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

Sakharov's conditions in the SM

To achieve BG, the Sakharov's conditions must be satisfied,
[Sakharov ('91)]

1. B violation
2. C and CP violation → × (CKM phase is too small.)
3. Departure from equilibrium → × (EWPT is not first order.)

In the SM, EWPT becomes first order when $m_h \lesssim 70\ \mathrm{GeV}.$
[Kajantie et al. ('95); Csikor et al. ('99)]

Motivation for Multi-step EWPT

As a one of the scalar extensions,
we consider Two Higgs Doublet Models (2HDMs).

Sakharov's conditions in the 2HDMs

1. B violation
2. C and CP violation → △ (EDM exp. constrain strictly)
   [Haarr, et al. ('16); Cheng, et al.('17)]
3. Departure from equilibrium → ○ (EWPT can be first order)

▼

However, this is in the case of a 1-step PT.
(The PT occurs just one time)

If we consider a **multi-step PT**,

EWBG has possibility to be achieved!

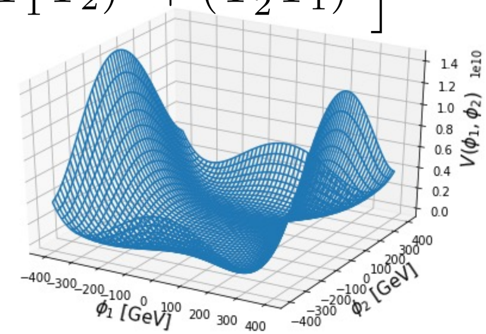
Two Higgs Doublet Model

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

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

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

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



Types of Yukawa interactions

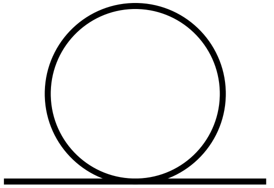
To avoid FCNC processes, assume two doublets has different Yukawa couplings.

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

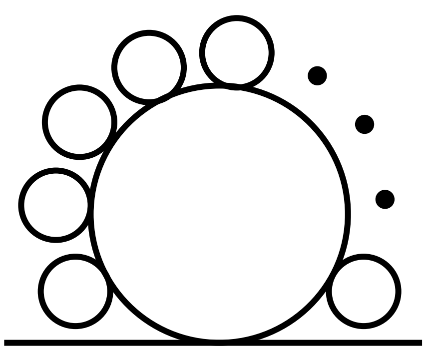
$$V^{\beta} = V_0 + V_1^0 + V_{\mathrm{CT}} + \underbrace{\overline{V}_1^{\beta}}$$ Thermal effect



- 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

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

CP-odd CP-even

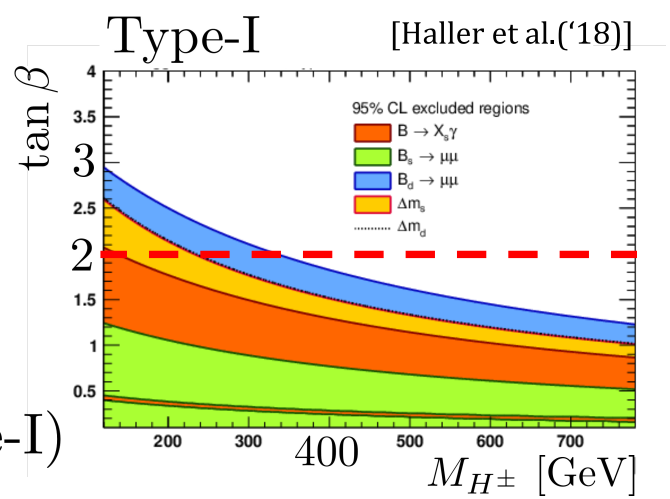
Flavor experiments

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

α, β mixing angles

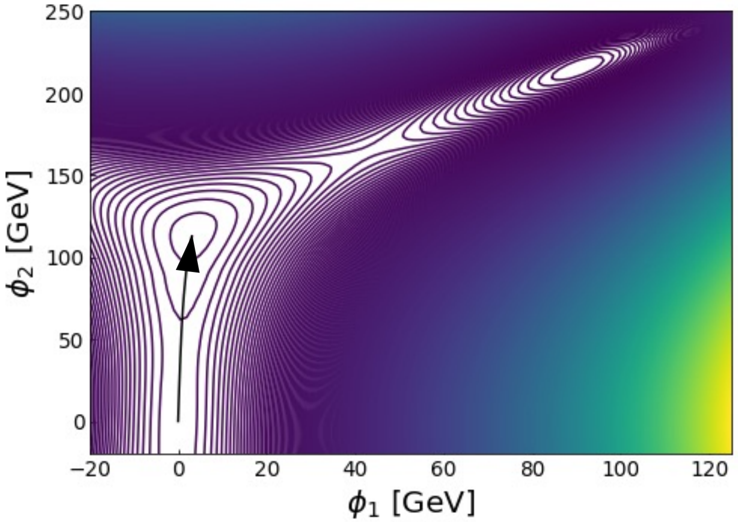
Higgs couplings strength [ATLAS Collab. ('19)]

