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 !

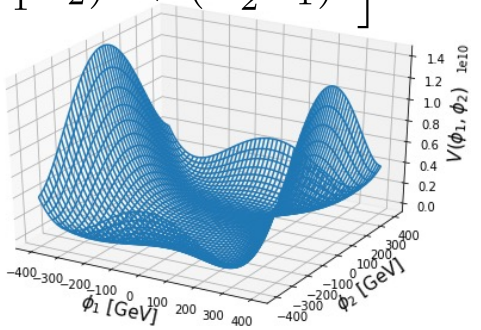
Inert 2HDM [Blinov et al. ('15)]

Two Higgs Doublet Model

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

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

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



Types of Yukawa interactions

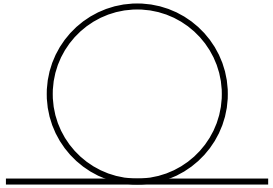
To avoid FCNC processes, assume two doublets has different Yukawa couplings.

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

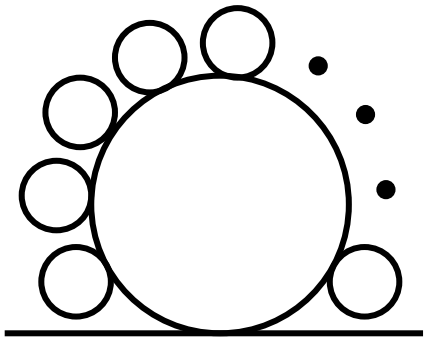
$$V^{\beta} = V_0 + V_1^0 + V_{\rm CT} + \underset{\sim}{\overline{V}}_1^{\beta}$$ Thermal effect



- V_1^0 the one-loop contributions at zero temperature
- $V_{\rm CT}$ the counter term for maintaining
  - the position of the minimum
  - the 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

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

CP-odd CP-even

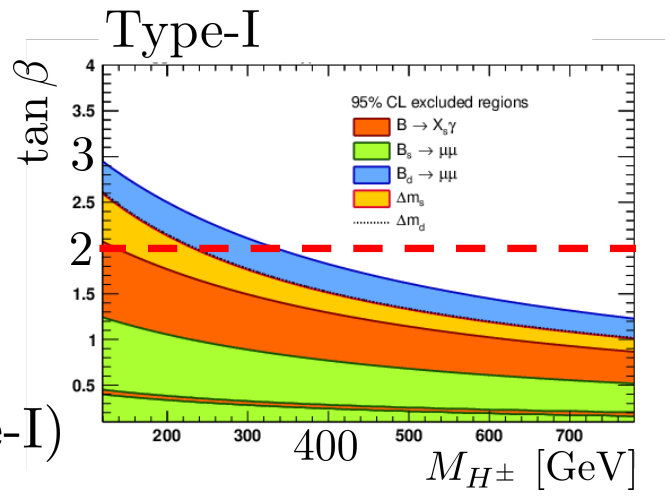
Flavor experiments

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

[Haller et al.('18)]

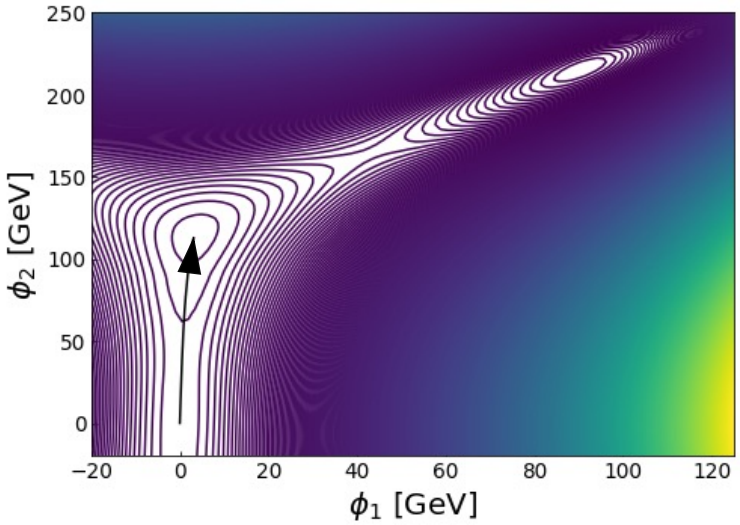
Higgs couplings strength [ATLAS Collab. ('19)]

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



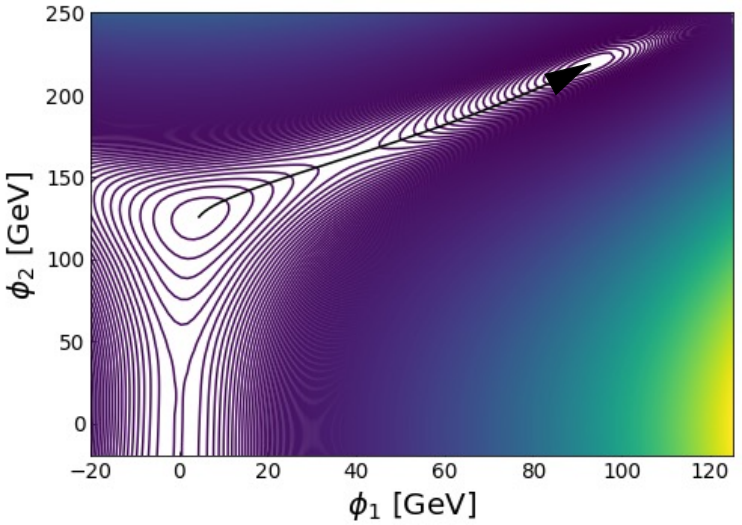
Pass of a multi-step EWPT

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

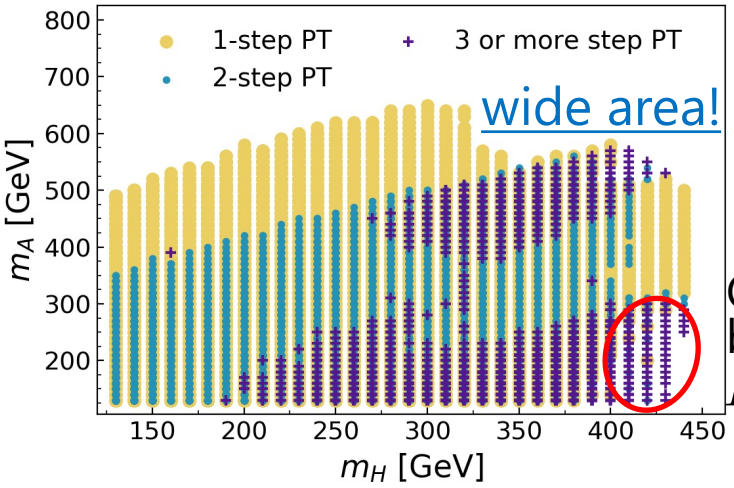
M. Aoki, T. Komatsu, H. S.
[arXiv:2106.03439]

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

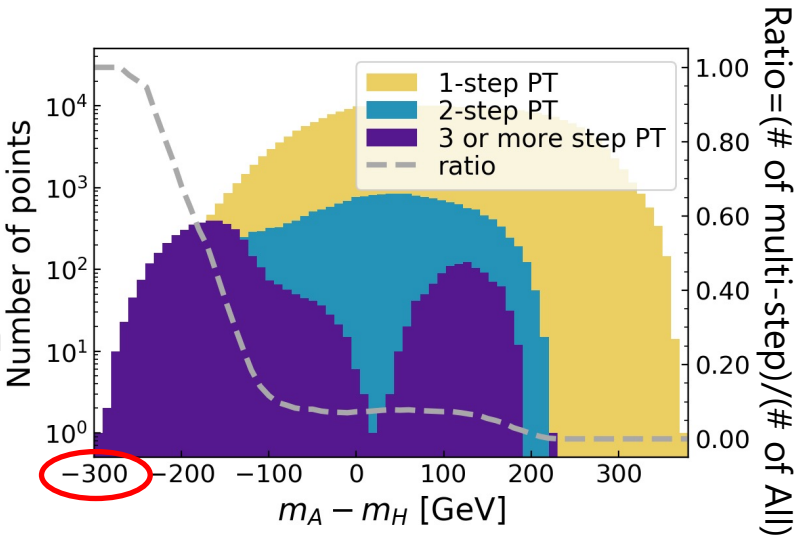
[Wainwright ('12)]

