Electroweak baryogenesis in the Higgs alignment scenario

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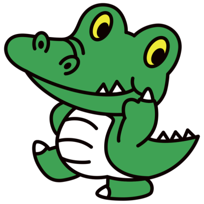
2022/5/13 Physics in LHC and Beyond in Matsue

Based on
K. Enomoto, S. Kanemura, and Y.M, JHEP 01 (2022) 104 [arXiv: 2111.13079]
and in preparation



Dr. Wani, OU mascot

Introduction

Standard Model (SM) is consistent with experimental data.

The origin of the Baryon Asymmetry of the Universe cannot be explained.

From Big Bang Nucleosynthesis,

$$\eta_B^{obs} = \frac{n_B}{n_\gamma} = 5.8 - 6.5 \times 10^{-10} \,.$$ PDG (2020)

This asymmetry is generated at the early Universe ⇨ Baryogenesis

For Baryogenesis,

Sakharov's Conditions A. D. Sakharov (1967)

① Baryon number violation
② C and CP violation
③ Out of thermal equilibrium

must be satisfied.

Some possibilities

- Affleck-Dine mechanism — I. Afflec et.al. (1985)
- Electroweak baryogenesis — V. A. Kuzmin et.al. (1985)
- Leptogenesis — M. Fukugita et.al. (1986)

etc.

Electroweak baryogenesis

Sakharov's Conditioins
① Baryon number violation
② C and CP violation
③ Out of thermal equilibrium

Electroweak Baryogenesis (EWBG)

① Sphaleron process
② C violation in chiral theory,
CP violation in Higgs sector
③ Strongly first order electroweak phase transition

EWBG in the SM,

- Insufficient CPV with Kobayashi-Masukawa phase P. Huet and E. Sather (1995)
- Electroweak phase transition becomes crossover K. Kajantie et.al. (1996)

The potential of the SM is just assumption.
Extended Higgs sectors can solve these problems !

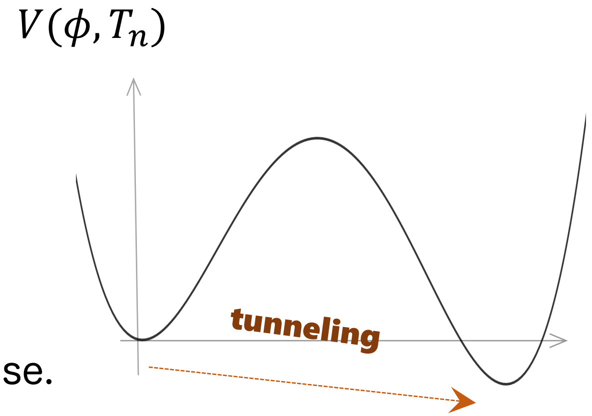
EWBG is fixed at the EW scale and Higgs Physics.

⇒ It can be tested by the future Higgs precision experiments !

Electroweak baryogenesis

EWPT is occurred at the temperature T_n,

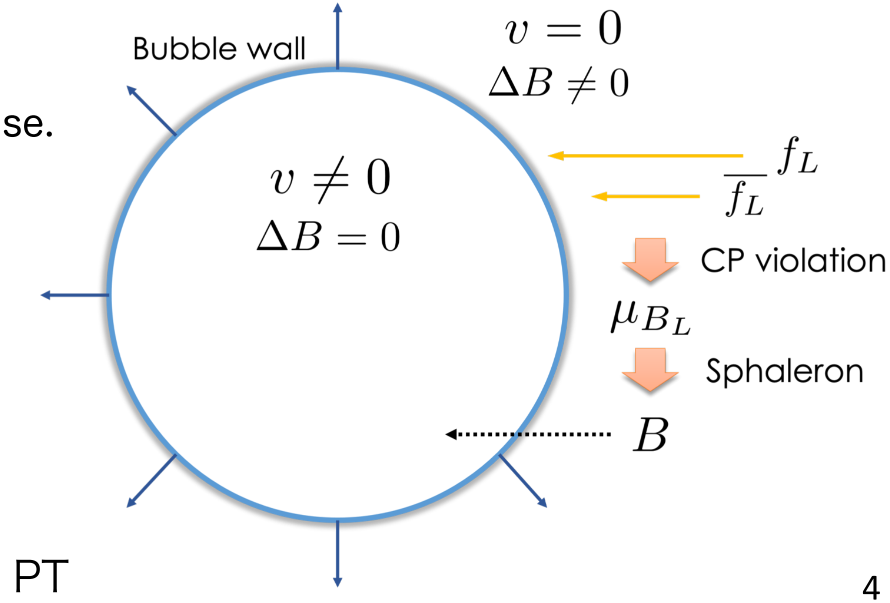
(The possibility of tunneling per Hubble) $\sim \boldsymbol{O}(\mathbf{1})$.