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



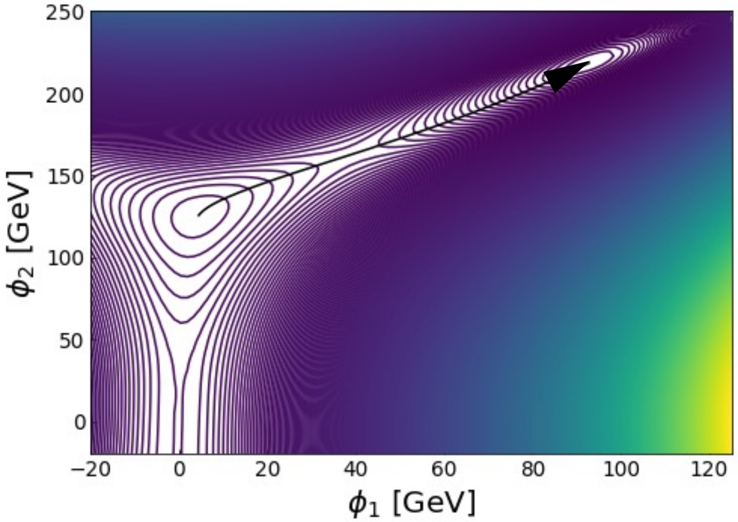
Pass of a multi-step EWPT

First step PT



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

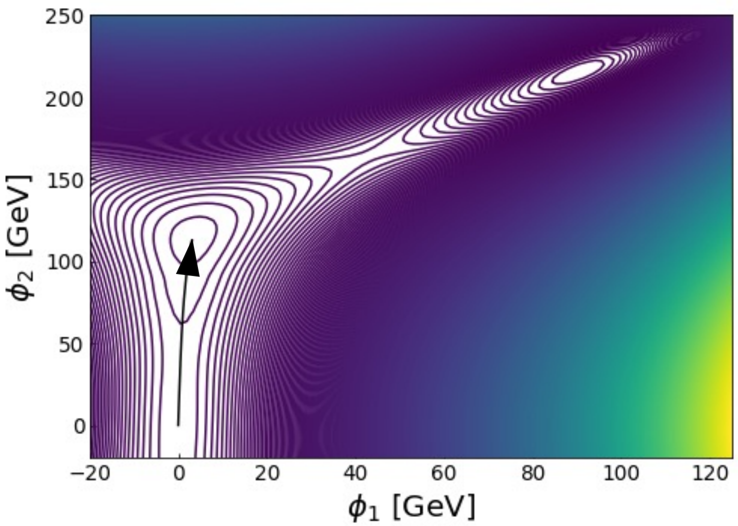
Second step PT



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

Pass of a multi-step EWPT

First step PT



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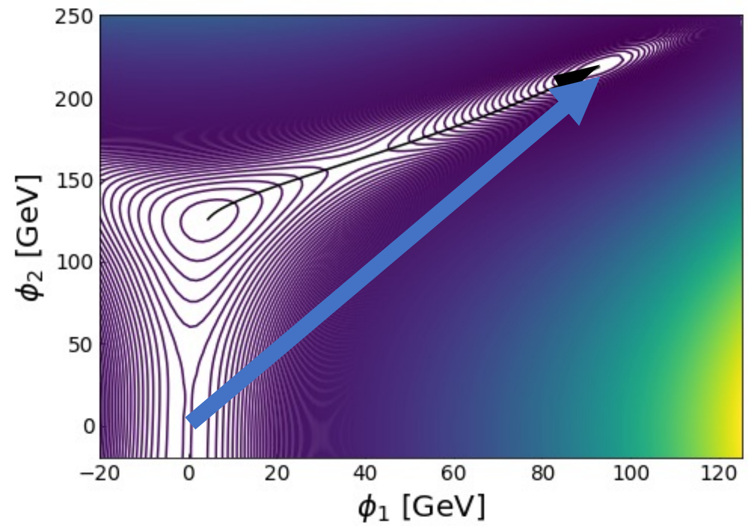
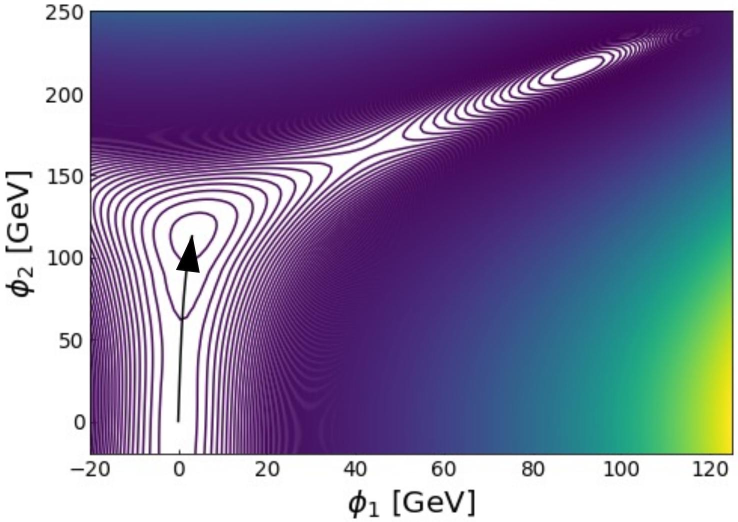