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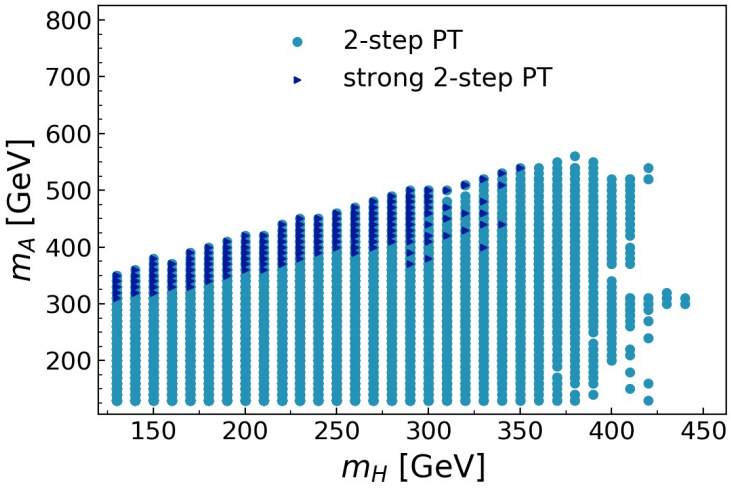
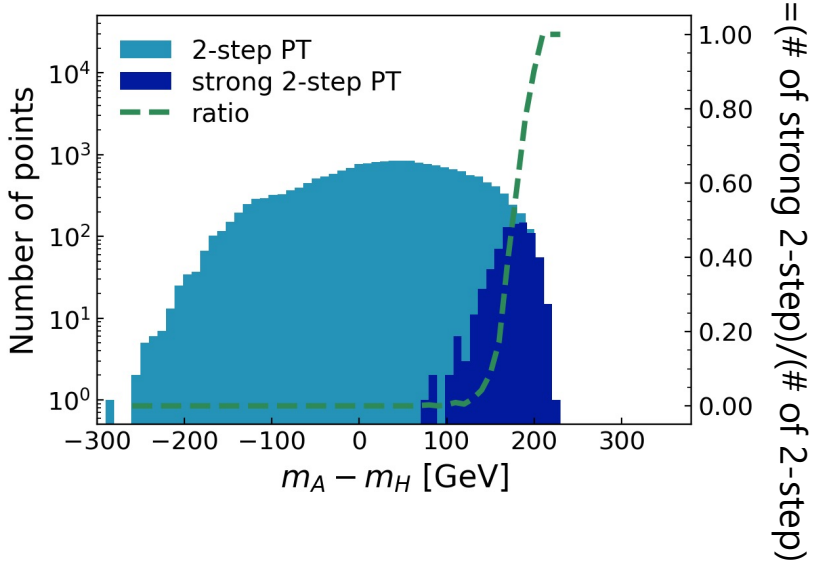
2-step PT vs. "strong 2-step" PT

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

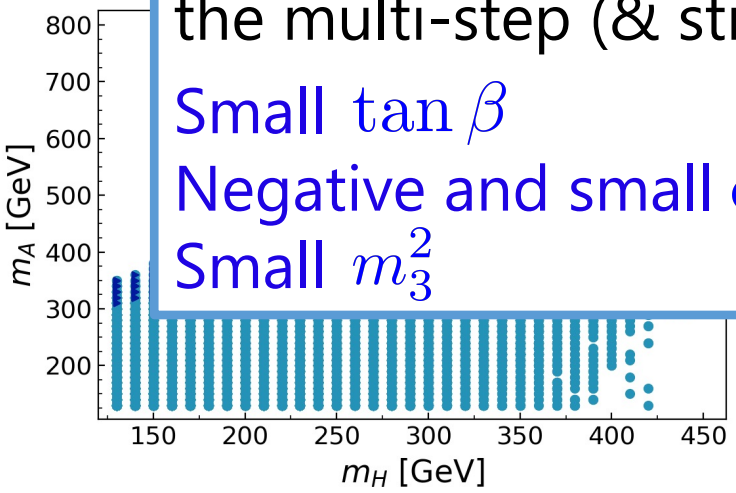
step

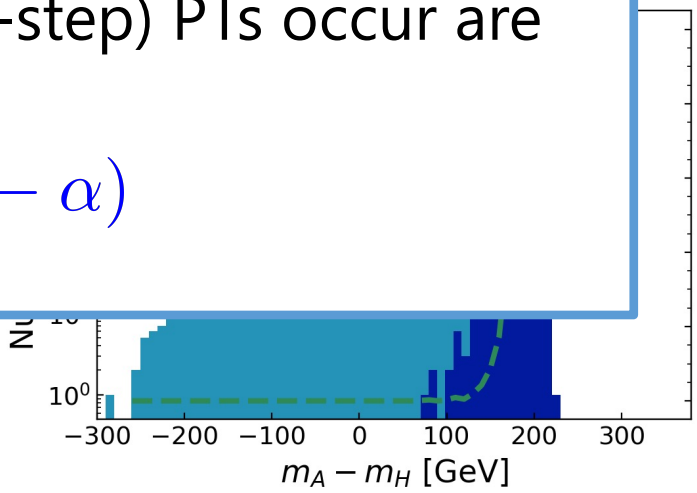
The other features of the region where the multi-step (& strong 2-step) PTs occur are

Small $\tan\beta$

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

Small m_3^2





Strong 2-step PTs only occur with

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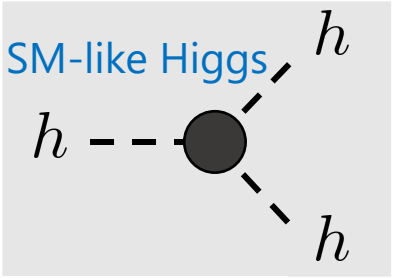
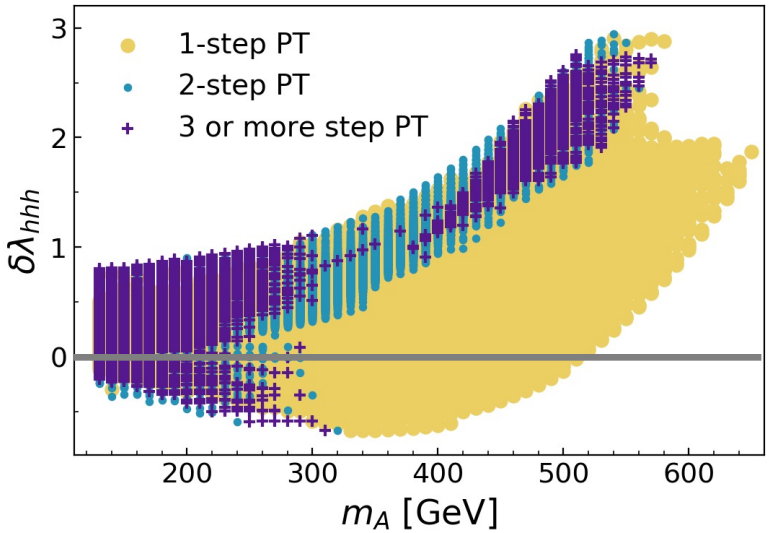
Opposite to the result of multi-step!