Sphaleron process ($\Delta B \neq 0$) frequently occurs in symmetric phase.

Left-handed baryons outside the wall are converted into baryon number.

Sphaleron process decouple in broken phase.
(Baryon number is conserved)



Sphaleron decoupling condition

$$\Gamma_{sph}^{brk}(T_n) < H(T_n) \implies \frac{v_n}{T_n} \gtrsim 1$$

→ "Strongly" first order PT

Recent works

Various models for EWBG

Ex) SM +SU(2)singlet J.R. Espinosa et. al. (2012), J.M. Cline and K. Kainulainen (2013), and more
SM +SU(2)doublet L. Fromme et. al. (2006), J. M. Cline et. al. (2011), and more

After the discovery of Higgs boson in 2012,

- LHC exp.
  - SM like couplings
  - Small mixing angle among scalars
- Electric Dipole Moment exp.

Electron EDM $|d_e| < 1.1\times10^{-29}$ e cm ACME (2018)
Constraints on CPV in extended Higgs sectors

Previous work

- "SM like" Higgs boson
- Destructive interference between CPV phases

S. Kanemura, M. Kubota and K. Yagyu (2020)

Todays talk about..

- **the benchmarks which can explain BAU under current data.**

K. Enomoto, S. Kanemura, and Y.M, JHEP 01 (2022) 104

- **the possibilities of predictable gravitational waves from first order EWPT.**

M. Kakizaki et. al. (2015), and more

In preparation

Aligned Two Higgs Doublet Model

SM Lagrangian + SU(2) scalar doublet : Two Higgs doublet model

The most general potential

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

Higgs basis S. Davidson and H. E. Haber (2005)

$$V = -{\mu_1}^2({\Phi_1}^\dagger\Phi_1) - {\mu_2}^2({\Phi_2}^\dagger\Phi_2) - \left({\mu_3}^2({\Phi_1}^\dagger\Phi_2) + h.c.\right)$$
$$+ \frac{1}{2}\lambda_1({\Phi_1}^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2({\Phi_2}^\dagger\Phi_2)^2 + \lambda_3({\Phi_1}^\dagger\Phi_1)({\Phi_2}^\dagger\Phi_2) + \lambda_4({\Phi_2}^\dagger\Phi_1)({\Phi_1}^\dagger\Phi_2)$$
$$+ \left\{\left(\frac{1}{2}\lambda_5{\Phi_1}^\dagger\Phi_2 + \lambda_6{\Phi_1}^\dagger\Phi_1 + \lambda_7{\Phi_2}^\dagger\Phi_2\right){\Phi_1}^\dagger\Phi_2 + h.c.\right\}, \quad (\mu_3, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Mass spectrum

Charged scalar $m^2_{H^\pm} = M^2 + \frac{1}{2}\lambda_3 v^2$ $\qquad M^2 \equiv -\mu_2^2$

Neutral scalar
$$\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 & \boxed{\mathrm{Re}\lambda_6} & \boxed{-\mathrm{Im}\lambda_6} \\ \boxed{\mathrm{Re}\lambda_6} & \frac{M^2}{v^2} + \frac{\lambda_3+\lambda_4+\mathrm{Re}\lambda_5}{2} & \cancel{-\frac{1}{2}\mathrm{Im}\lambda_5} \\ \boxed{-\mathrm{Im}\lambda_6} & \cancel{-\frac{1}{2}\mathrm{Im}\lambda_5} & \frac{M^2}{v^2} + \frac{\lambda_3+\lambda_4-\mathrm{Re}\lambda_5}{2} \end{pmatrix}$$

Experimental fact "mixing angle among neutral scalars is small"

We assume $\lambda_6 = 0$ (Higher loop corrections are non-zero)

⇨
$$= \begin{pmatrix} m_h^2 & 0 & 0 \\ 0 & m_{H_2}^2 & 0 \\ 0 & 0 & m_{H_3}^2 \end{pmatrix}$$

Coupling consts. coincide with SM ones

Higgs alignment

Finally, only the CP phase $\arg[\lambda_7] \equiv \theta_7$ remains.