From ϕ_2 axis to EW vacuum,
1st or 2nd order PT occurs.

Above pass is realized when m3 is small enough because $V_0(\phi_1, \phi_2) \supset -m_3^2 \phi_1 \phi_2$.
So, we take $0 \leq m_3^2 \leq 100^2\ \mathrm{GeV}^2$.

Pass of a multi-step EWPT

First step PT



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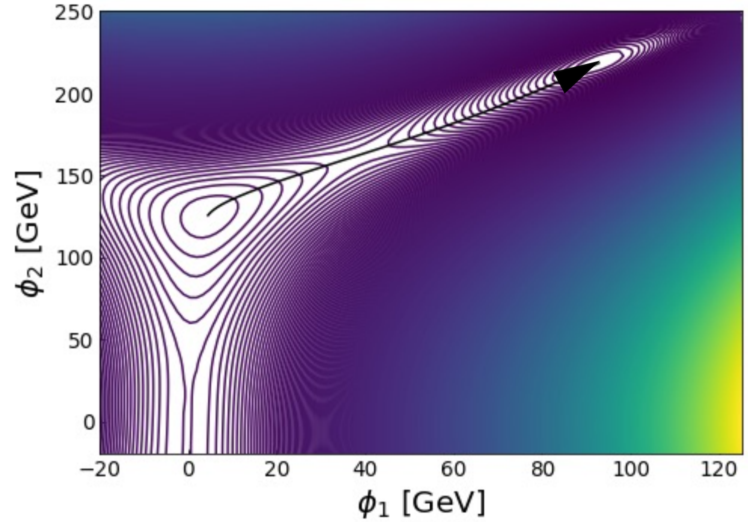
Second step PT



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

"Strongly" 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)]

