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

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Mayumi Aoki, Takatoshi Komatsu, H. S. [arXiv:2106.03439]

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Introduction

Baryogenesis (BG)

We still do not know how baryons were produced…

$$\frac{n_B}{s} = (8.59 \pm 0.08) \times 10^{-11}$$

[Plank Collaboration ('18)]

n_B : number density of baryons
s : entropy density

Electroweak phase transition (EWPT)

To achieve BG in EW scale, EWPT is need to be 1st order.

[Kuzmin et al. ('85)]

- **Standard model (SM)** EWPT does not become 1st order.
  [Kajantie et al. ('95); Csikor et al. ('99)]
- **Two Higgs Doublet Model (2HDM)**
  Difficult to achieve BG because of strict constraints from EDM expt.
  [Haarr, et al. ('16); Cheng, et al.('17)]

➡ Multi-step EWPT has possibility to achieve EWBG !

Inert 2HDM [Blinov et al. ('15)]

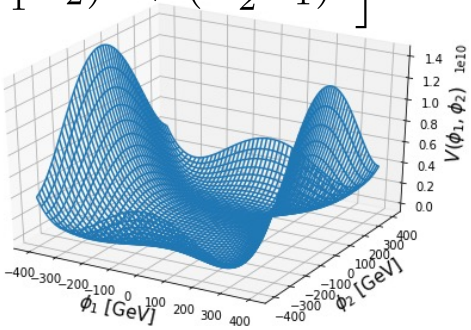
Two Higgs Doublet Model

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

$$V_0(\Phi_1,\Phi_2) = -m_1^2\Phi_1^\dagger\Phi_1 - m_2^2\Phi_2^\dagger\Phi_2 \underline{- m_3^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1)} + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1) + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

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



Types of Yukawa interactions

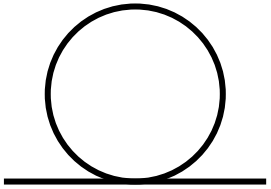
To avoid FCNC processes, assume two doublets has different Yukawa couplings.

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

The Effective Potential

The one-loop corrected effective potential

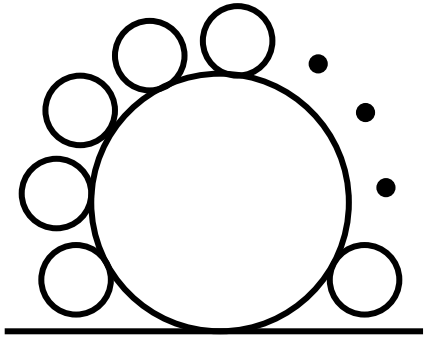
$$V^{\beta} = V_0 + V_1^0 + V_{\mathrm{CT}} + \underbrace{\overline{V}_1^{\beta}}_{\text{Thermal effect}}$$



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

Resummation [Parwani ('92)]

We perform the numerical method for taking into account contributions from "Daisy diagram." [Dolan, Jackiw ('74)]



Constraints

Theoretical constraints

Bounded from below

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

Tree-level unitarity

Stability of EW vacuum (confirmed in $|\phi_i| < 10$ TeV)

Experimental constraints

Electroweak precision data

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

CP-odd CP-even

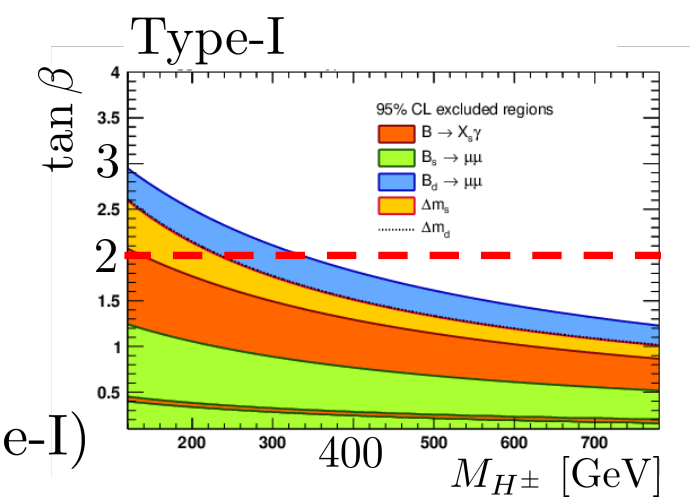
Flavor experiments

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

[Haller et al.('18)]

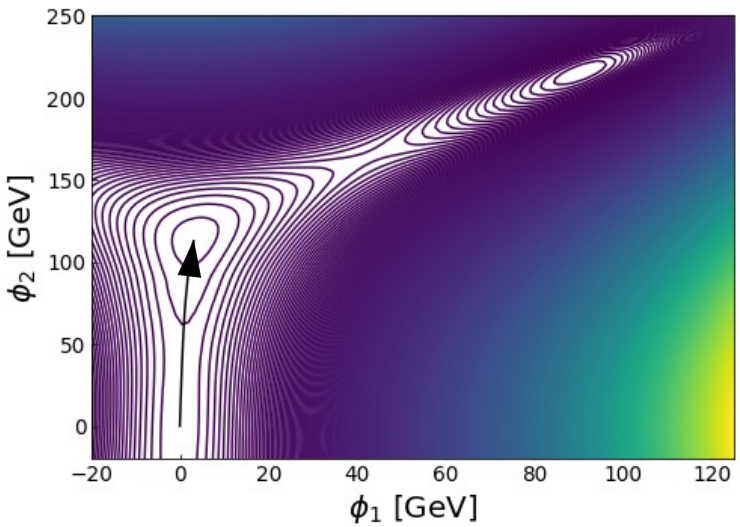
Higgs couplings strength [ATLAS Collab. ('19)]

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



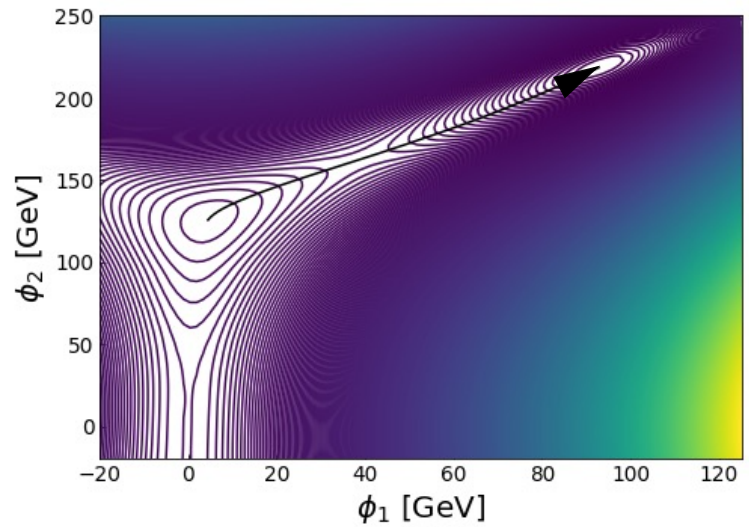
Pass of a multi-step EWPT

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

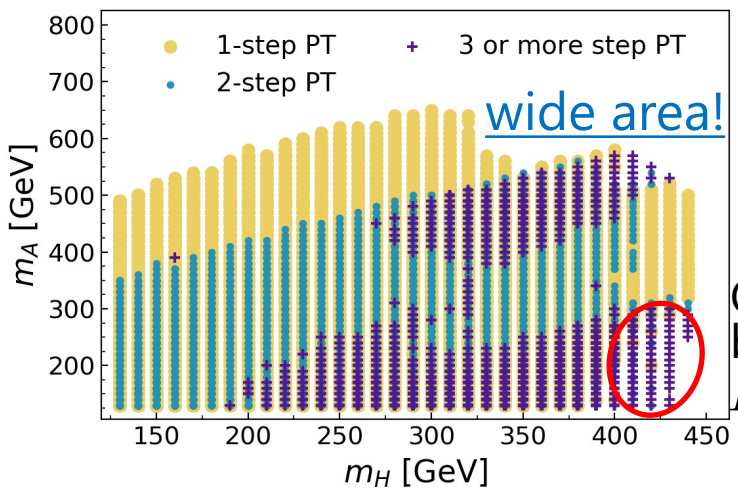
M. Aoki, T. Komatsu, H. S.
[arXiv:2106.03439]

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

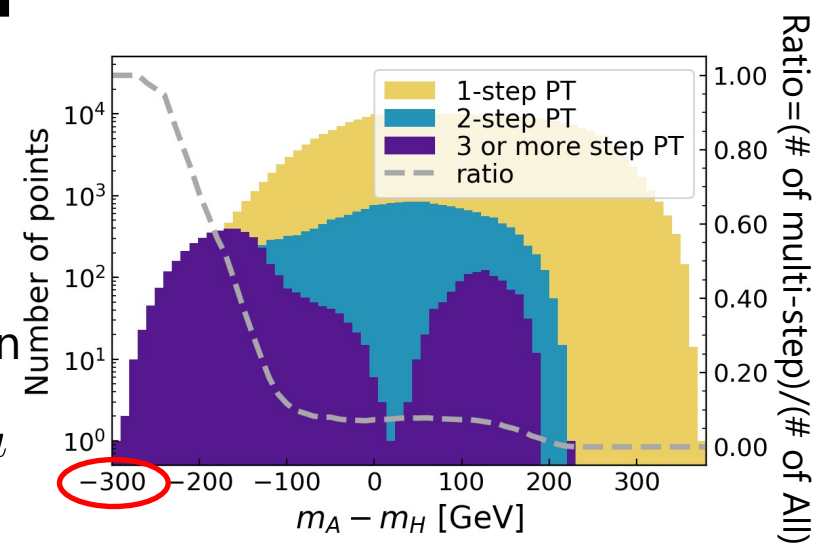
[Wainwright ('12)]

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 $|m_A - m_H|$.