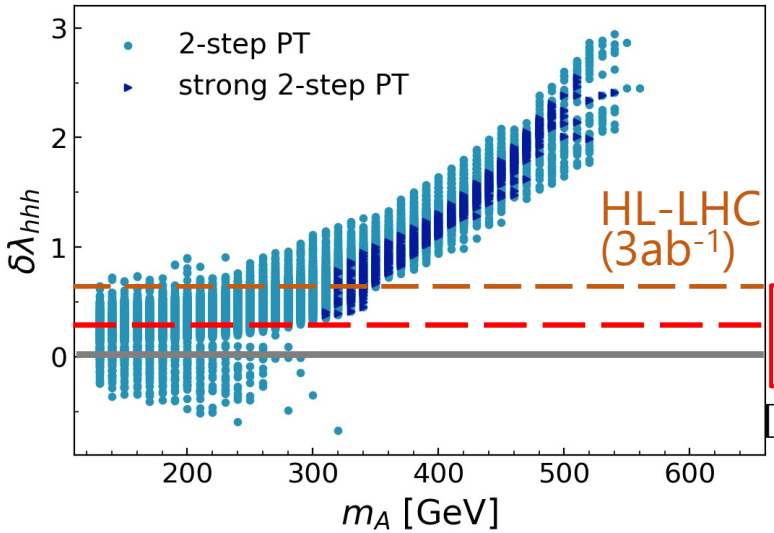
Higgs trilinear couplings

The deviation of the Higgs trilinear coupling from that in SM

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





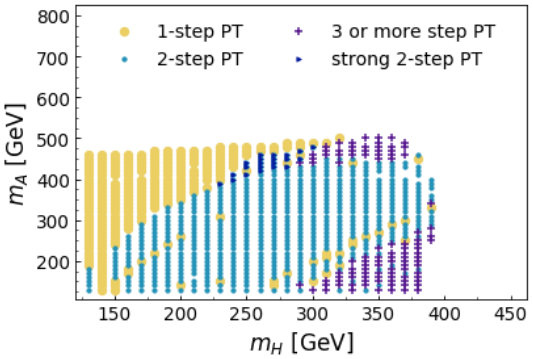


[Fujii et al. (15)]

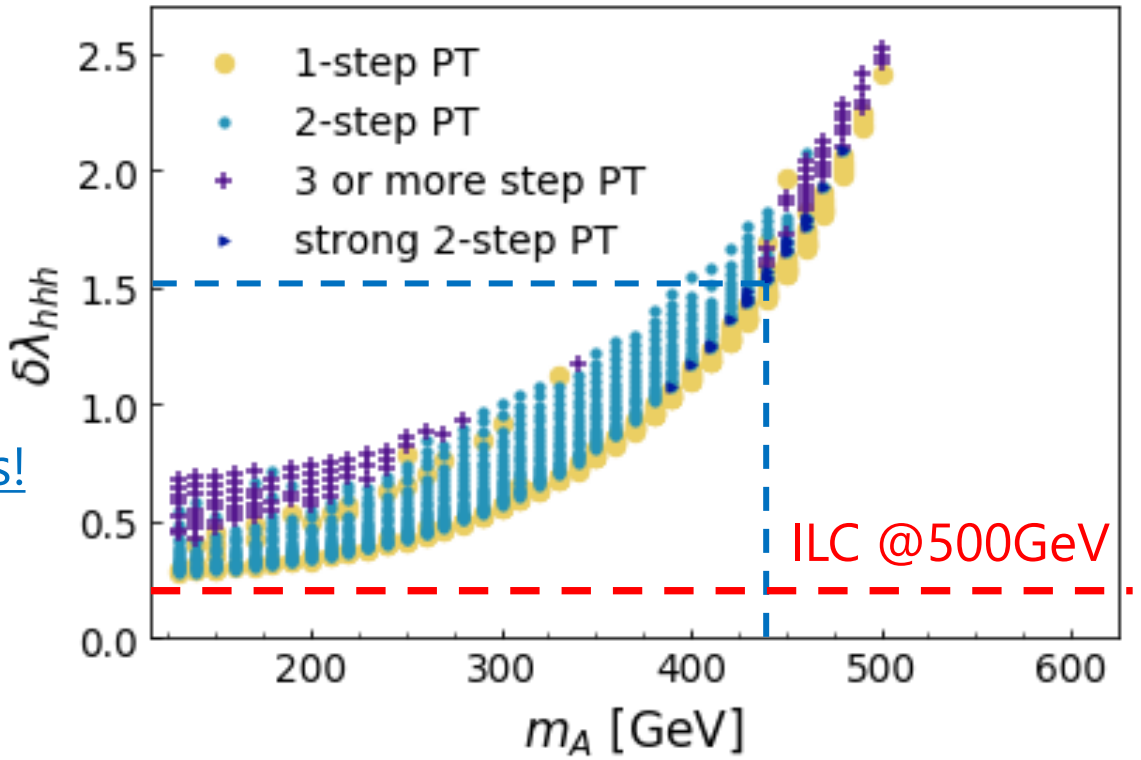
The deviations have a tendency to increase when the multi-step PTs occur. Especially, the deviations with the strong 2-step PTs are about 50%–250%.

Case of fixing parameters

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



Divided into
1-step & multi-step PTs!



When $\delta\lambda_{hhh} \simeq 1.5,$ the multi-step PTs occur at $m_A \simeq 400 - 440\ \mathrm{GeV}$ and the strong 2-step PTs at $m_A \simeq 440\ \mathrm{GeV}.$

The trilinear coupling is an important observable for multi-step!

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 more than about 50% in the cases of the "strong 2-step" PTs, which can be detected by the ILC operating at 500GeV!
- With a combination of other signatures (like gravitational wave spectrum), it might be possible to identify whether the multi-step PT occurs or not.

