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

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Motivation

Baryon Asymmetry (BA)

Our world is made of only particles. Why?

$$\frac{n_B}{s} = (8.59 \pm 0.08) \times 10^{-11}$$ [Planck ('18)]

A strongly first-order electroweak (EW) phase transition (PT) can achieve BA.
[Kuzmin et al. ('85)]

SM The PT is not first-order.

Two Higgs Doublet Model (2HDM)
Difficult to make enough BA
[Haarr, et al. ('16);Cheng ,et al.('17)]

→ Multi-step PT has a possibility of making BA!

Two Higgs Doublet Model

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

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

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

We took the 1-loop and the dominant higher loop corrections into account.

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

	u type	d type	lepton
Type-I	Φ_2	Φ_2	Φ_2

Constraints

Parameter Conversion

Parameters in the scalar potential

$$m_1^2,\ m_2^2,\ m_3^2,\ \lambda_i\ (i=1,\cdots,5).$$

$$m_H,\ m_A,\ m_{H\pm},\ \tan\beta,\ \cos(\beta-\alpha),\ m_3^2,$$

$$m_h = 125\ \mathrm{GeV},\ v = 246\ \mathrm{GeV}.$$

$\alpha,\ \beta$: mixing angles

Constraints

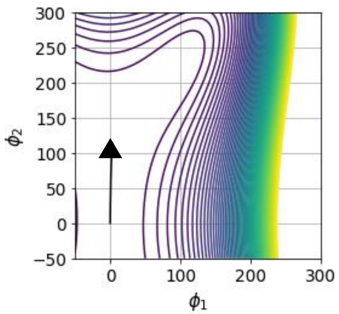
We consider following constraints

BFB
Perturbative theory
Tree-level unitarity
Global minimum
Electroweak Precision
Flavor
Higgs coupling

Pass of 2-step PT

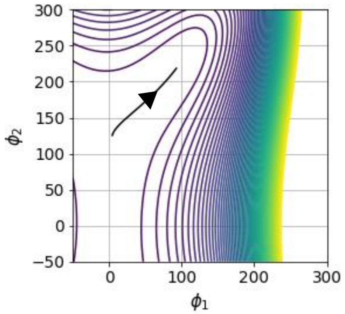
$\phi_1,\ \phi_2$: neutral CP-even scalar field values

First step



PT occurs along ϕ_2 axis from the origin.

Second step



PT occurs in the direction of the EW vacuum.

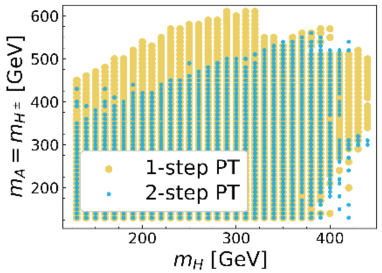
Pass like above is realized when m_3^2 is small.

Numerical Results

Using CosmoTransitions, [Wainwright ('12)]

$m_A = m_{H^\pm}$	m_A [GeV]	m_H [GeV]	$\tan\beta$	$\cos(\beta-\alpha)$	m_3^2 [GeV^2]
All region	140–1000	140–1000	2–10	−0.25–0.25	0–10^4
1-step PT	140–600	140–440	2–10	−0.25–0.25	0–10^4
2-step PT	140–560	140–420	2–10	−0.25–0.25	0–10^4

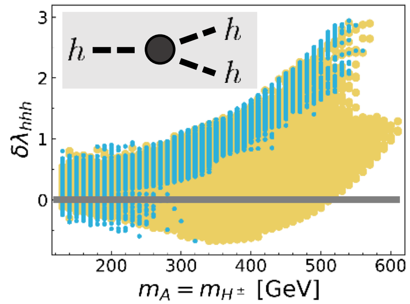
Similar! (particularly near $m_3^2 = 0$.)



The multi-step PTs occur in the wide parameter ranges!

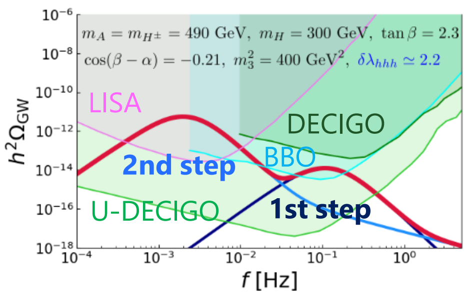
Physical Signatures

Higgs trilinear coupling & GW spectrum



$$\delta\lambda_{hhh} \equiv \frac{\lambda_{hhh}^{2HDM} - \lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}}$$

The deviations have a tendency to rise when the multi-step PTs occur.



Multi-peaked GW spectrum could be observed in future programs!

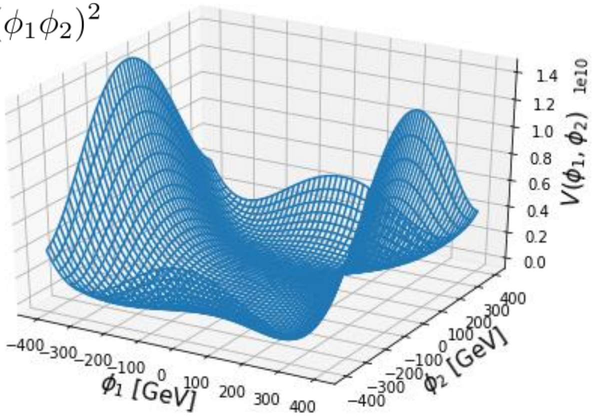
BACK UP

Scalar potential

$$V_0(\phi_1,\phi_2) = \frac{m_1^2}{2}\phi_1^2 + \frac{m_2^2}{2}\phi_2^2 - m_3^2\phi_1\phi_2 + \frac{\lambda_1}{8}\phi_1^4 + \frac{\lambda_2}{8}\phi_2^4 + \frac{1}{4}(\lambda_3+\lambda_4+\lambda_5)(\phi_1\phi_2)^2$$