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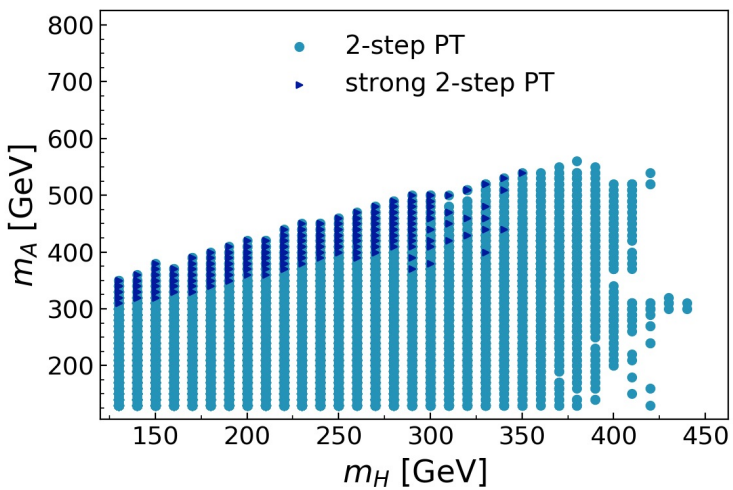
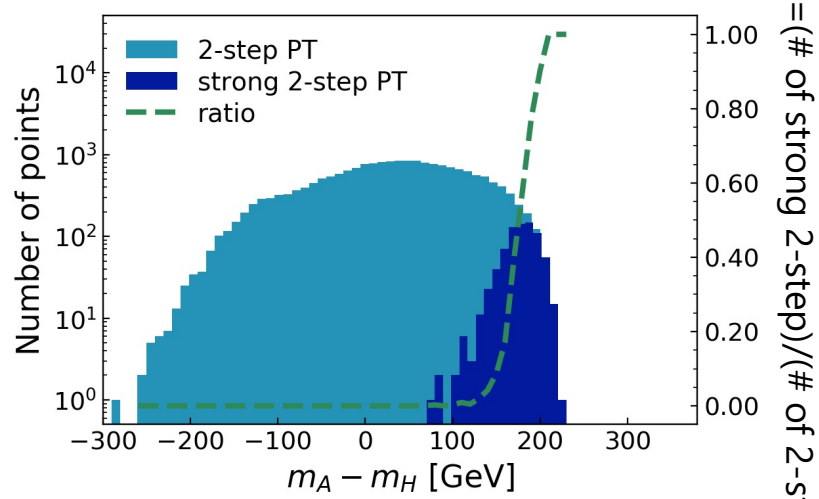
2-step PT vs. "strong 2-step" PT

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!

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2-ste

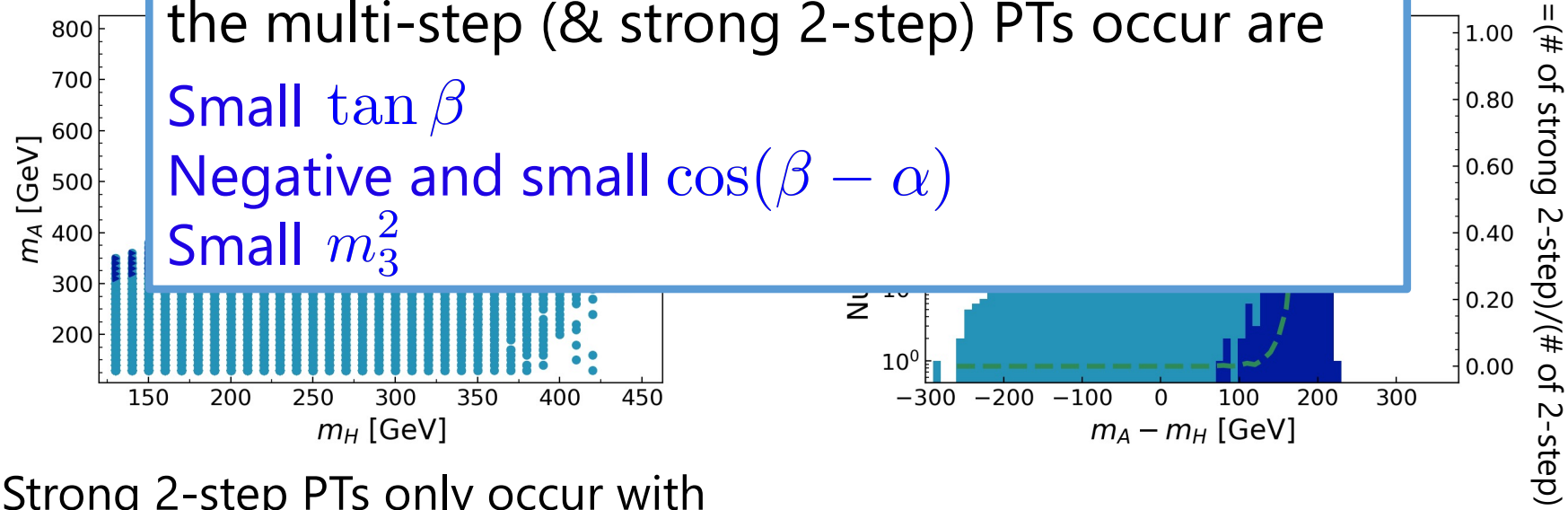
step

The other features of the region where the multi-step (& strong 2-step) PTs occur are

Small $\tan\beta$

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

Small m_3^2



Strong 2-step PTs only occur with

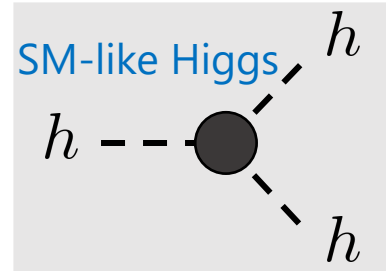
$m_A - m_H > 0$

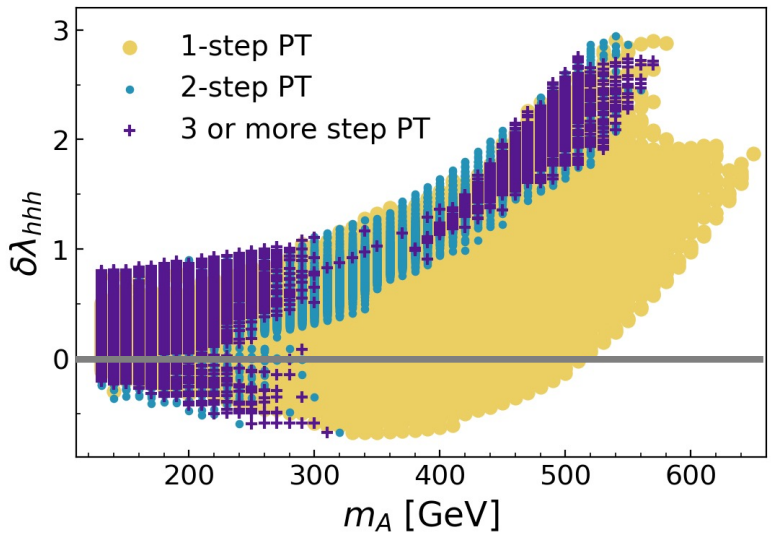
Opposite to the result of multi-step!