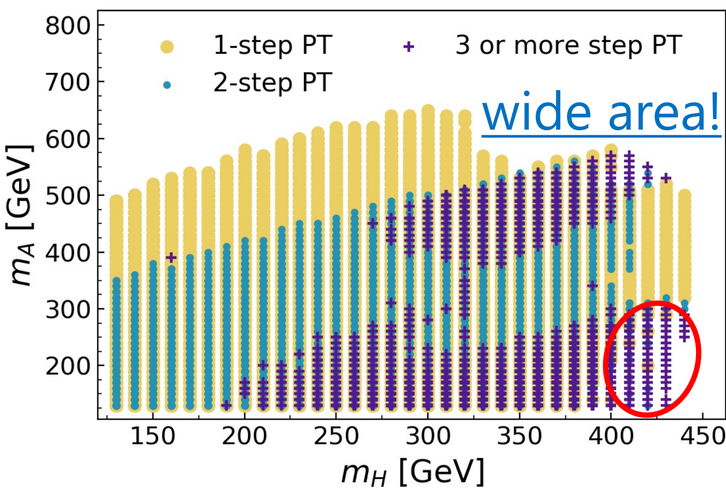
Numerical Results

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

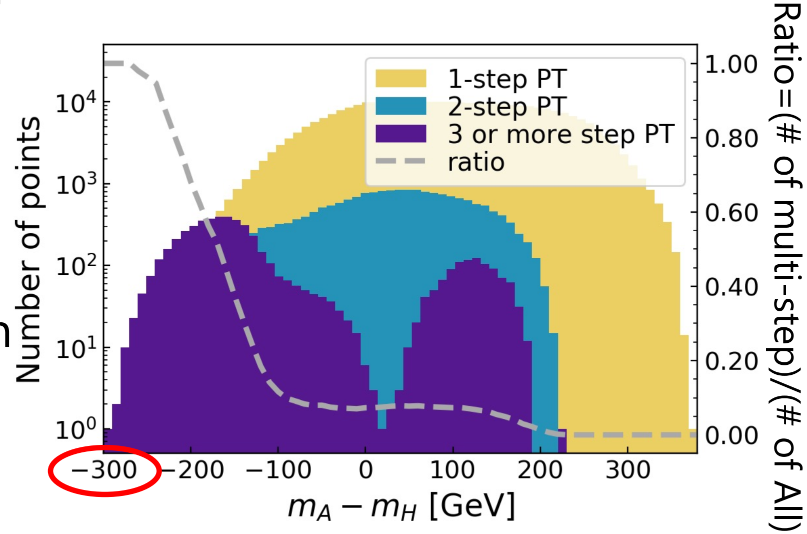
Case of Type-I $(\mathbf{m_A = m_{H^\pm}})$ (we use CosmoTransitions) [Wainwright ('12)]

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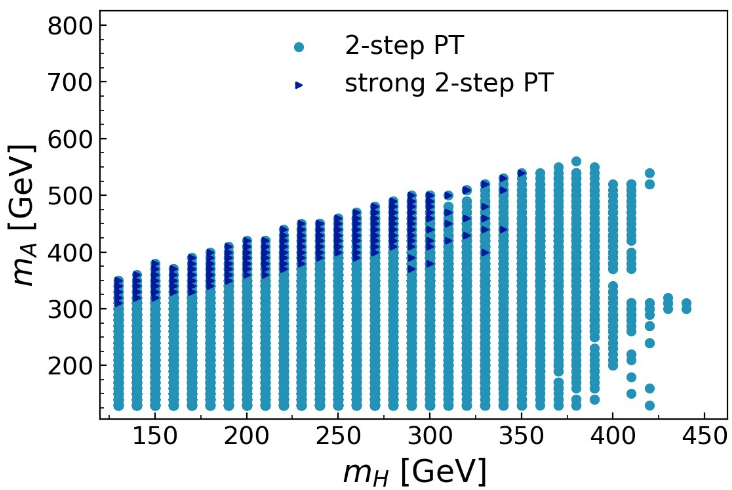
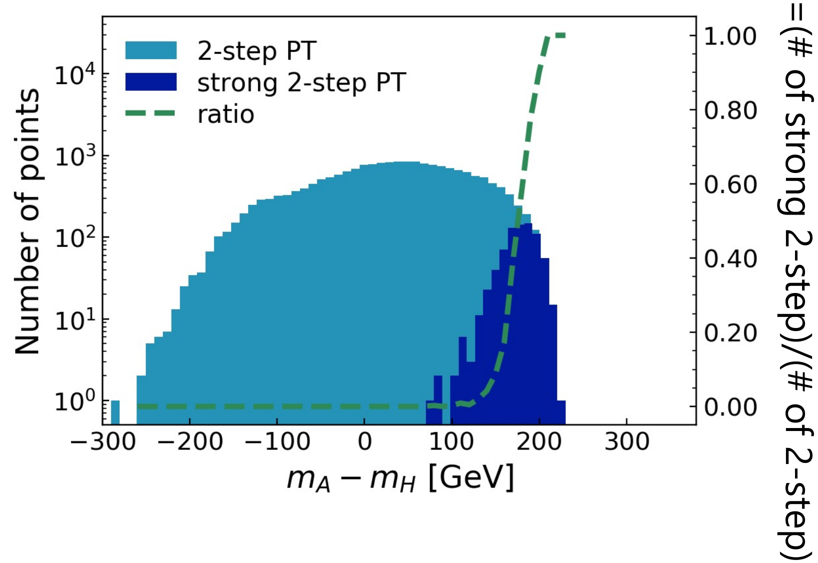
2-step PT vs. "strong 2-step" PT

