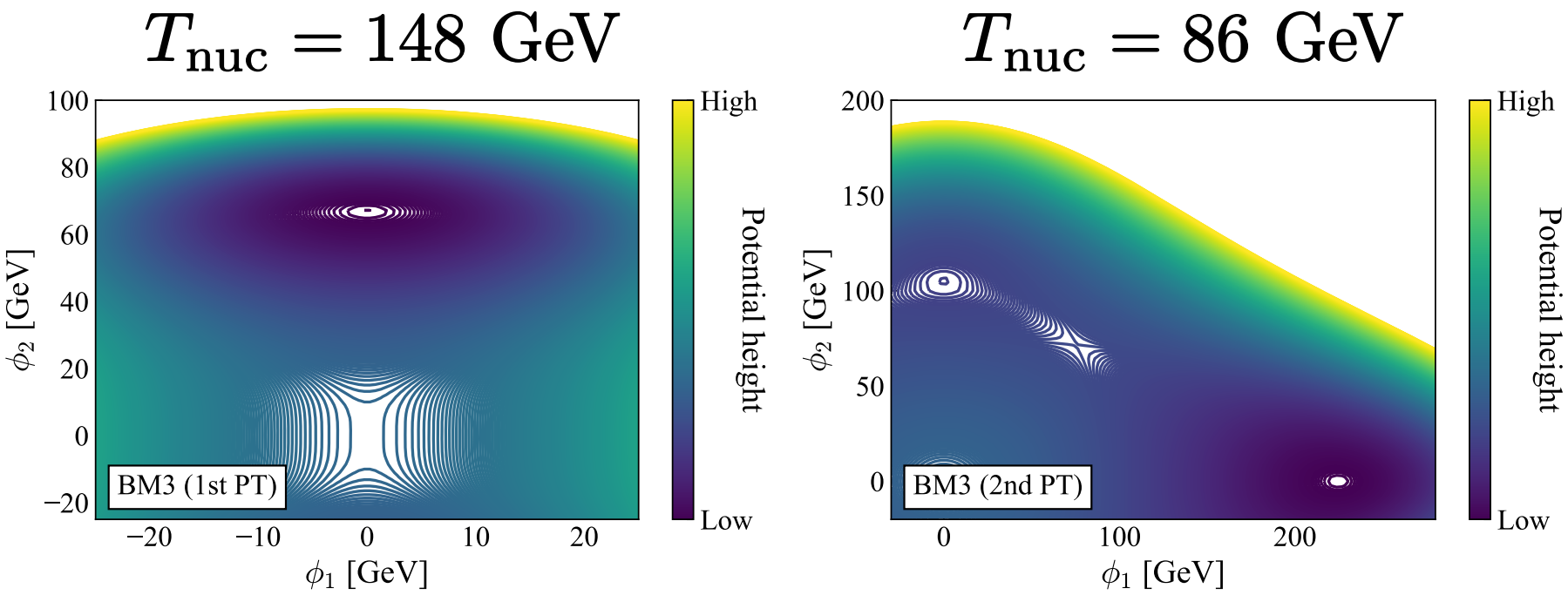
$$\rho_{\rm rad}(T_n) = g_* \frac{\pi^2 T_n^4}{30}$$

$$\tilde{\beta} \equiv \frac{\beta}{H(T=T_n)} = T_n \, \frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Bigg|_{T=T_n}$$

Back up (Dark matter)

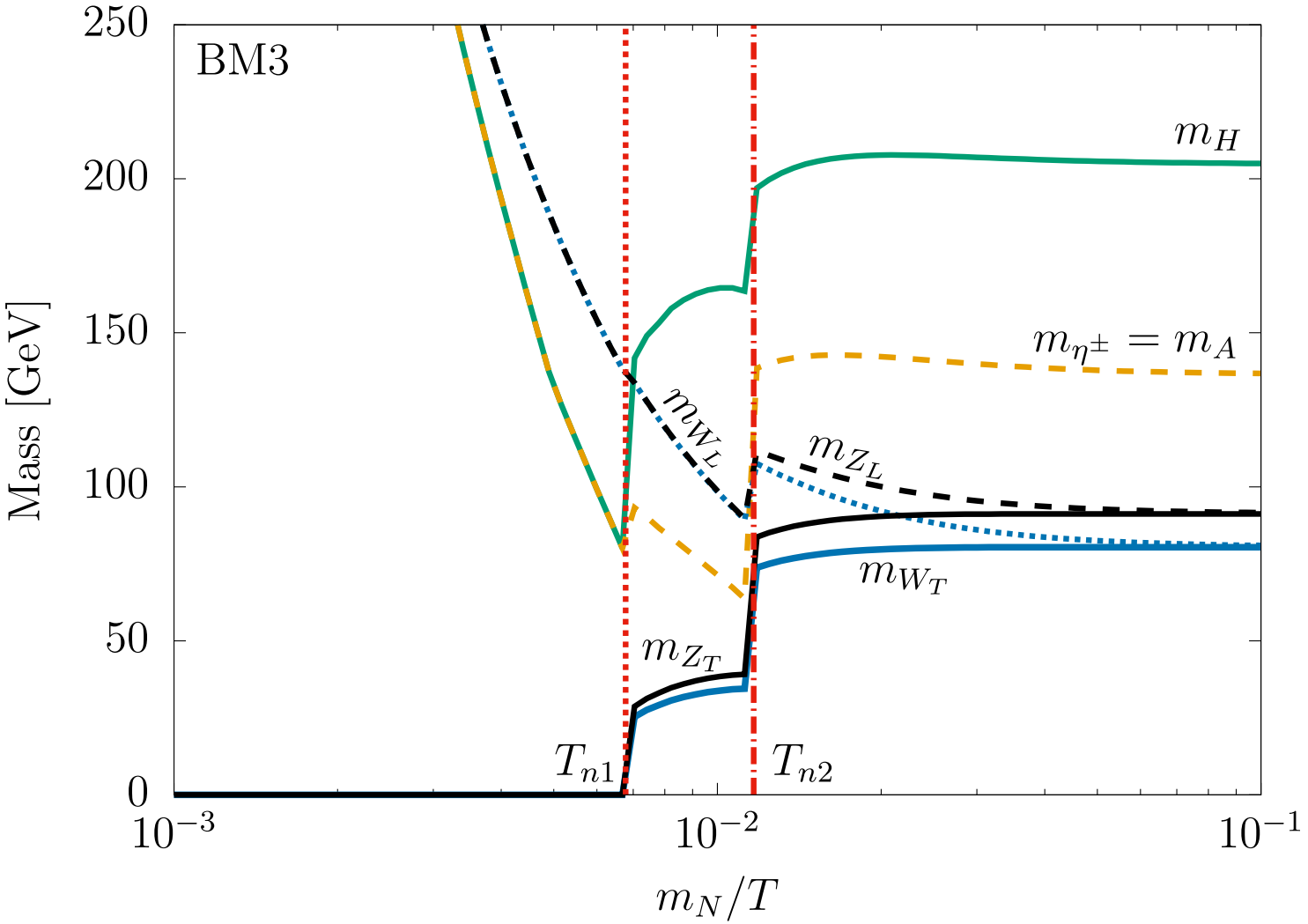
2-step PT in the scotogenic model

[HS, Toma ('22), arXiv:2207.14662]



Scalar mass changes at a 2-step PT

[HS, Toma ('22), arXiv:2207.14662]



DM abundance changed by a 2-step PT

[HS, Toma ('22), arXiv:2207.14662]