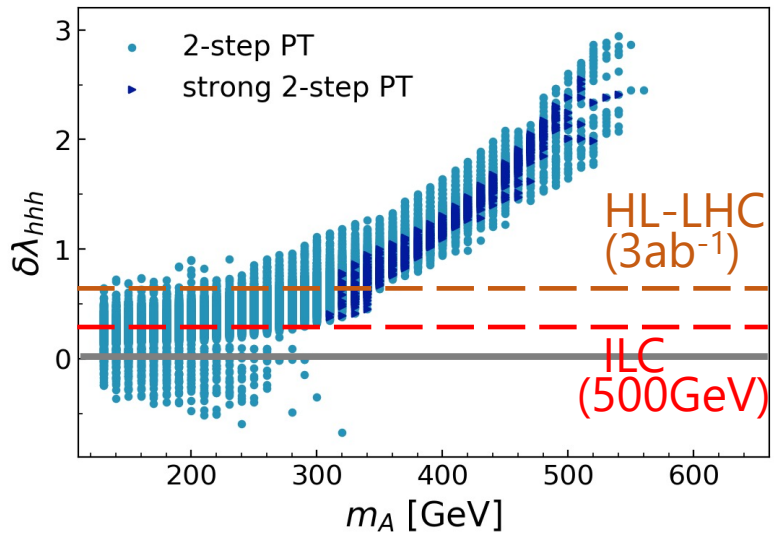
Higgs trilinear couplings

The deviation of the Higgs trilinear coupling from that in SM

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







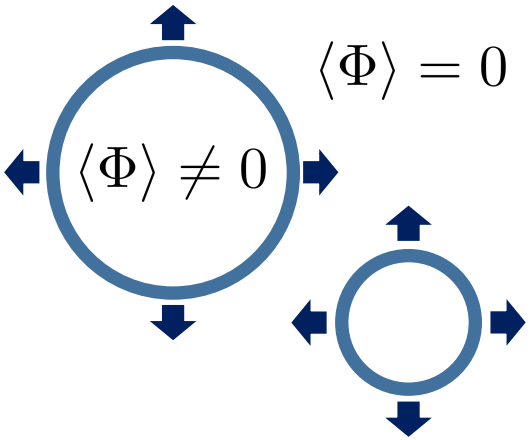
The deviations have a tendency to increase when the multi-step PTs occur. Especially, the deviations with the strong 2-step PTs are about 50%–250%.

Multi-peaked Gravitational Wave

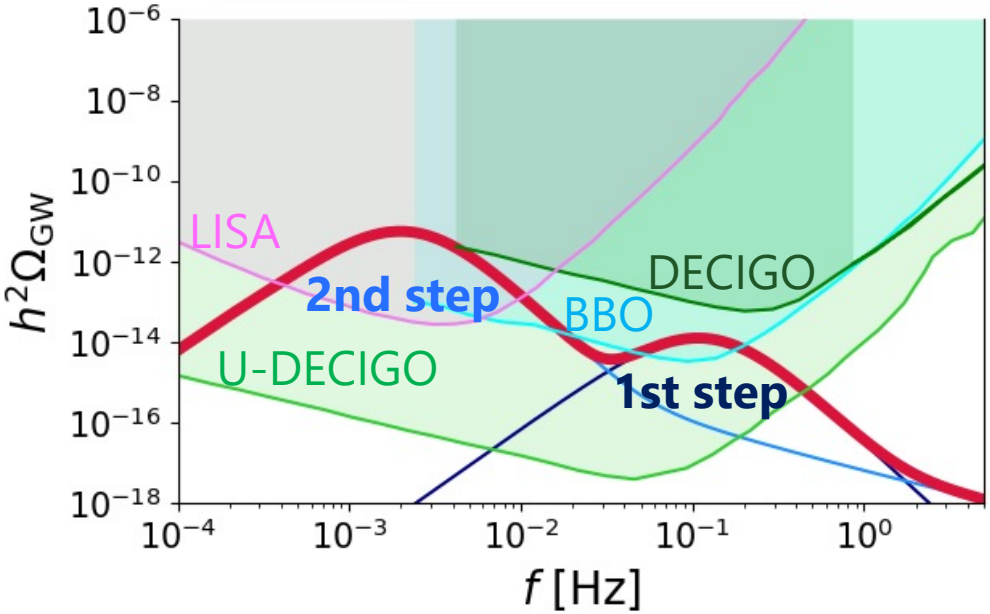
Sources of GW from a PT

There are three sources producing the GWs

$$\Omega_{\rm GW} \simeq \Omega_{\rm coli} + \underbrace{\Omega_{\rm sw}}_{\text{dominant}} + \Omega_{\rm turb}$$ [Bian, Liu ('18)]



The GWs from a 2-step PT



$$m_A = m_{H^\pm} = 490 \text{ GeV}$$

$$m_H = 300 \text{ GeV}$$

$$\tan\beta = 2.3$$

$$\cos(\beta - \alpha) = -0.21$$

$$m_3^2 = 400 \text{ GeV}^2$$

$$\delta\lambda_{hhh} \simeq 2.2$$

$$\xi_1 = 2.1, \ \xi_2 = 4.2$$

Summary

- In the CP-conserving 2HDMs, we find wide areas where the multi-step PTs occur and their features.
  $m_A - m_H < 0$ (multi-step), $m_A - m_H > 0$ (strong 2-step)

- The deviation of the Higgs trilinear coupling from that in SM has a tendency to increase when the multi-step PT occurs. Especially, the deviation is >50% in the cases of the "strong 2-step" PTs.

- The future space-based gravitational wave detectors such as LISA, BBO and U-DECIGO could observe the signatures of the multi-step PT.

Back Up

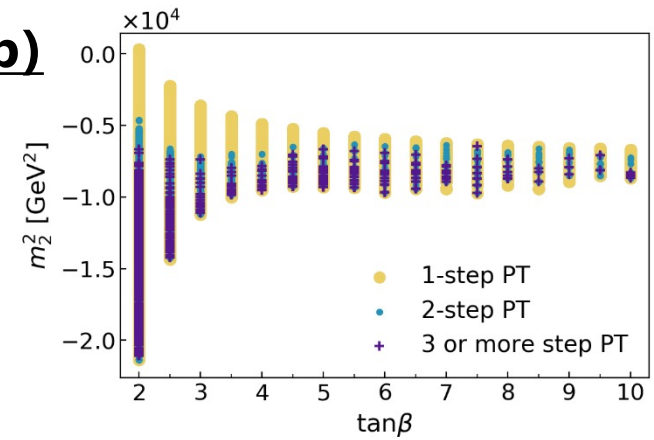
Features of regions for multi-step PTs

Features for multi-step (& strong 2-step)

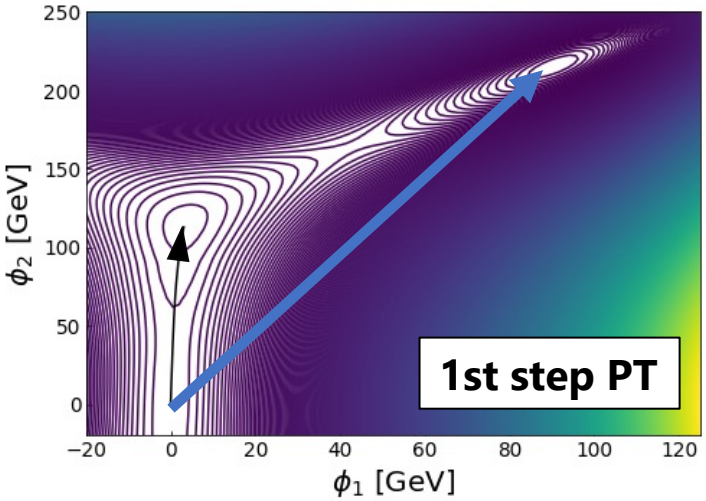
small $\tan\beta$

negative & small $\cos(\beta-\alpha)$ ➡ related with m_2^2

small m_3^2



To move to ϕ_2 axis at the 1st step PT, m_2^2 is need to be small enough.



$$V_0(\phi_1,\phi_2) \supset m_2^2\phi_2^2 - m_3^2\phi_1\phi_2$$

If m_3^2 is too large,
the PT would only occur just one time
(which is 1-step PT).