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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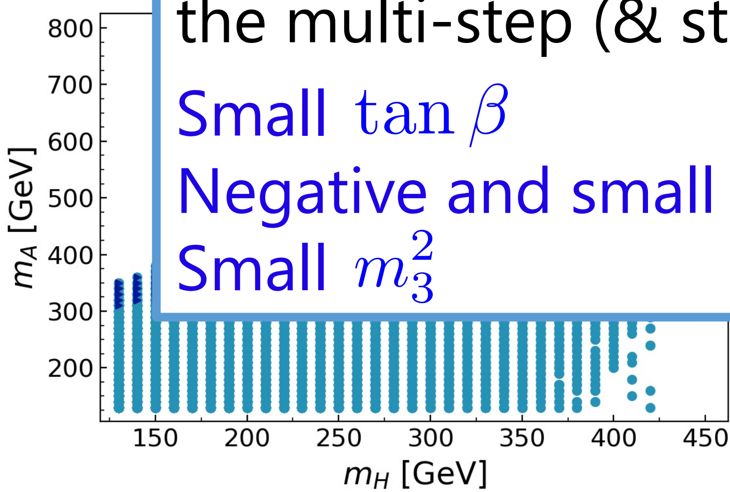
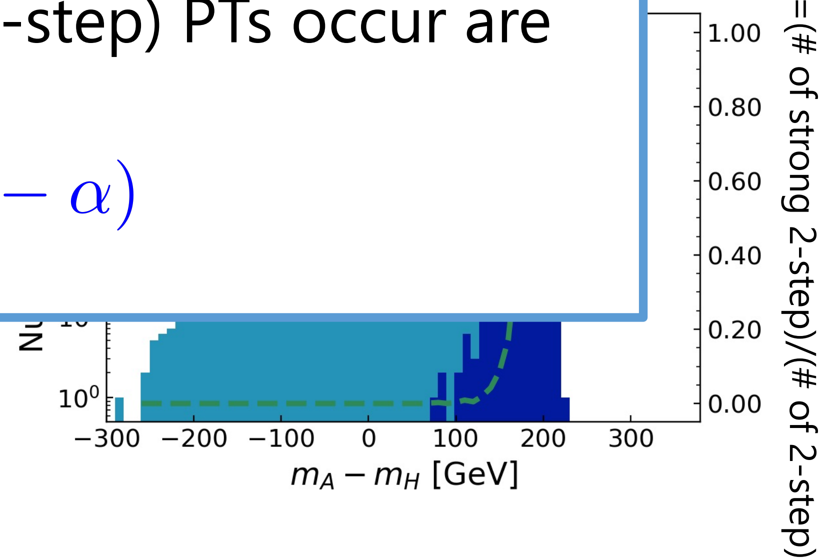
2-ste … step

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!

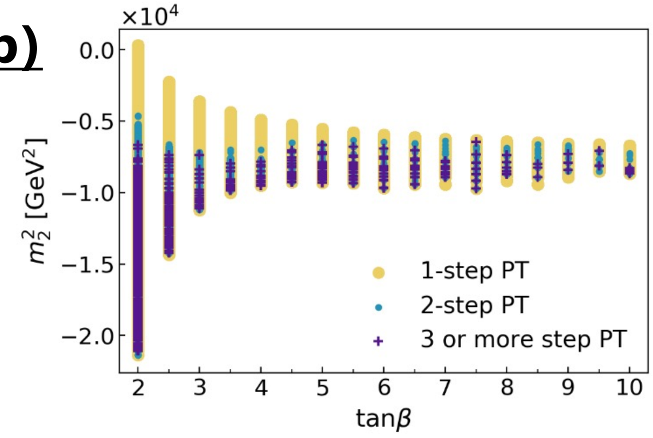
Features of regions for multi-step PTs

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

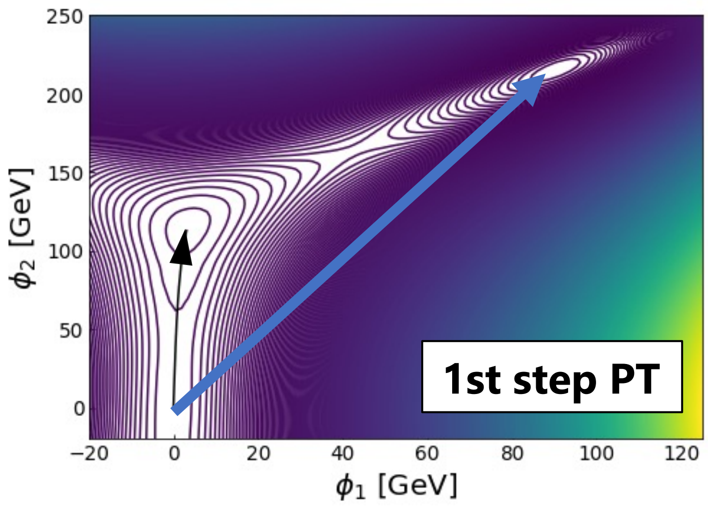
small $\tan\beta$

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.