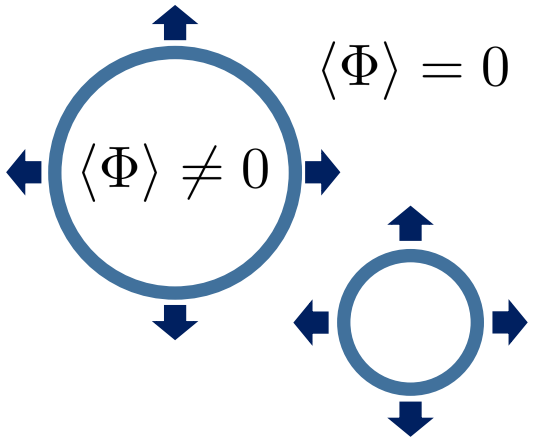
Back Up

Multi-peaked Gravitational Wave

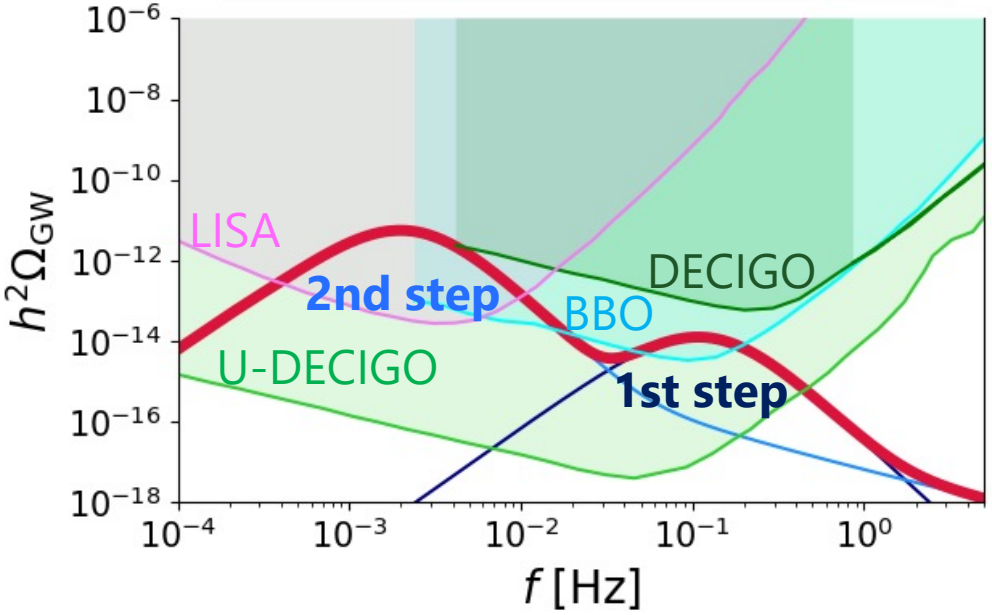
Sources of GW from a PT

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



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

$m_H = 300$ GeV

$\tan\beta = 2.3$

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

$m_3^2 = 400$ GeV^2

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

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

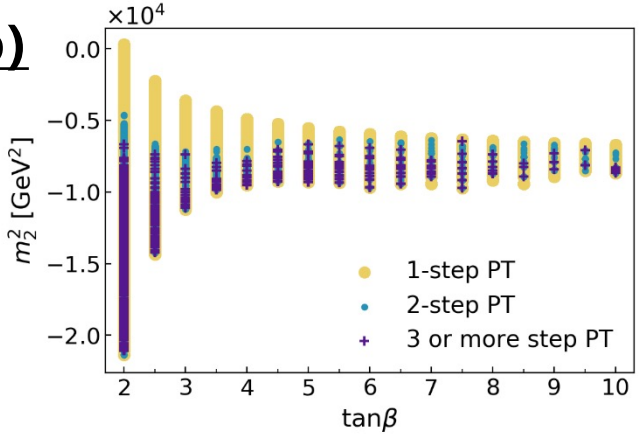
Features of regions for multi-step PTs

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

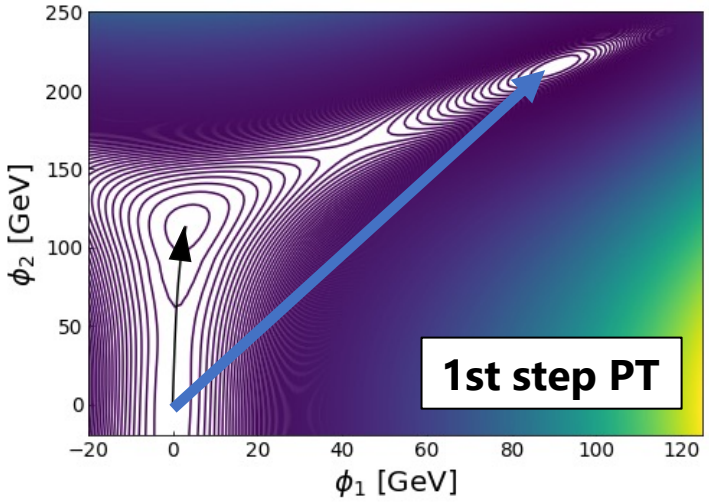
small $\tan\beta$

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.

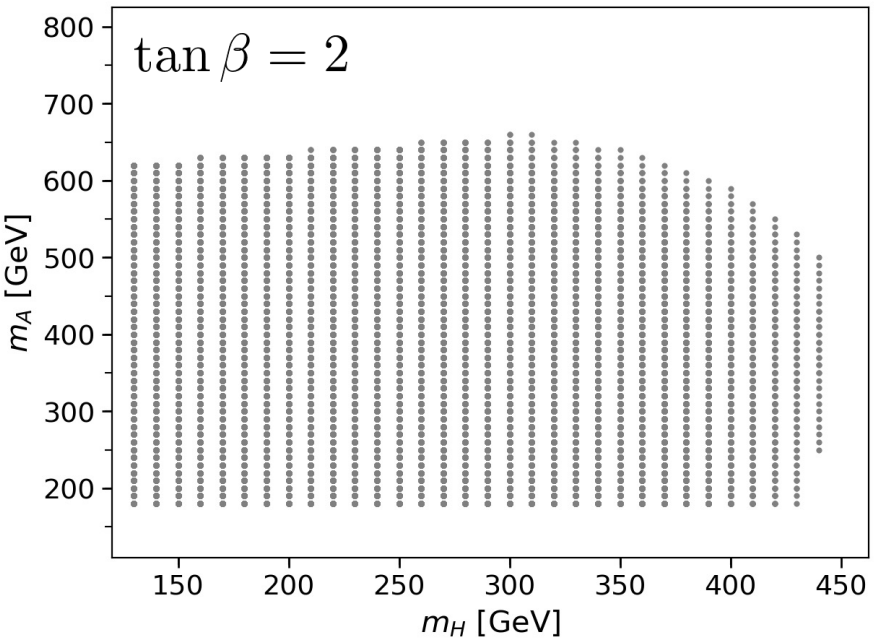


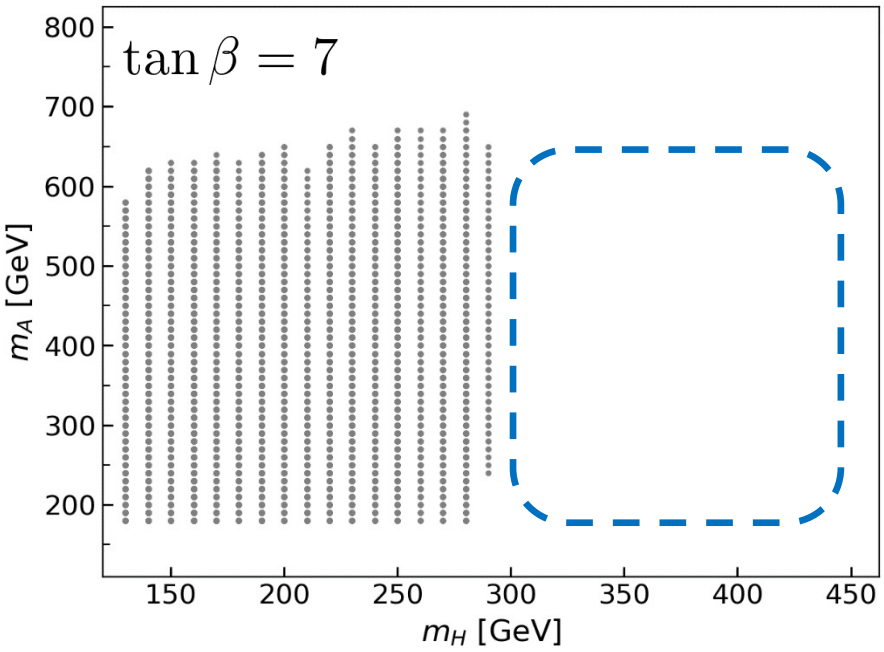
$$V_0(\phi_1,\phi_2) \supset m_2^2\phi_2^2 - m_3^2\phi_1\phi_2$$

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

Theoretical Constraints

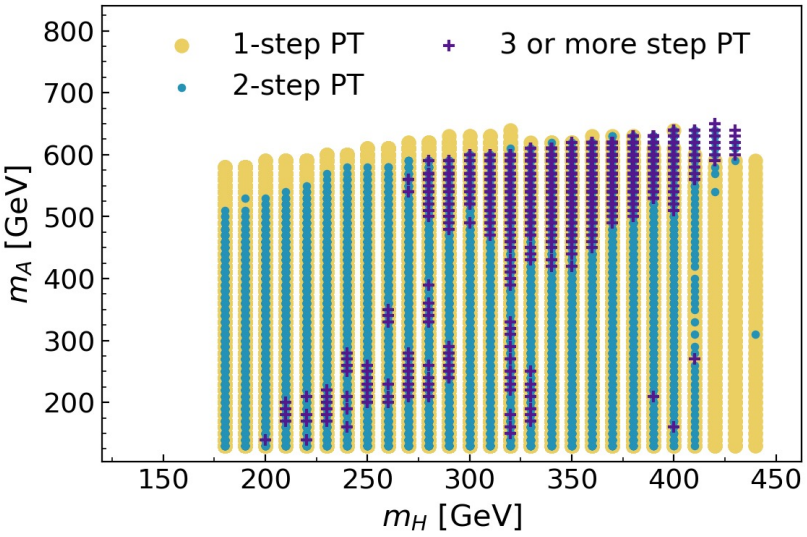
Allowed area by constraints from BFB, perturbative theory and tree-level unitarity in Type-I with $m_A = m_{H^\pm}$