Definition of counterterm potential

Coleman-Weinberg potential changes the position of minimum.
To avoid this, we add a counterterm potential

$$V_{\rm CT} = \delta m_1^2 \phi_1^2 + \delta m_2^2 \phi_2^2 + \delta\lambda_1 \phi_1^4 + \delta\lambda_2 \phi_2^4 + \delta\lambda_{12} \phi_1^2 \phi_2^2$$ [Bernon et al. ('18)]

Conditions for deciding parameters

$$\begin{cases} \left.\dfrac{\partial V_{\rm CT}}{\partial \phi_i}\right|_{\langle\phi\rangle} = -\left.\dfrac{\partial V_1^0}{\partial \phi_i}\right|_{\langle\phi\rangle} \quad (i,j=1,2\ ;\langle\phi\rangle=(v_1,v_2)) \\ \left.\dfrac{\partial^2 V_{\rm CT}}{\partial \phi_i \partial \phi_j}\right|_{\langle\phi\rangle} = -\left.\dfrac{\partial^2 V_1^0}{\partial \phi_i \partial \phi_j}\right|_{\langle\phi\rangle} \end{cases}$$

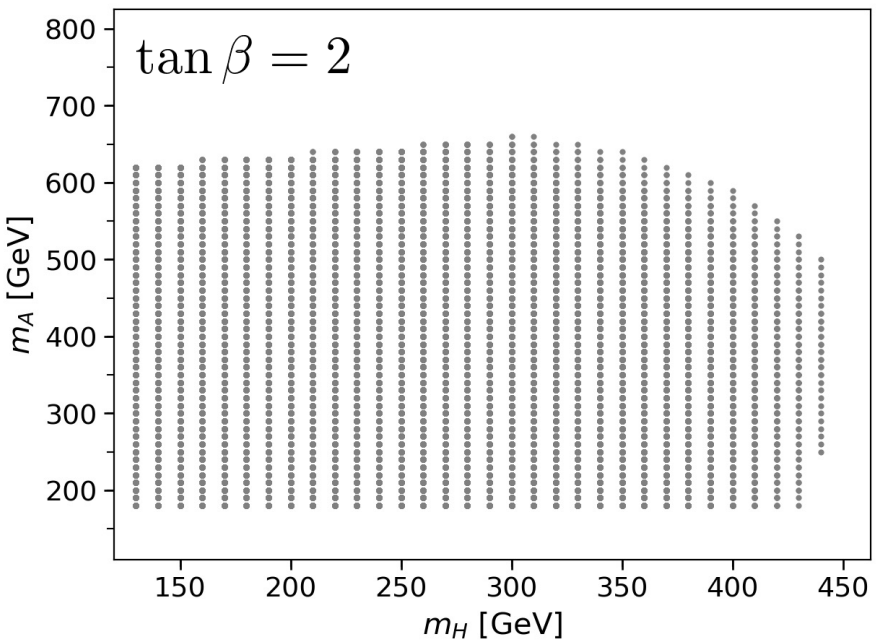
Infrared divergences

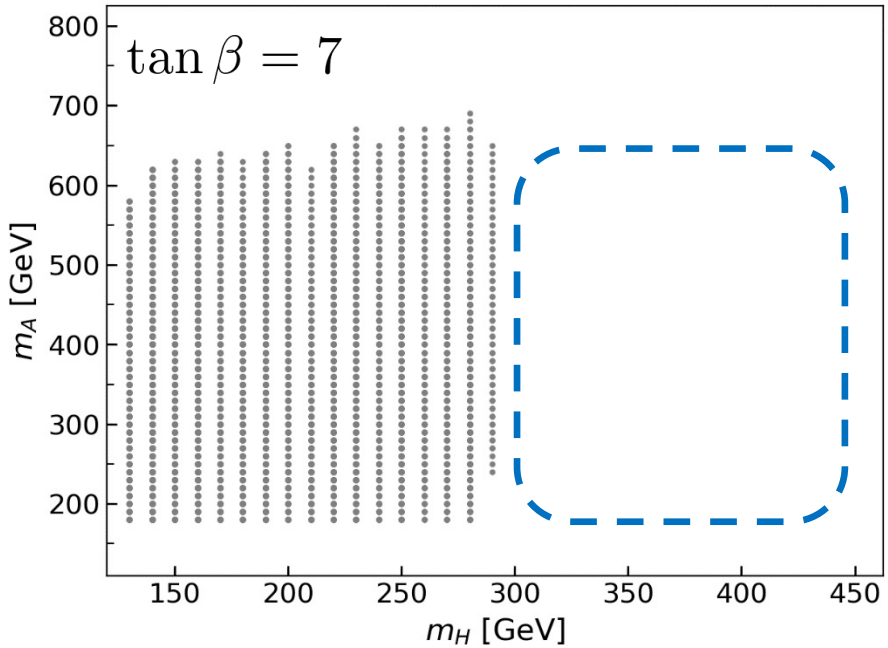
To avoid these divergences, we set cut-off.
In the second derivatives, we approximate $m_{\rm NG}^2 \to m_h^2 \simeq 125\ [{\rm GeV}]$

[Cline, Kainulainen ('11)]

Theoretical Constraints

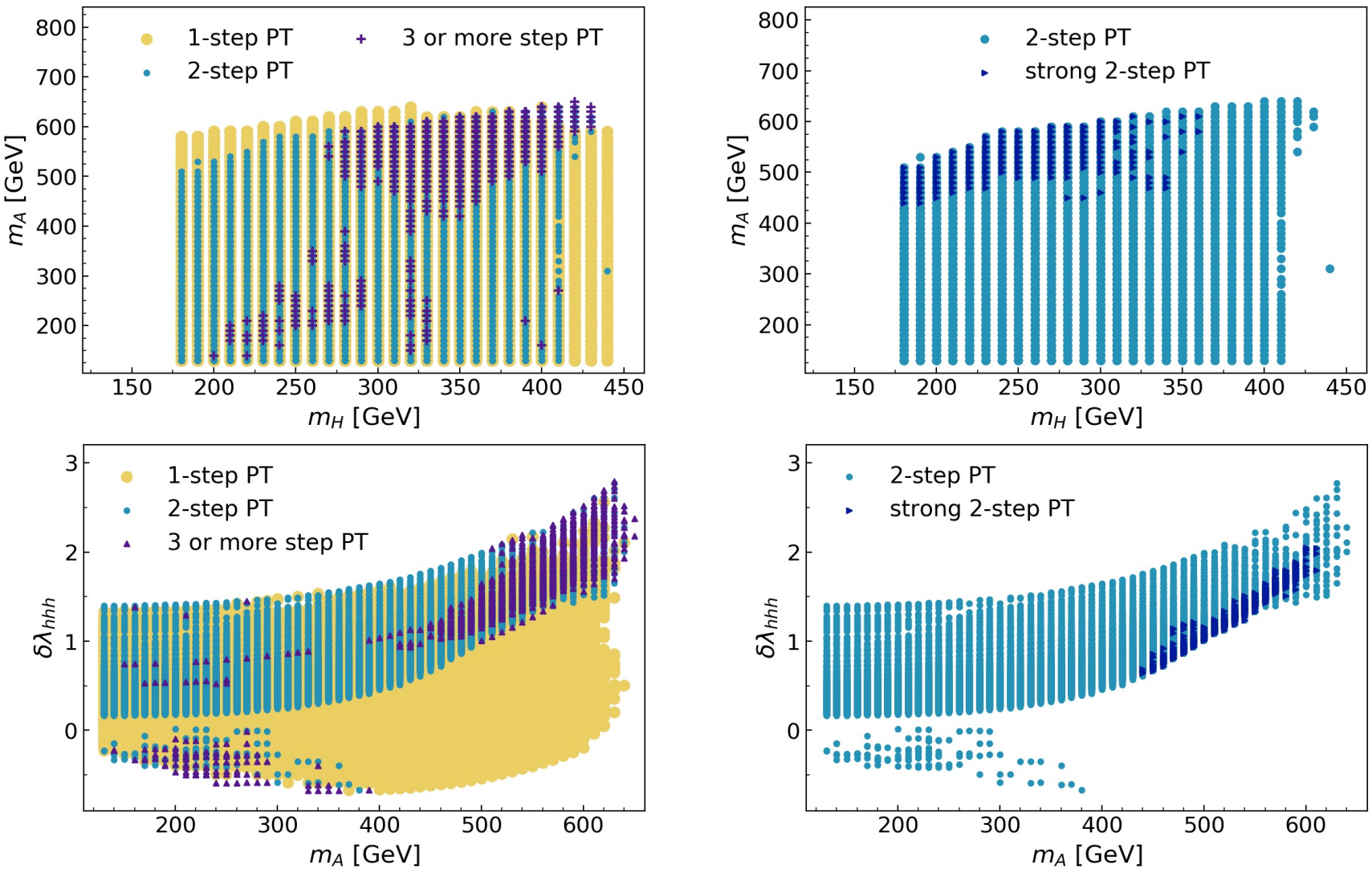
Allowed area by constraints from BFB, perturbative theory and tree-level unitarity in Type-I with $m_A = m_{H^\pm}$