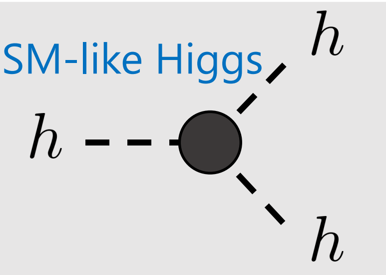
$$V_0(\phi_1,\phi_2) \supset m_2^2\phi_2^2 - m_3^2\phi_1\phi_2$$

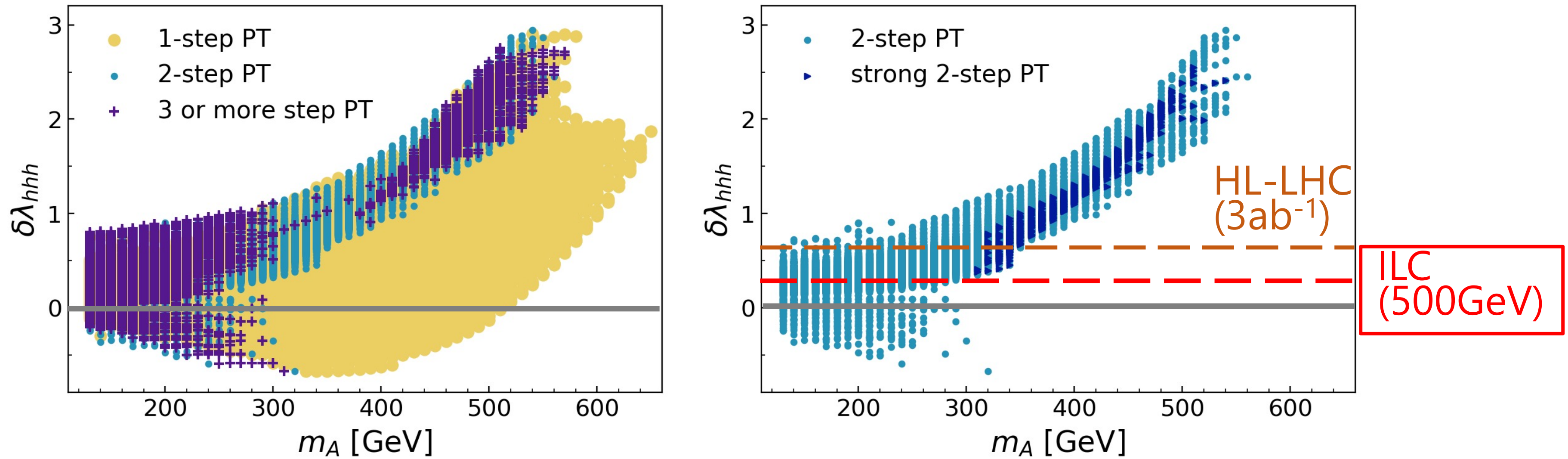
If m_3^2 is too large,
the PT would only occur just one time
(which is 1-step PT).