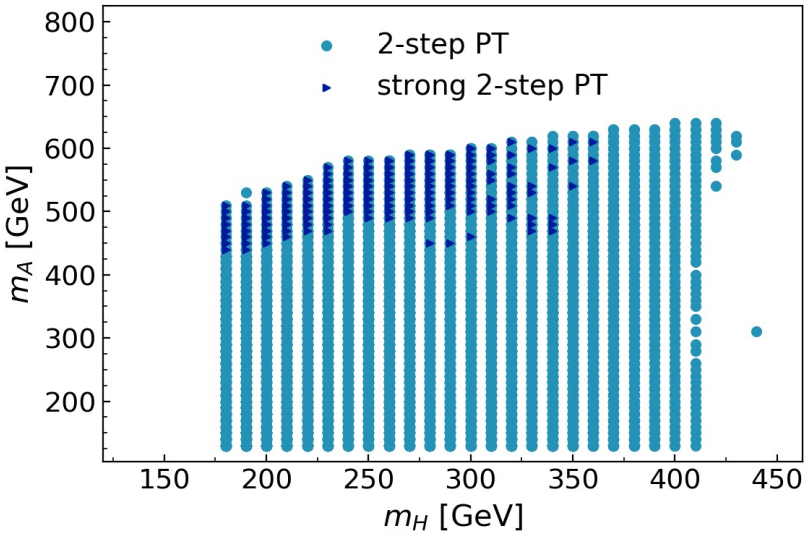


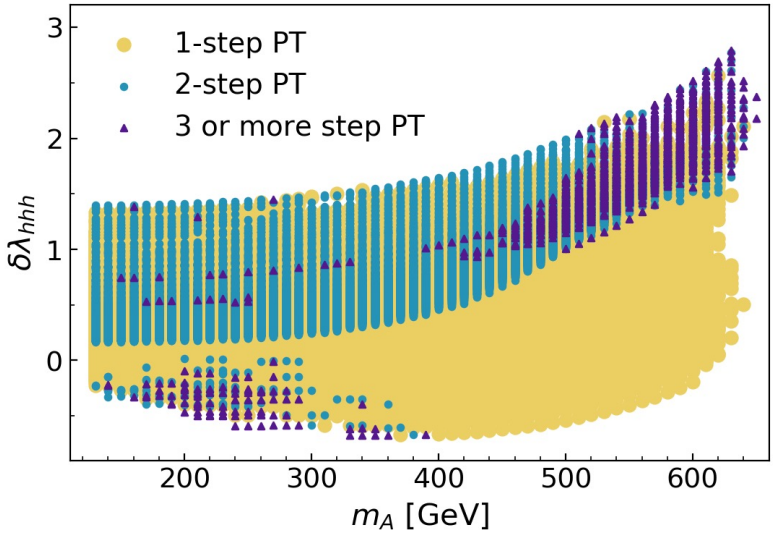


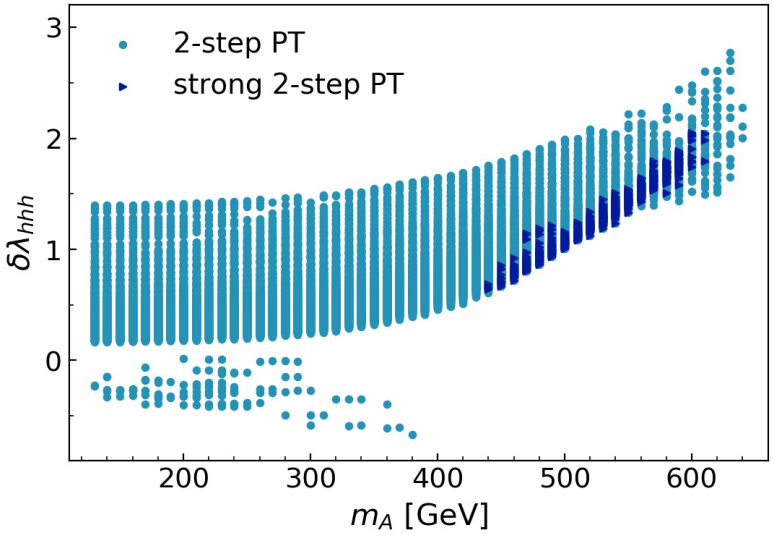
Even if in Type-I with $m_H = m_{H^\pm}$, large m_H is constrained at large $\tan\beta$.