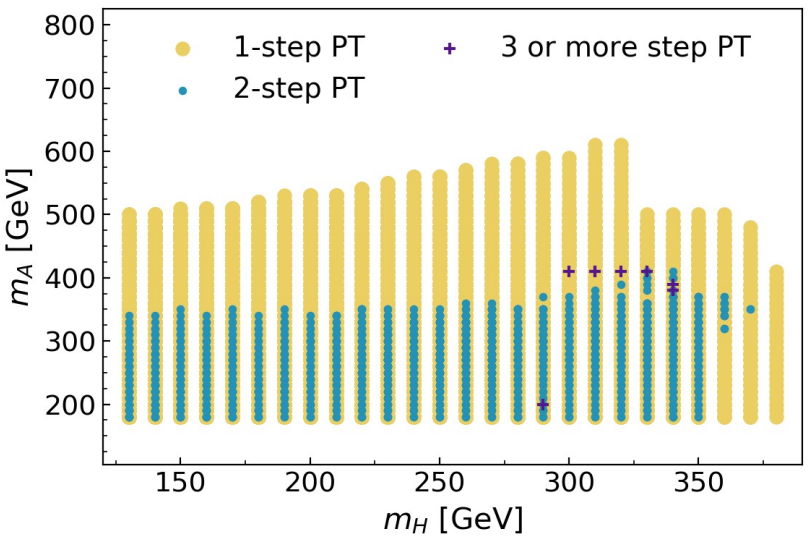


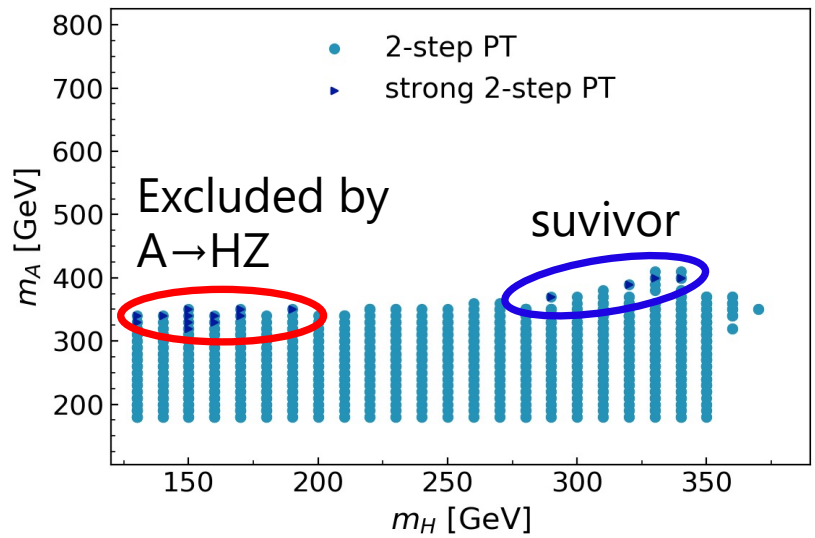
Even if in Type-I with $m_H = m_{H^\pm}$, large m_H is constrained at large $\tan\beta$.