Higgs trilinear couplings

The deviation of the Higgs trilinear coupling from that in SM

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

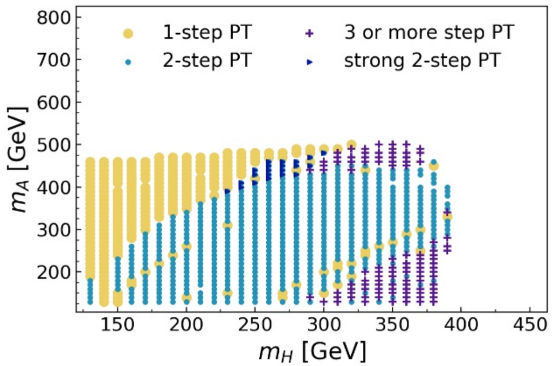




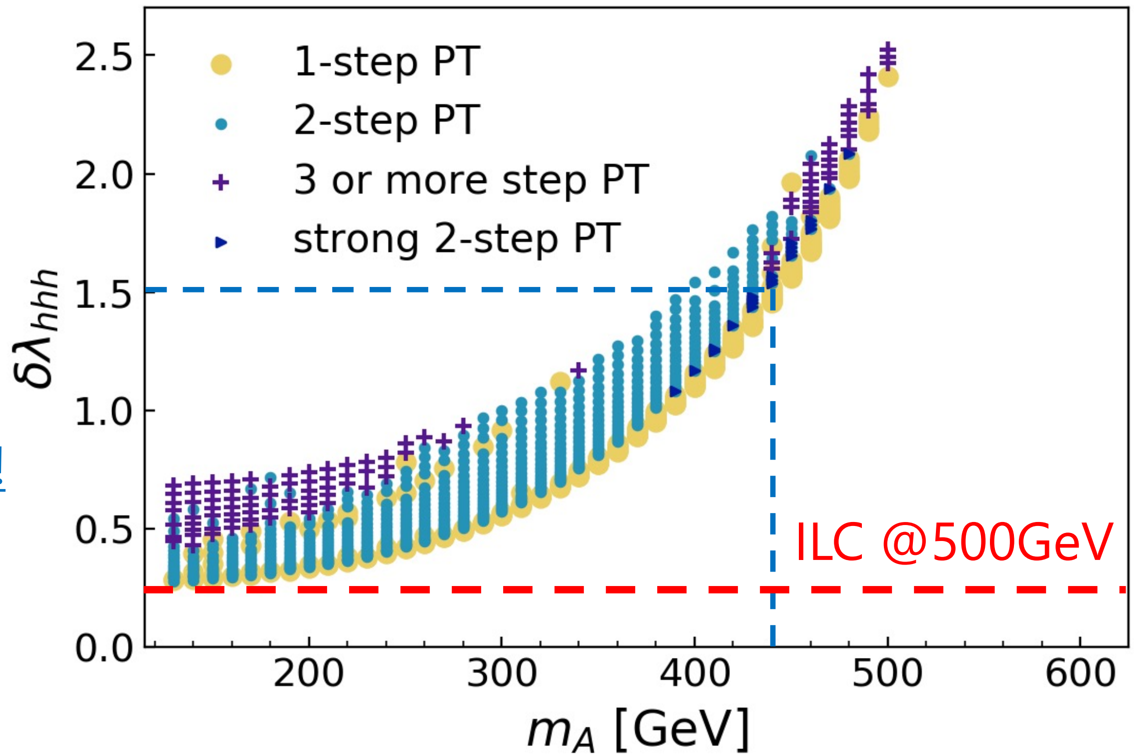
The deviations have a tendency to increase when the multi-step PTs occur. Especially, the deviations with the strong 2-step PTs are about 50%–250%.

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 $m_A \simeq 440\ \mathrm{GeV}.$

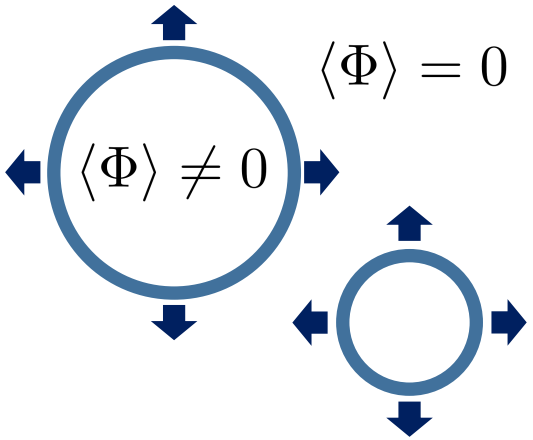
The trilinear coupling is a important observable for multi-step!