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

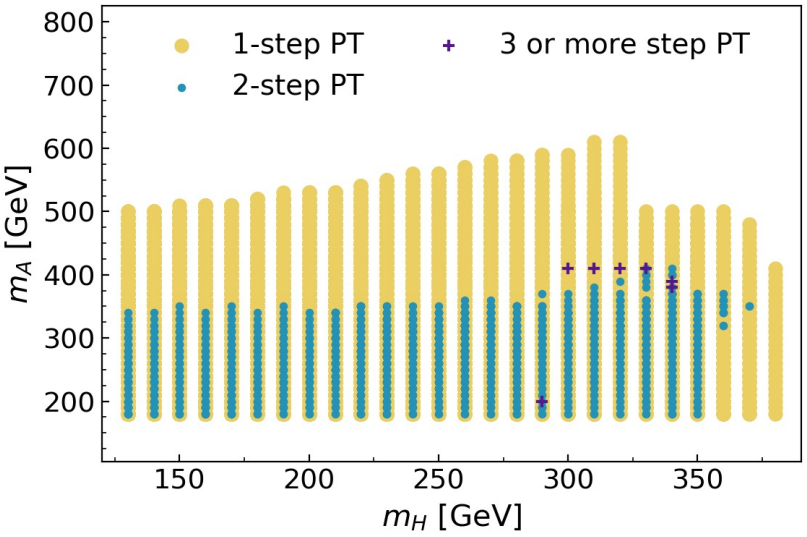


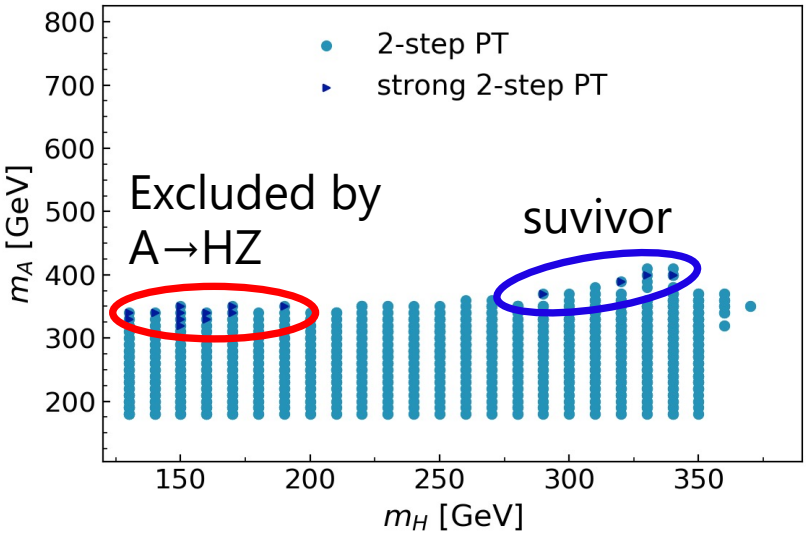


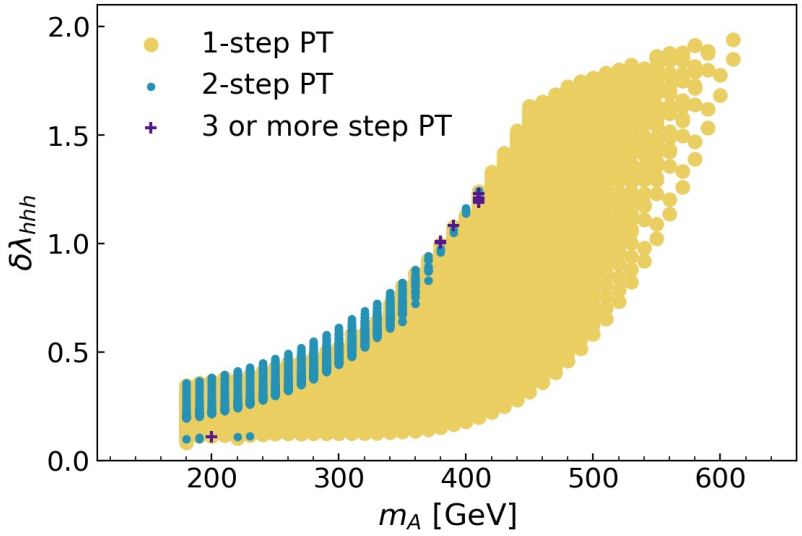


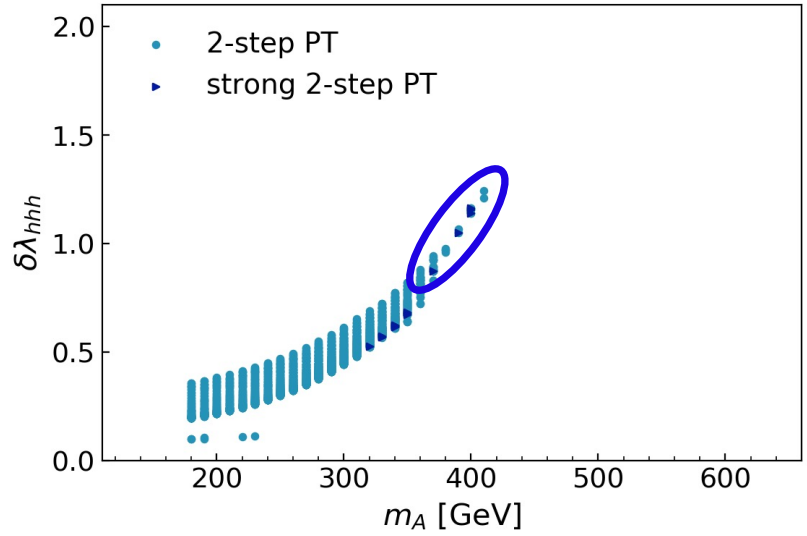


Type-X$(m_A = m_{H^\pm})$

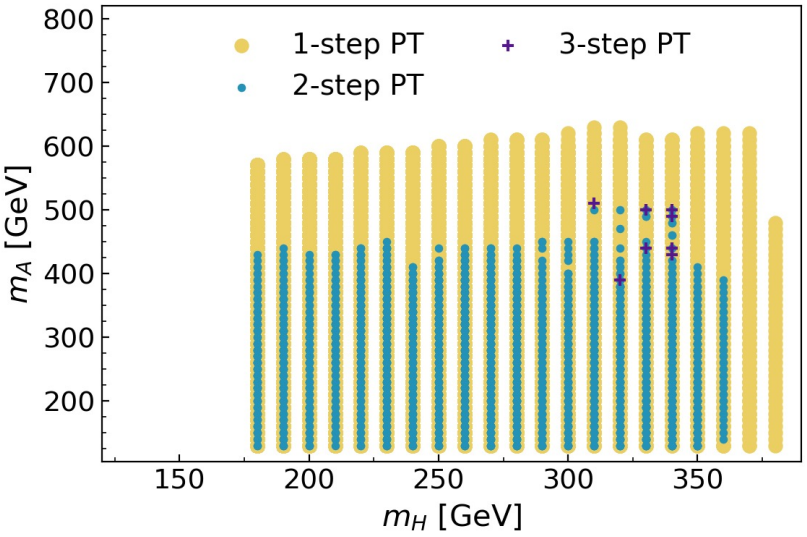


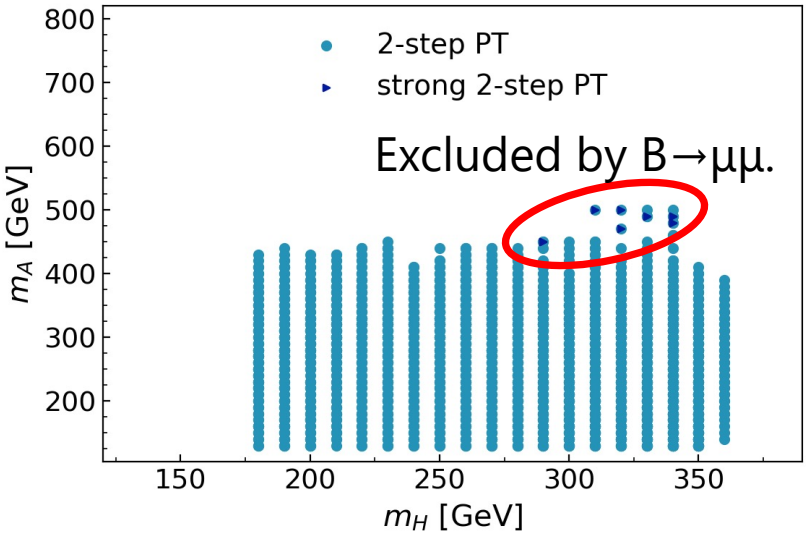


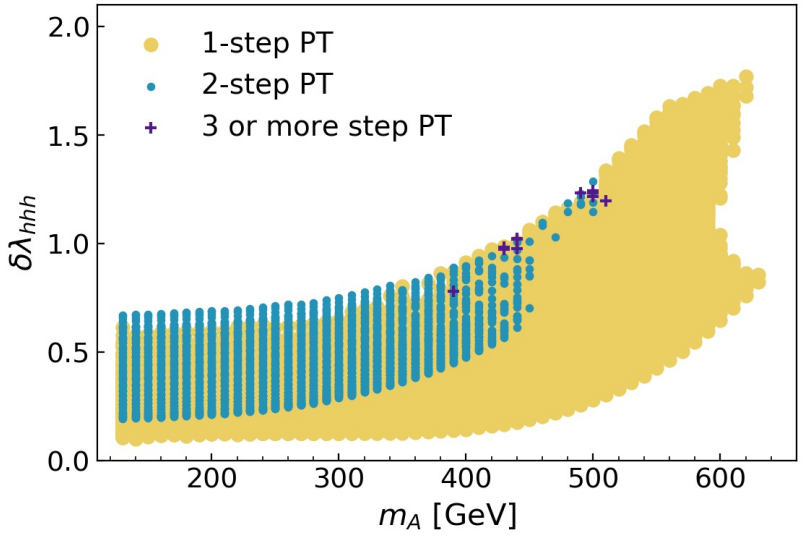


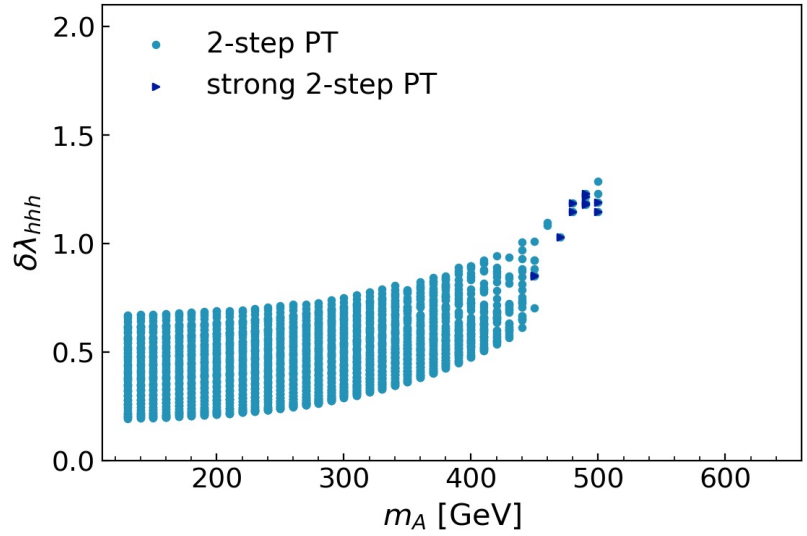


Type-X$(m_H = m_{H^\pm})$