Regard values of the neutral CP-even scalar fields ϕ_1 and ϕ_2 as parameters.

$$\langle\phi_i\rangle|_{T=0} = v_i \ \ (i=1,2)$$



Effective potential

One-loop corrected effective potential

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

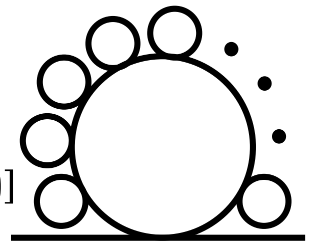
V_1^0 one-loop contributions at

$V_{\rm CT}$ counter term for maintaining
- the position of the minimum
- the input parameters

$\bar{V}_1^\beta$ one-loop contributions at

Resummation

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



Constraints

Theorical

Bound from below (BFB) [Deshpande, Ma ('78)]

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

Tree-level unitarity [Akeroyd et al.('00)]

Global minimum $\sqrt{v_1^2+v_2^2} = 246\ \mathrm{GeV}$

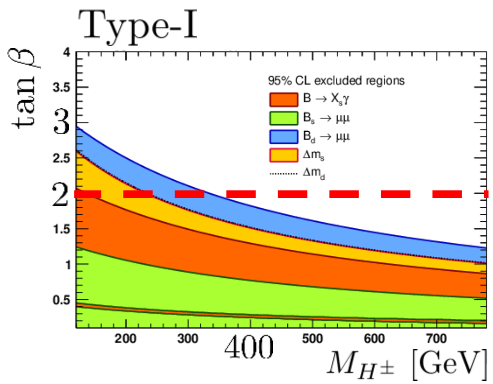
Experimental

Electroweak precision data [Haller et al.('18)]

$\rightarrow\ m_{H^\pm} = m_A$ or m_H

Favor experiments [Haller et al.('18)]

$\rightarrow \tan\beta \gtrsim 2$ for Type-I (from $\mathrm{B_d} \rightarrow \mu\mu$)



Higgs couplings strength

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

[ATLAS Collaboration ('19)]

BACK UP 2

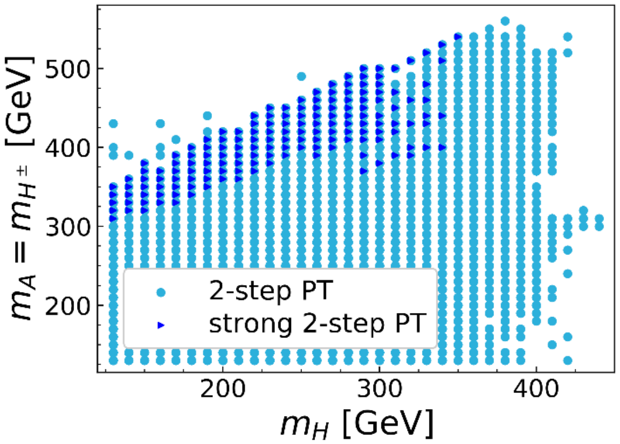
Numerical results

Strong 2-step PTs

Two-step PTs whose 1st PT is strongly first order.

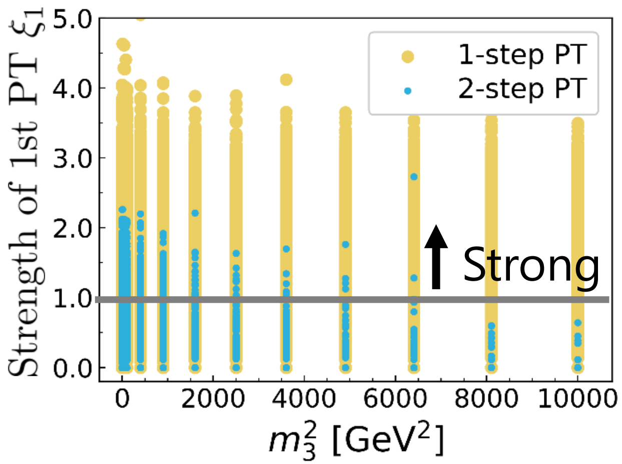
Strongly means the PT satisfy the condition which suppress the spharelon process $v(T_c)/T_c \geq 1$

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



Strong 2-step PTs occur when the mass hierarchy $m_A > m_H$ exists.

The range of m3



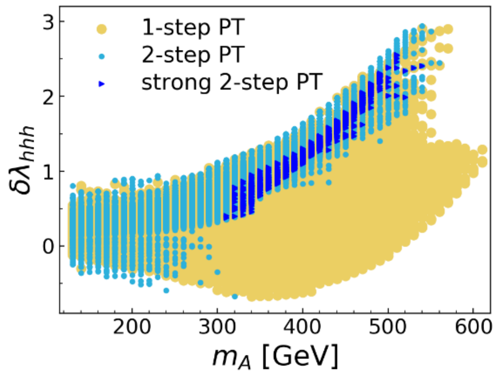
Strong PTs have tendency to occur near $m_3^2 = 0$.

Therefore, we examined the region.

Higgs trilinear coupling

The deviation of the Higgs trilinear coupling from that of SM

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



When strong 2-step PTs occur the deviations have tendency to increase.

GW spectrum

Sources of GWs from the PT

There are three sources producing the GWs

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

dominant