Multi-peaked Gravitational Wave

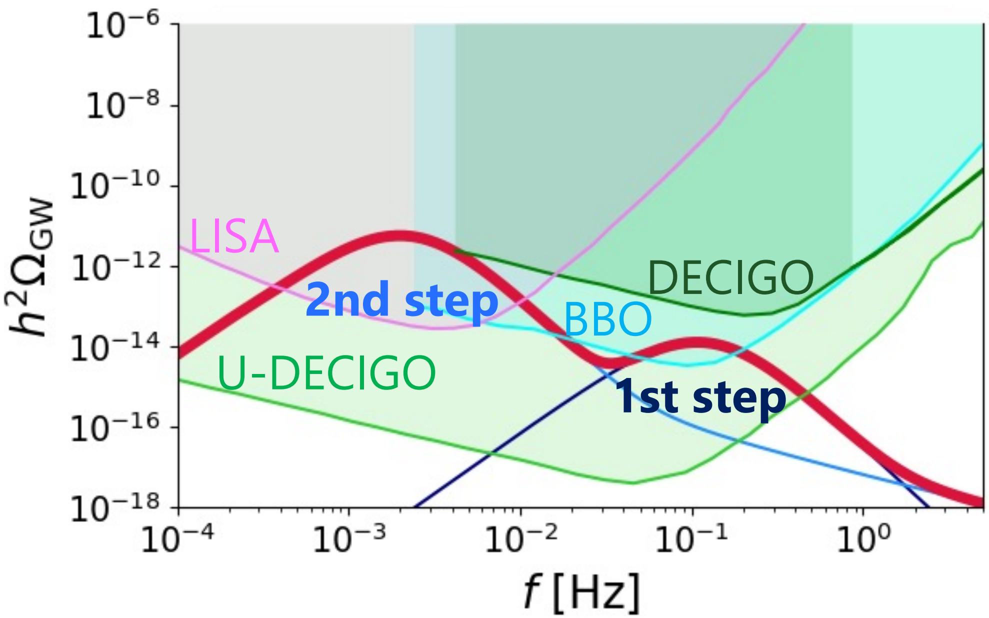
Sources of GW from a PT

There are three sources producing the GWs

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



The GWs from a 2-step PT



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

$m_H = 300$ GeV

$\tan\beta = 2.3$

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

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

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

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

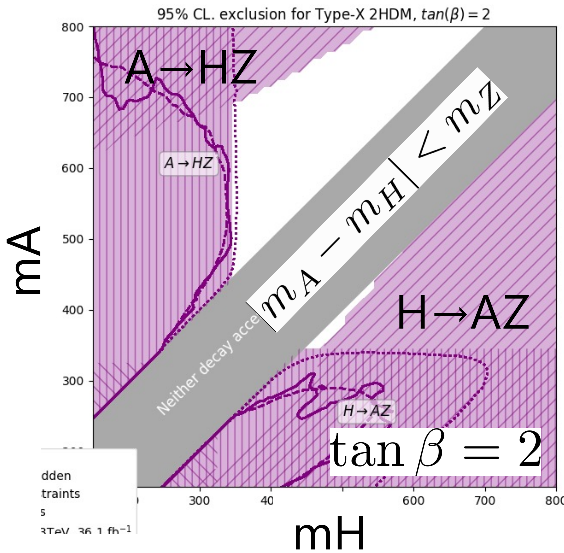
The other Types

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

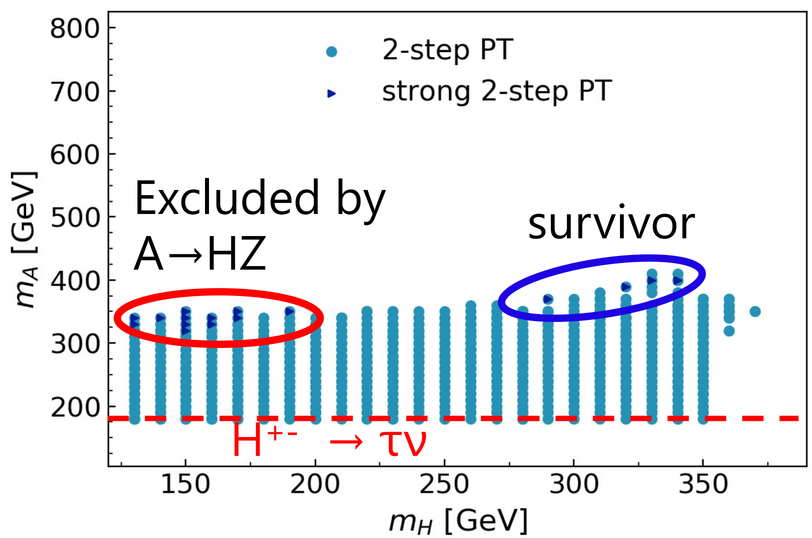
Similar features obtained as in the case of $m_A = m_{H^\pm}$.

Type-X $(m_A \text{ or } m_H = m_{H^\pm},\ \cos(\beta-\alpha) = 0)$

Similar features are obtained, but strict constraints from the exotic decay modes H→AZ & A→HZ exist.



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



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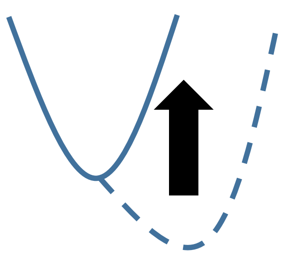
Similar features are obtained, but strict constraints from the exotic decay modes H→AZ & A→HZ exist.

Type-II & Y $(m_A \text{ or } m_H = m_{H^\pm},\ \cos(\beta-\alpha)=0,\ m_{H^\pm} \geq 590\ \text{GeV})$

The EW vacuum is not the global minimum at T=0 because the exotic heavy scalar mass lifts up the potential at loop level.

We take $m_3^2 \leq 100^2\ \text{GeV}^2$.



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 more than about 50% in the cases of the "strong 2-step" PTs.

- With a combination of other signatures (like gravitational wave spectrum), it might be possible to identify whether the multi-step PT occurred or not.