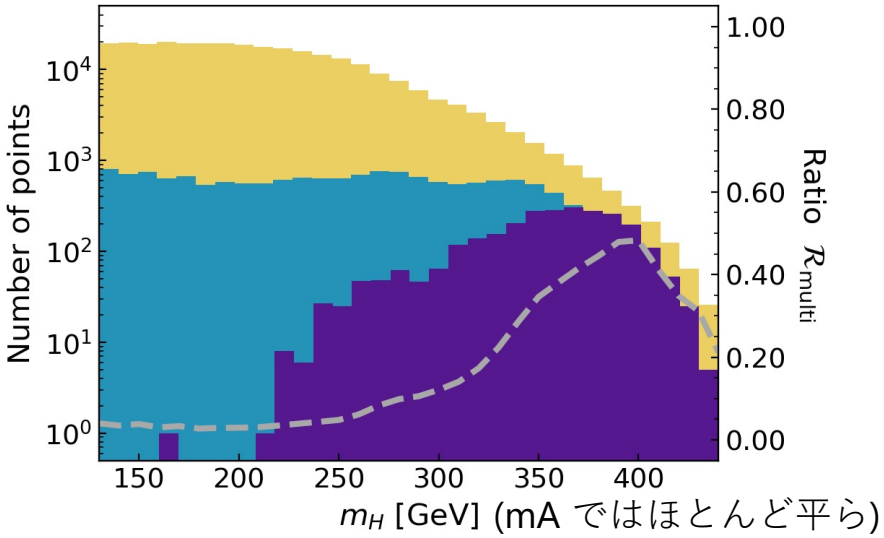


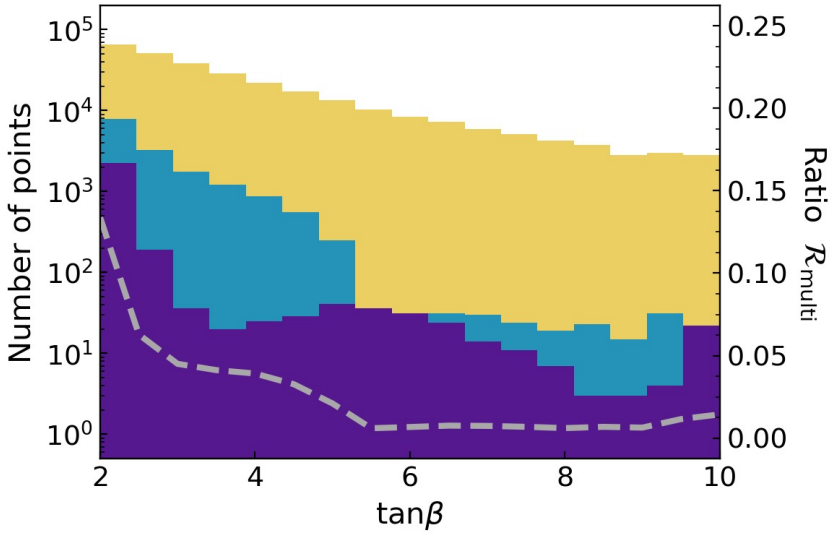


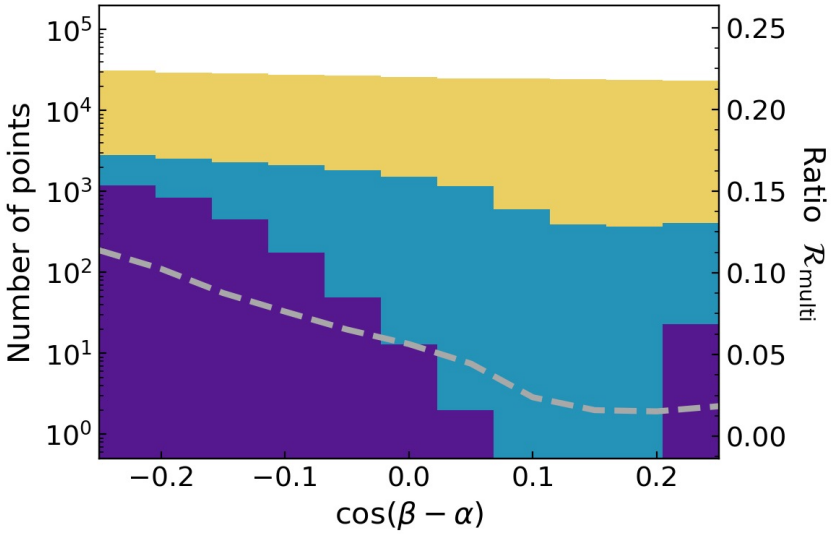


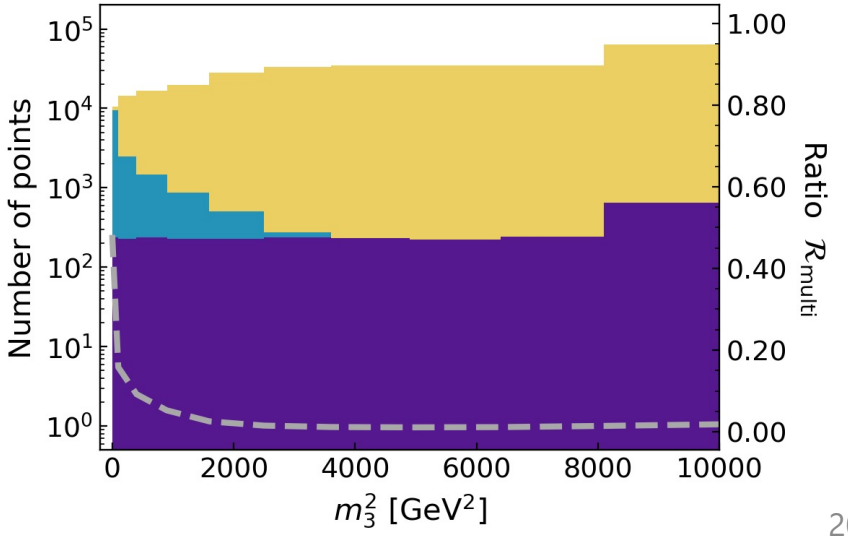
Number Analyses for multi-step PTs

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



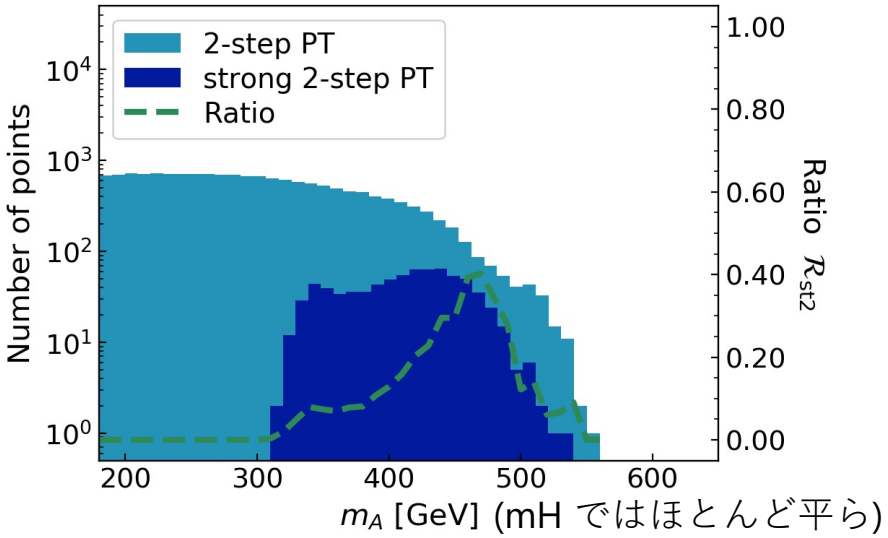


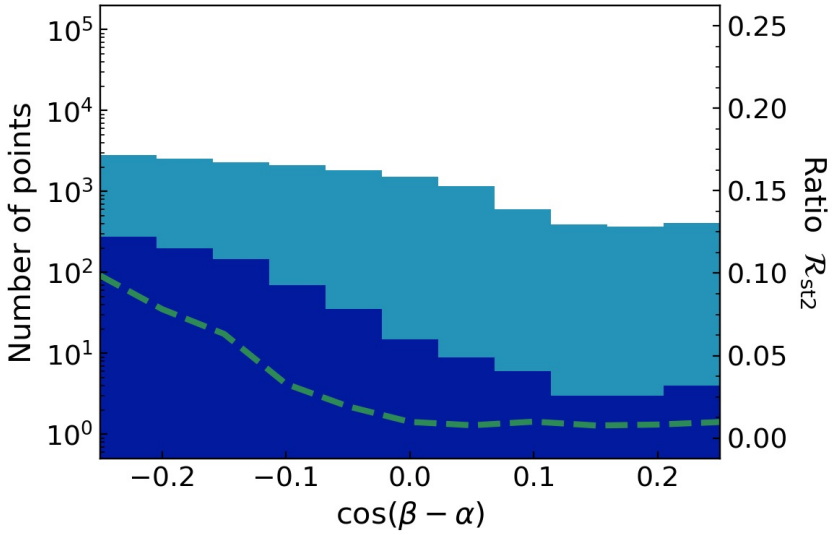


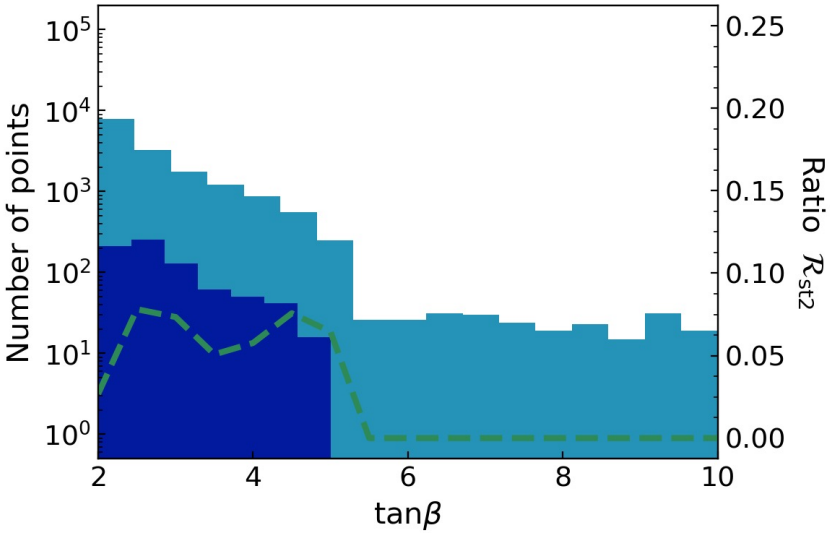


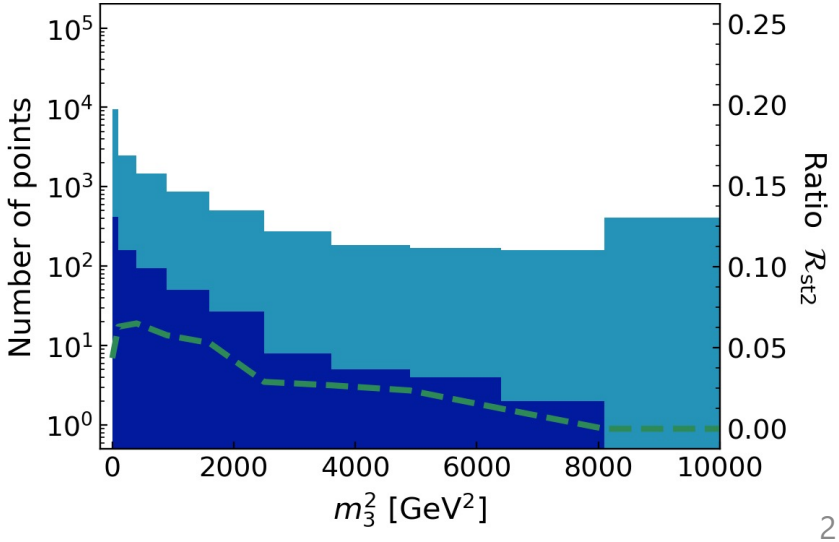