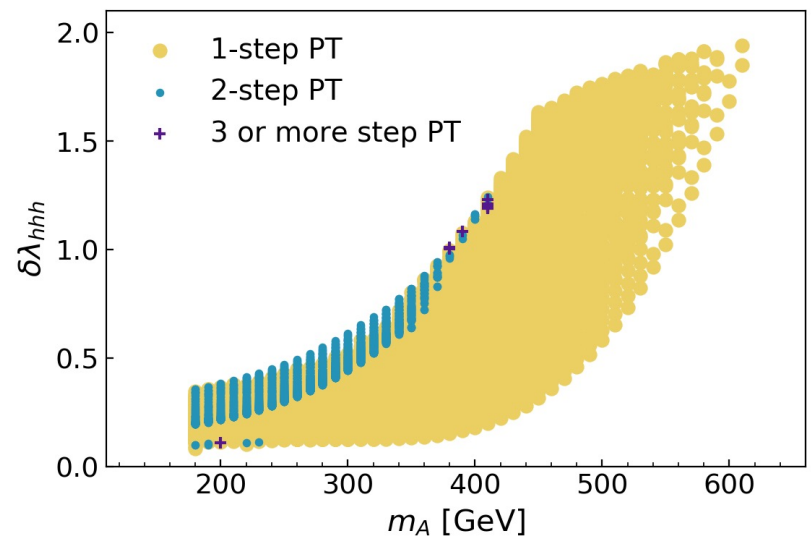
Type-I $(m_H = m_{H^\pm})$

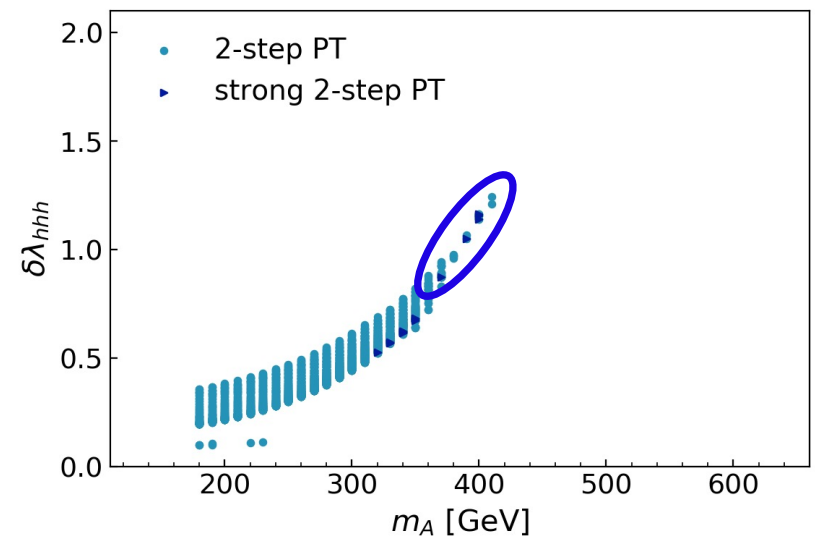


Type-X$(\mathbf{m_A = m_{H^\pm}})$

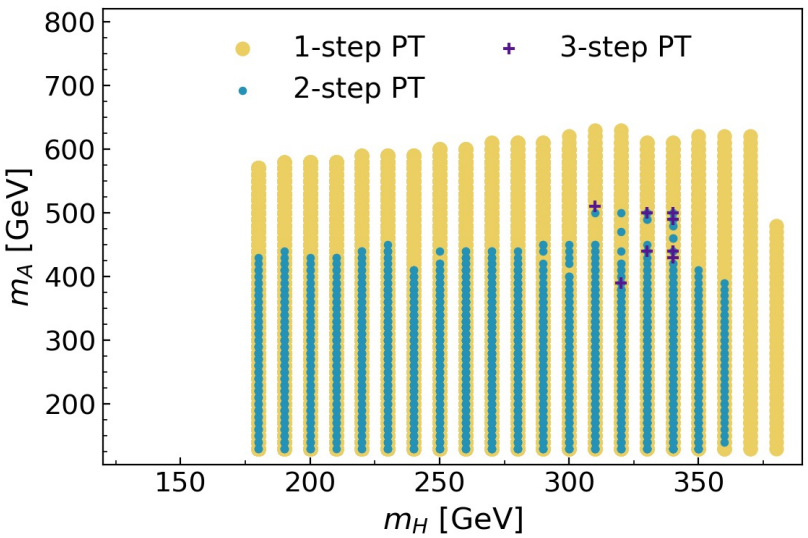


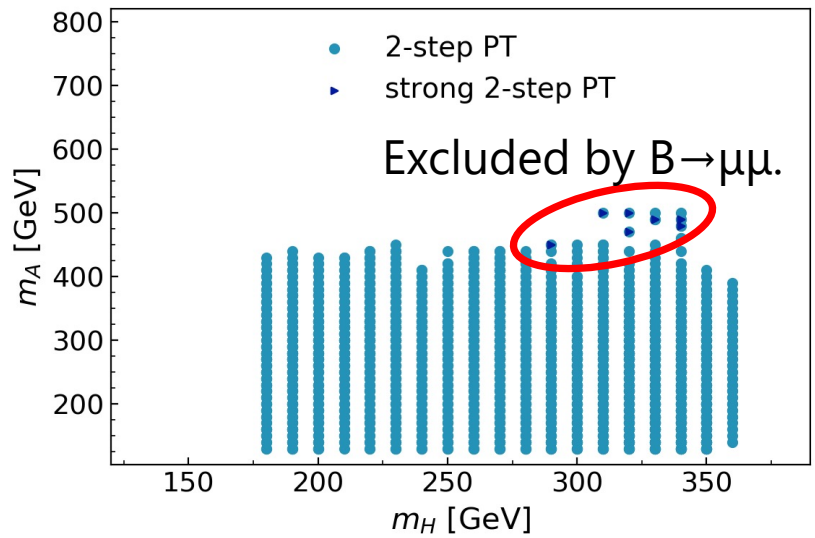


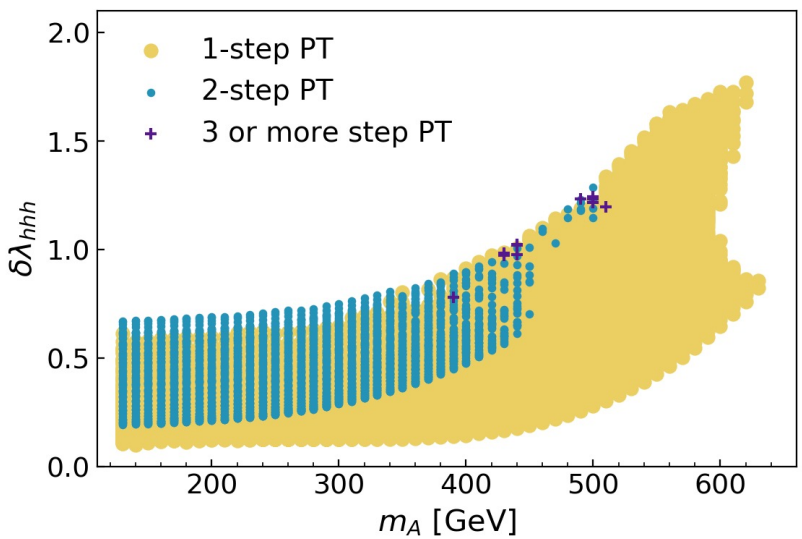


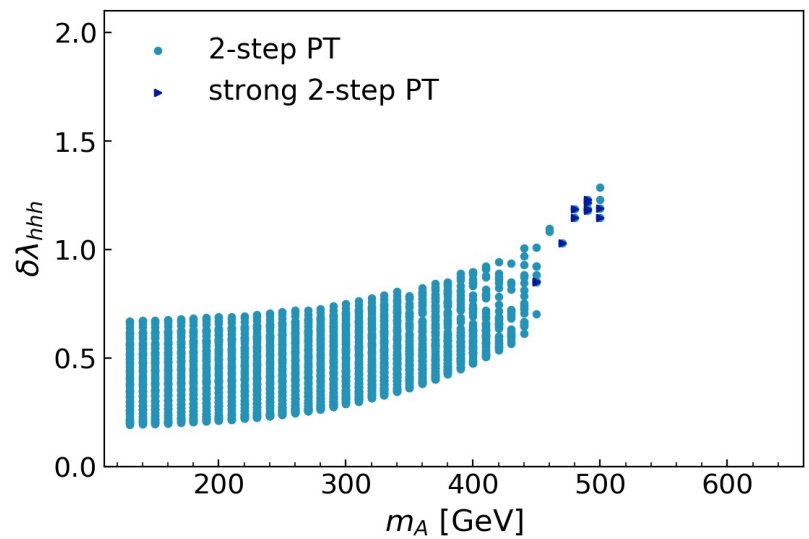


Type-X$(\mathbf{m_H = m_{H^\pm}})$





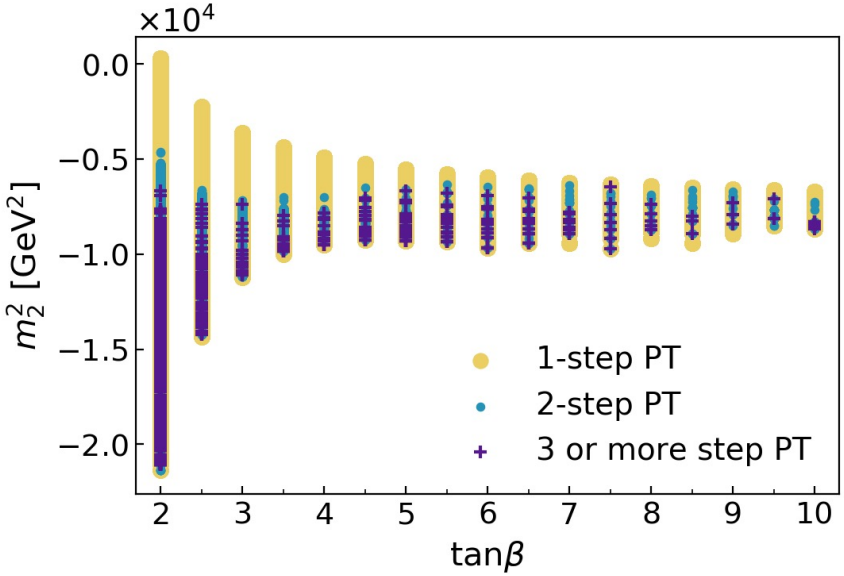


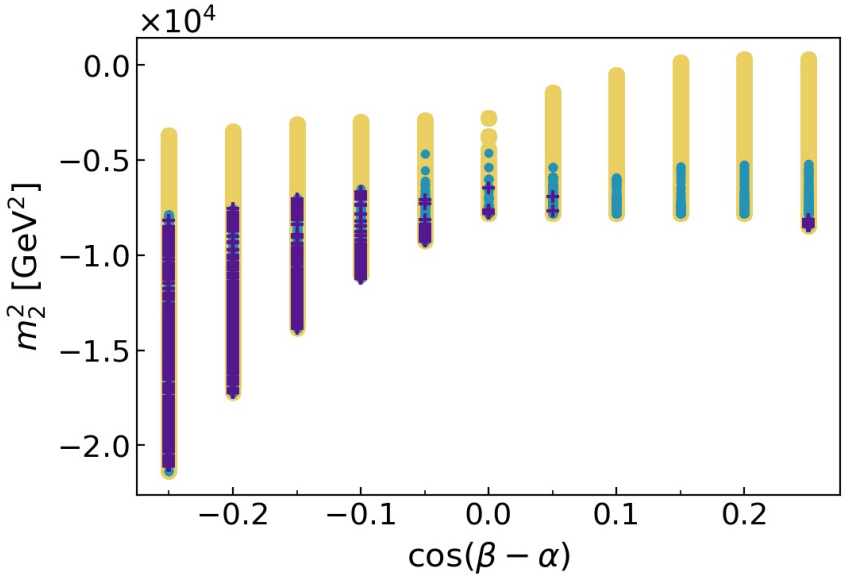


Parameters related to $\mathbf{m_2^2}$

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

Leading contribution
except for near sinα=0

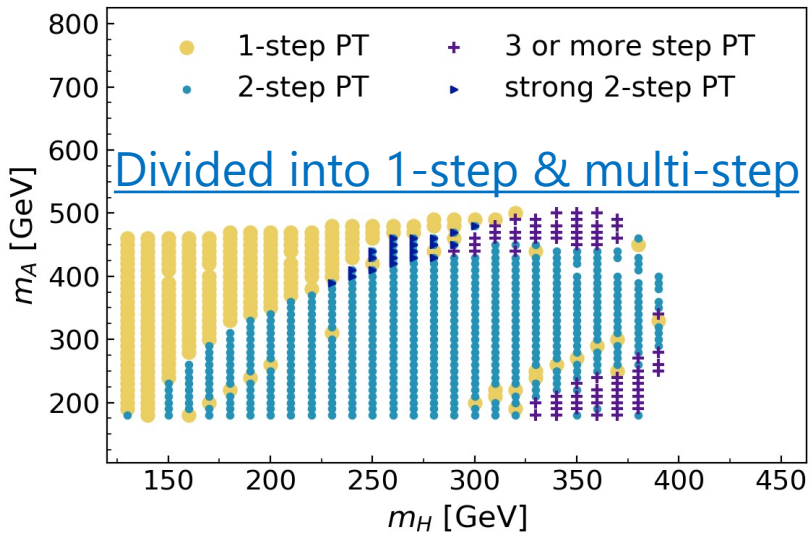


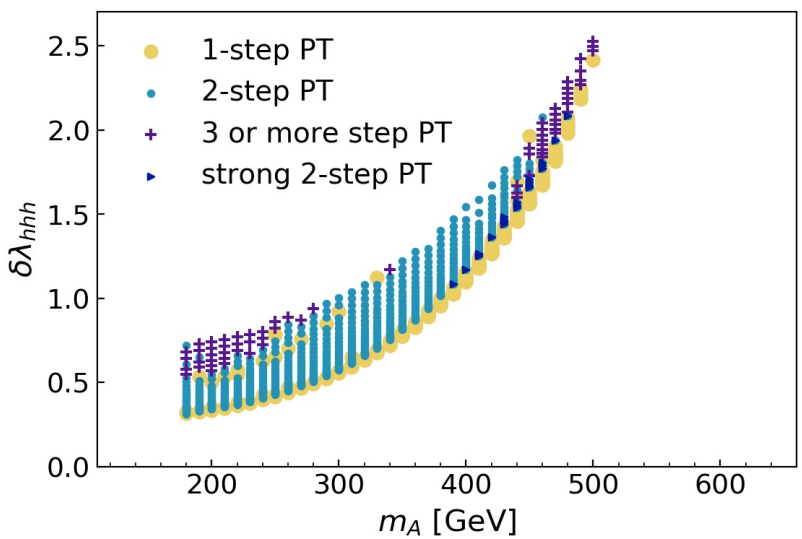


Large ← $|\sin\alpha|$

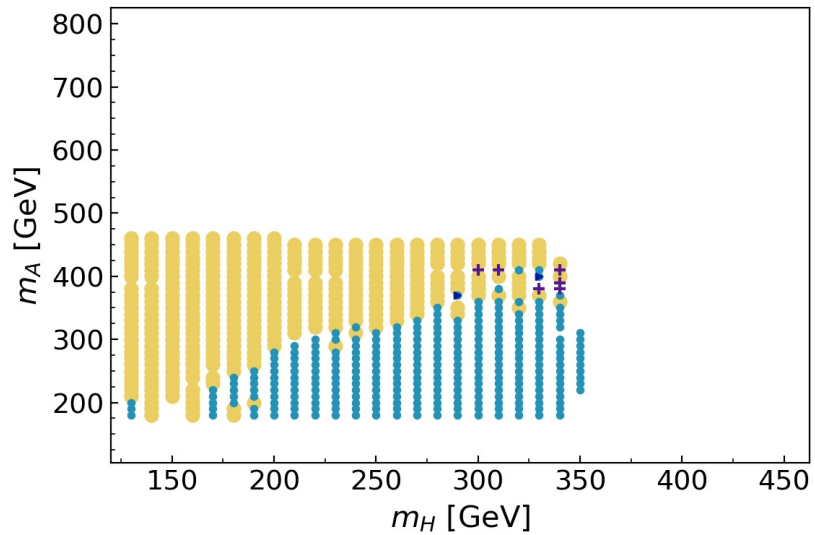
Cases of fixing parameters Type-I $(m_A = m_{H^\pm})$

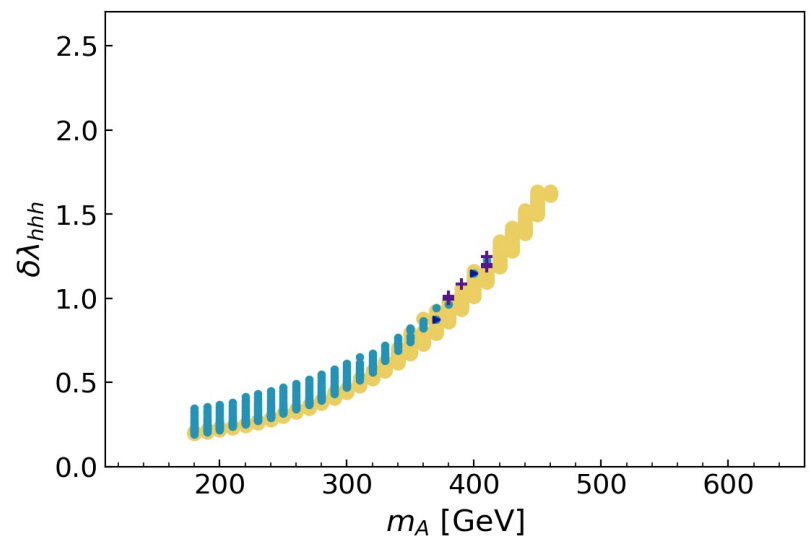
$\tan\beta = 2, \cos(\beta-\alpha) = -0.2, m_3^2 = 0\ \mathrm{GeV}^2$





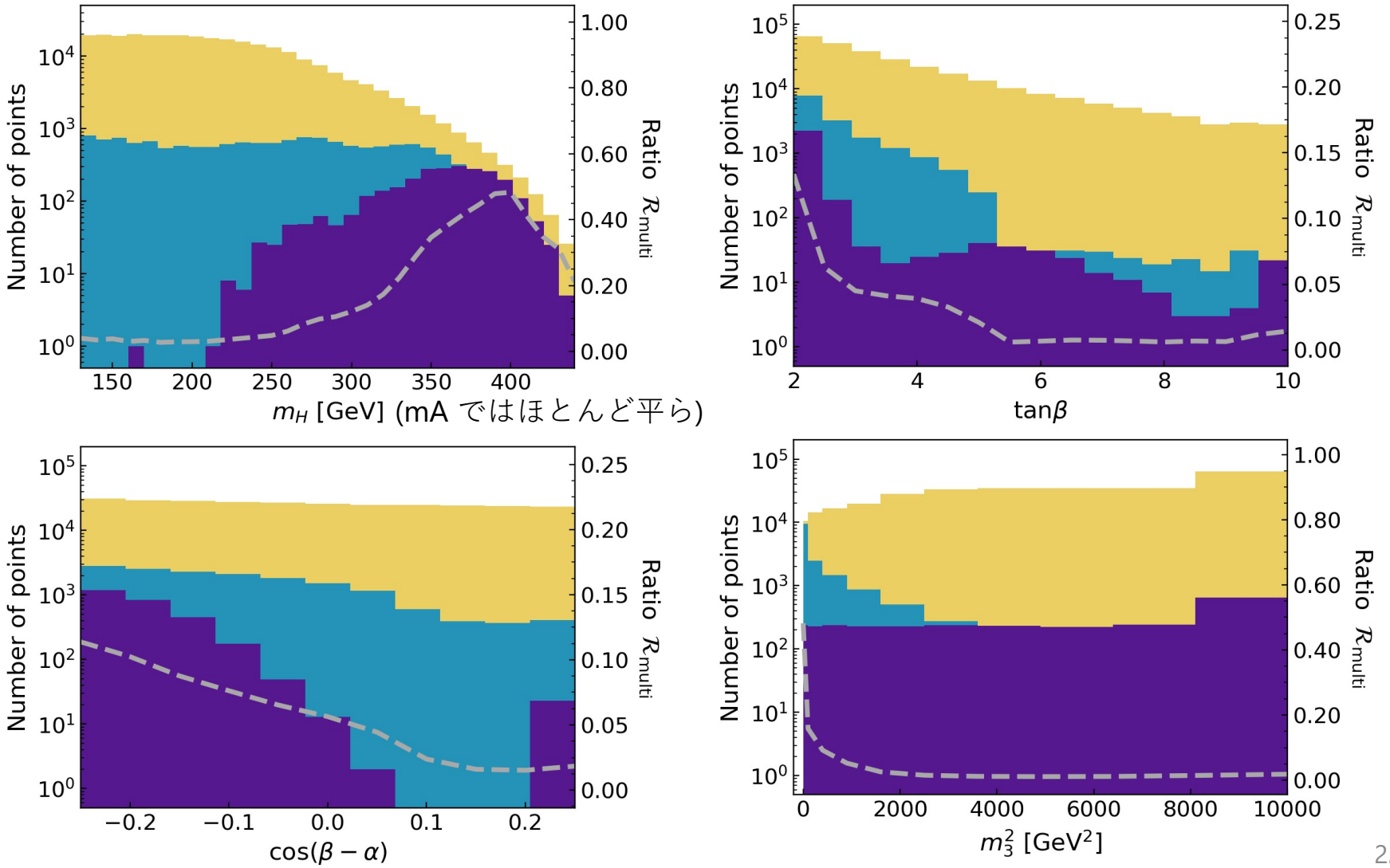
$\tan\beta = 2, \cos(\beta-\alpha) = 0, m_3^2 = 0\ \mathrm{GeV}^2$