Number analyses for strong 2-step PTs

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



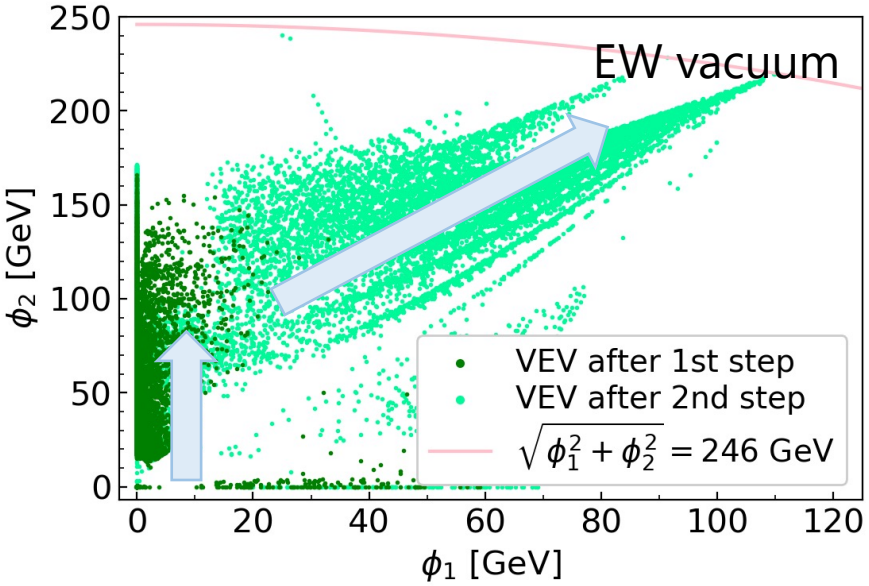




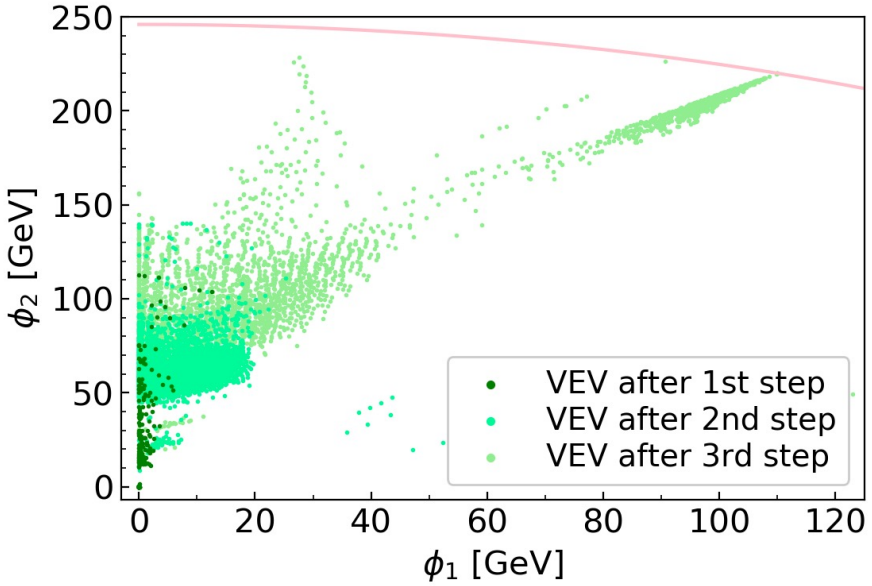


Passes of multi-step PTs

2-step PTs



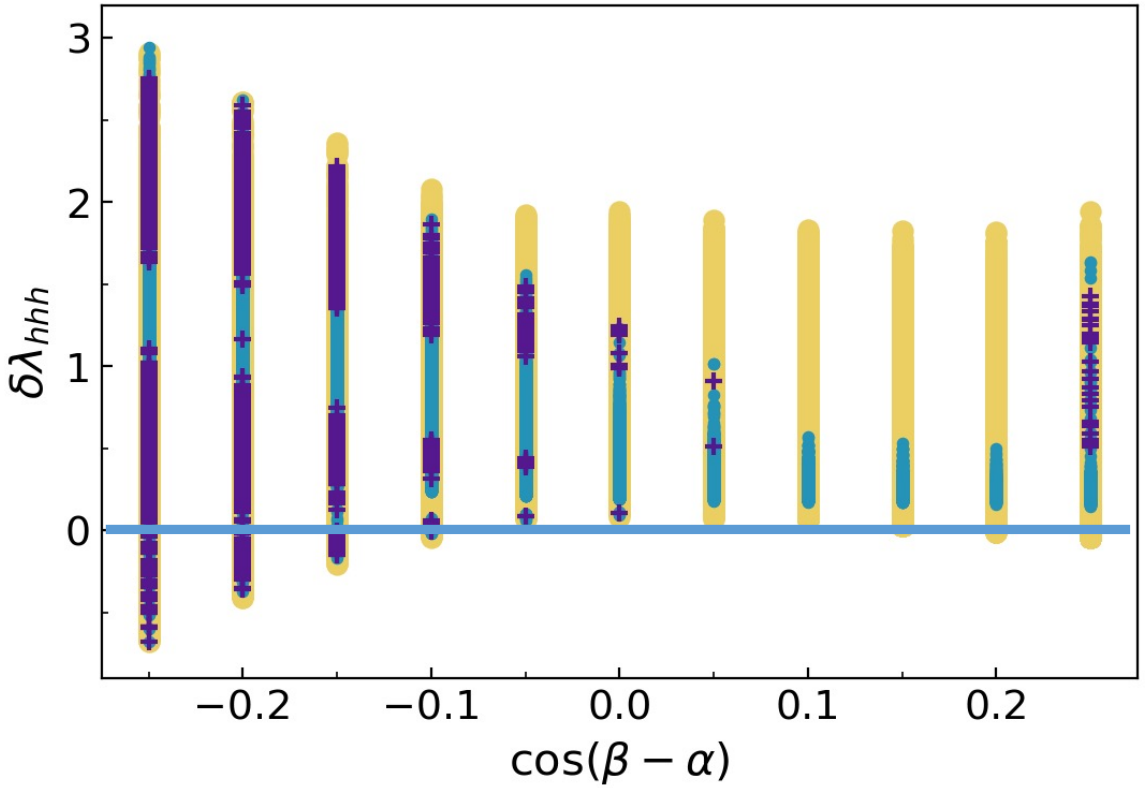
3-step PTs



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

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

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