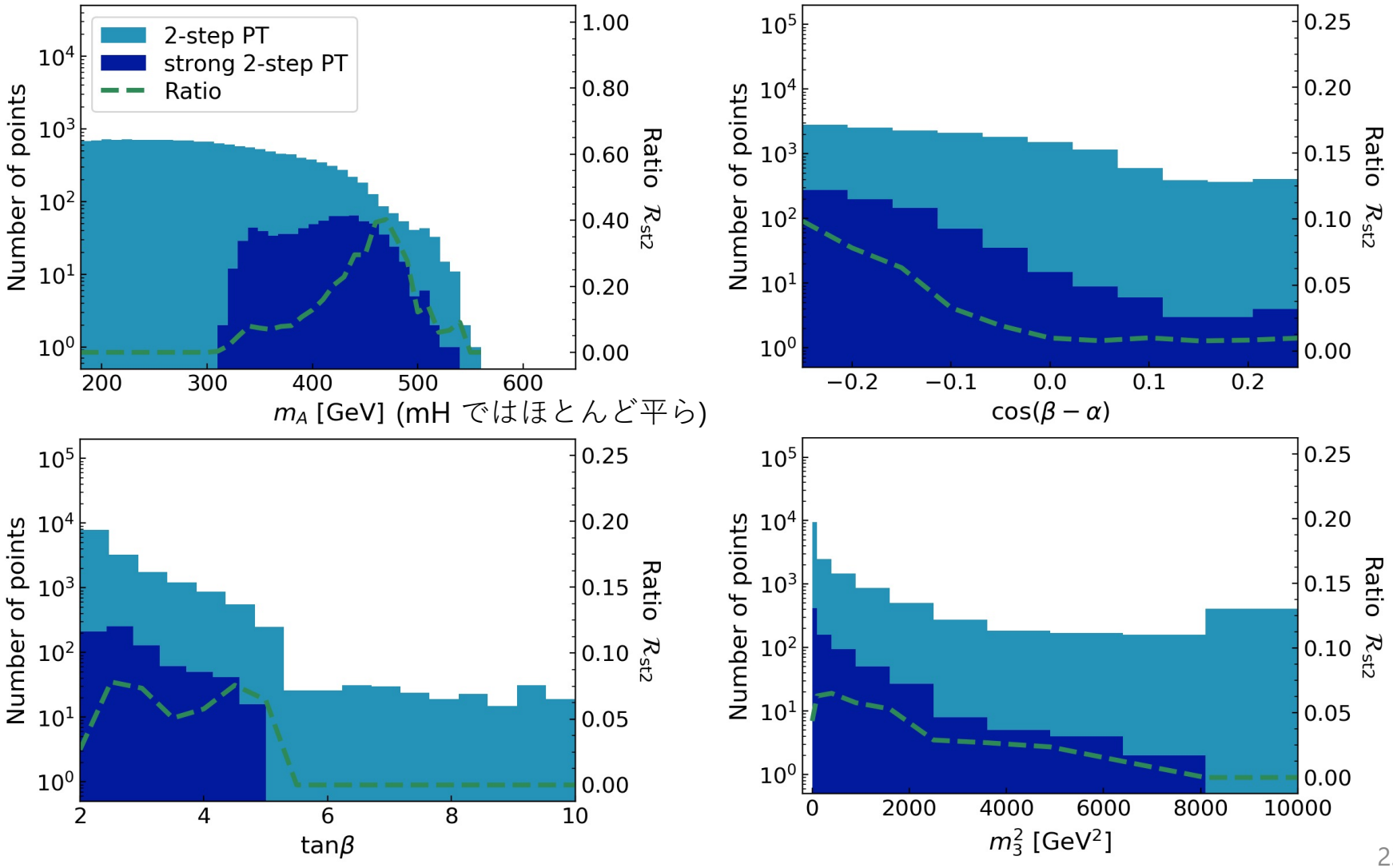
Number Analyses for multi-step PTs

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



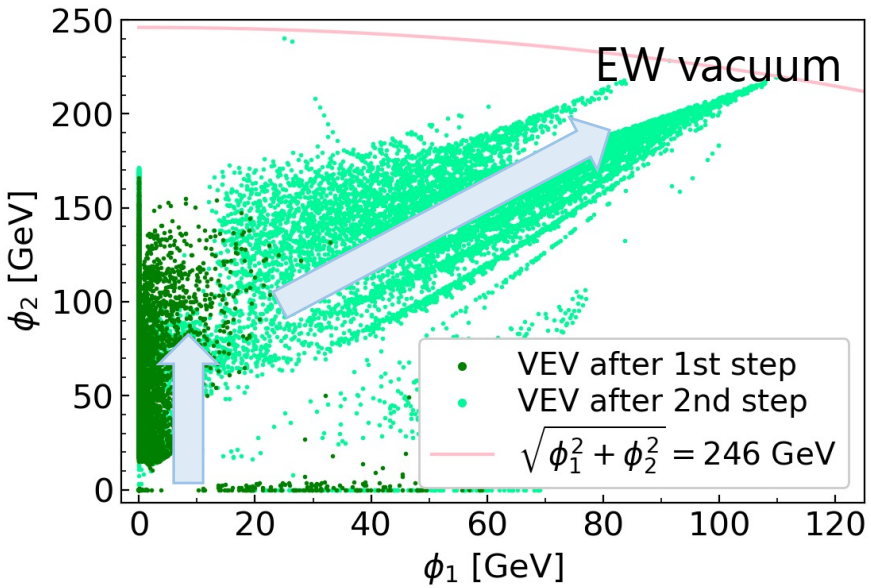
Number analyses for strong 2-step PTs

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

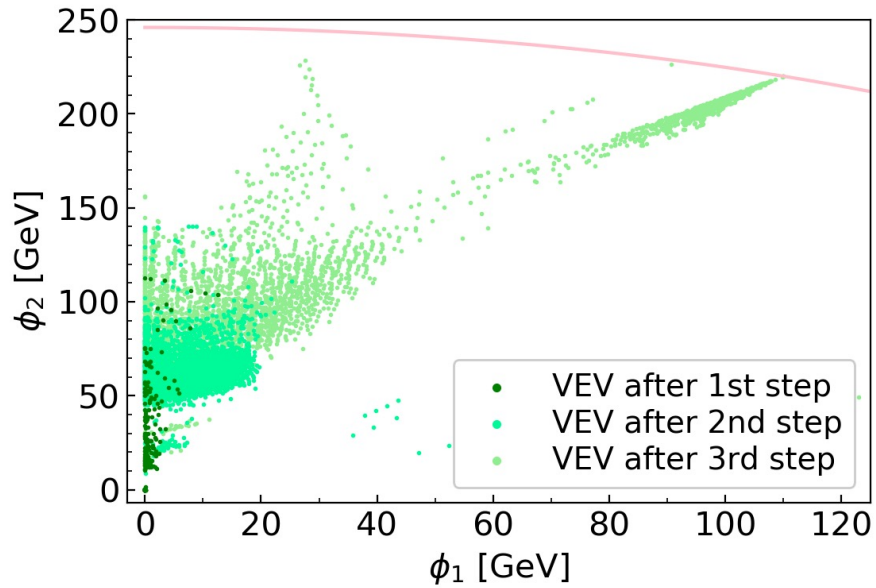


Passes of multi-step PTs

2-step PTs



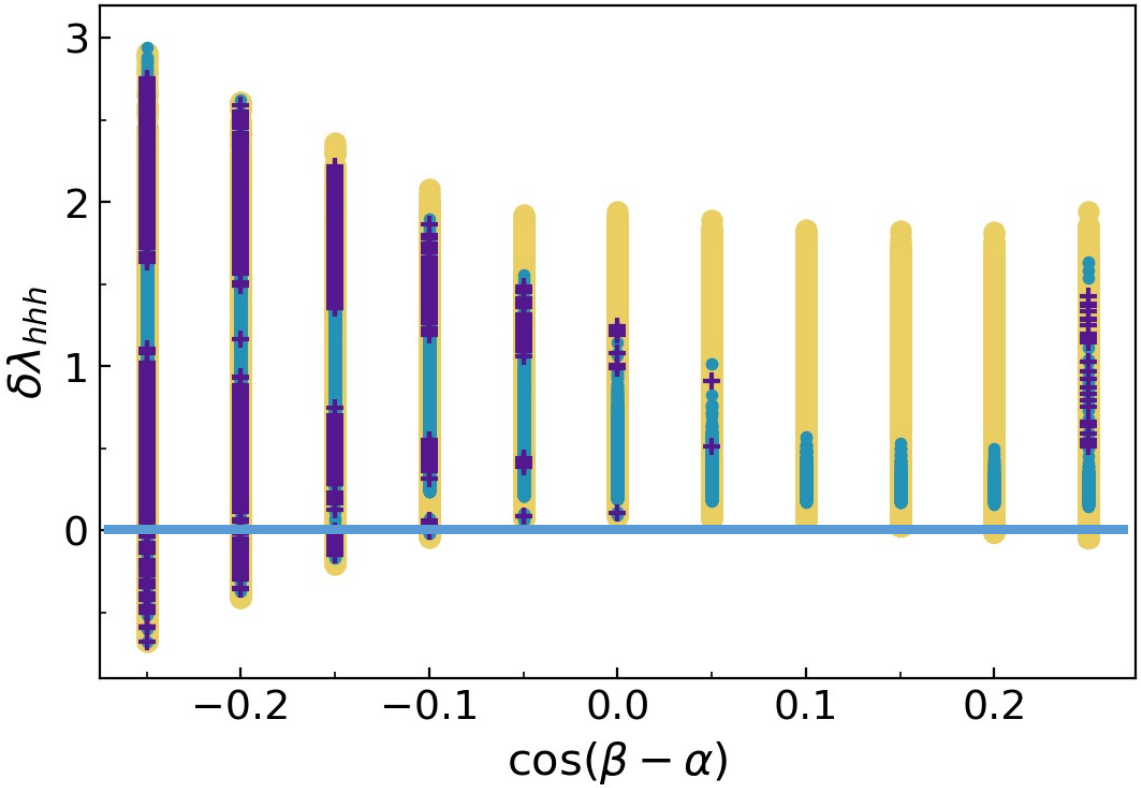
3-step PTs



In the first step, PT occurs along the axis.
In the last step, PT occurs in 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
$|\cos(\beta - \alpha)| \gtrsim 0.1$
$(m_3^2 \gtrsim 2500\ \mathrm{GeV}^2)$