Aligned Two Higgs Doublet Model

The most general Yukawa interaction

$$-\mathcal{L}_y = \sum_{k=1}^{2} \left(\overline{Q}'_L (y_u^k)^\dagger \tilde{\Phi}_k u'_R + \overline{Q}'_L y_d^k \Phi_k d'_R + \overline{L}'_L y_e^k \Phi_k e'_R + h.c. \right)$$

Experimental fact “Flavor Changing Neutral Current must be suppressed”

We assume $y_f^2 = \zeta_f y_f^1 \quad (f = u, d, e)$ Yukawa alignment

A. Pich and P. Tuzon (2009)

$$\zeta_u, \zeta_d, \zeta_e \in \mathbb{C}$$

$$\mathcal{L}_y = -\overline{Q}_L \frac{\sqrt{2}M_u}{v} \left(\tilde{\Phi}_1 + \zeta_u^* \tilde{\Phi}_2 \right) u_R - \overline{Q}_L \frac{\sqrt{2}M_d}{v} \left(\Phi_1 + \zeta_d \Phi_2 \right) d_R - \overline{L}_L \frac{\sqrt{2}M_e}{v} \left(\Phi_1 + \zeta_e \Phi_2 \right) e_R + h.c.$$

Summary of CP phases in the model

Potential $\arg[\lambda_7] \equiv \theta_7$

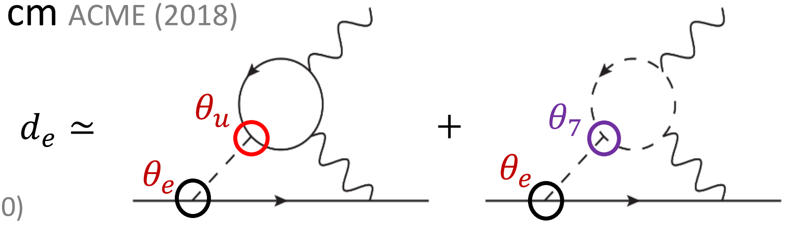
Yukawa $\arg[\zeta_u] \equiv \theta_u$, $\arg[\zeta_d] \equiv \theta_d$, $\arg[\zeta_e] \equiv \theta_e$

Constraints in the model

Severe electron EDM bound $|d_e| < 1.1\times10^{-29} e$ cm ACME (2018)

Avoiding EDM bound with destructive interference

S. Kanemura, M. Kubota and K. Yagyu (2020)



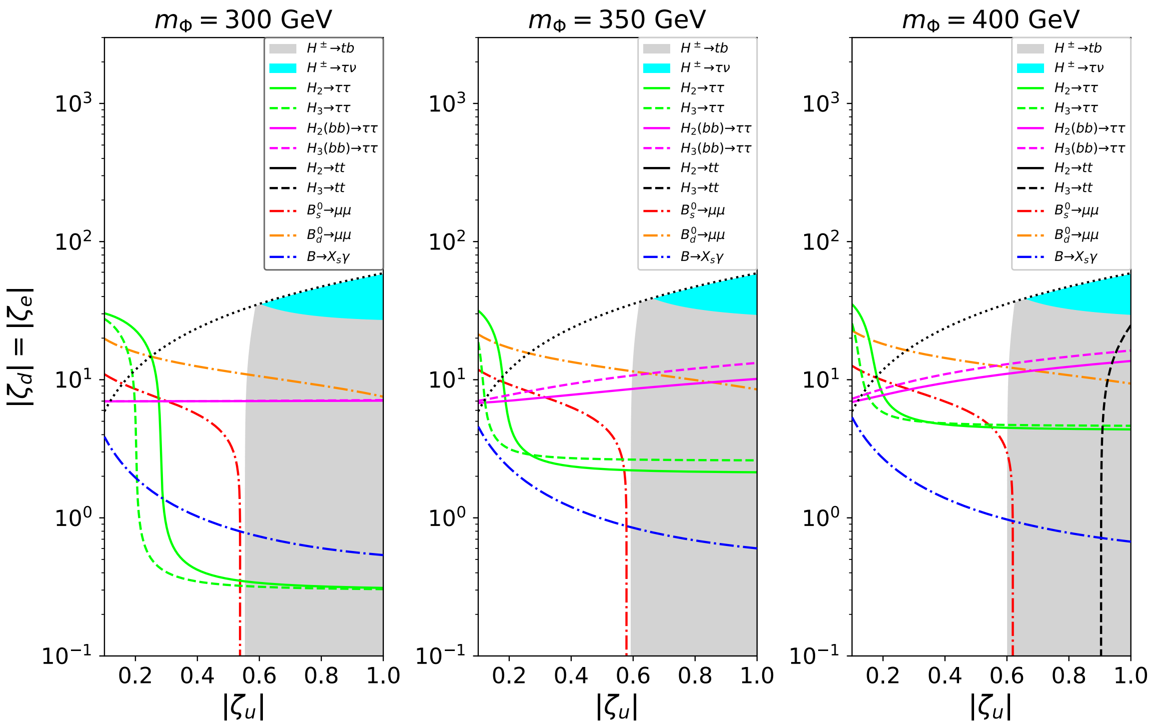
(a) Fermion-loop. (b) Higgs boson-loop.

Direct search and flavor exp.

ζ_u is important for BAU.

$B_s \to \mu\mu$ (Red) HFLAV (2019)
$H^\pm \to tb$ (Gray) ATLAS (2021)

Upper bound : $|\zeta_u| \lesssim 0.6$



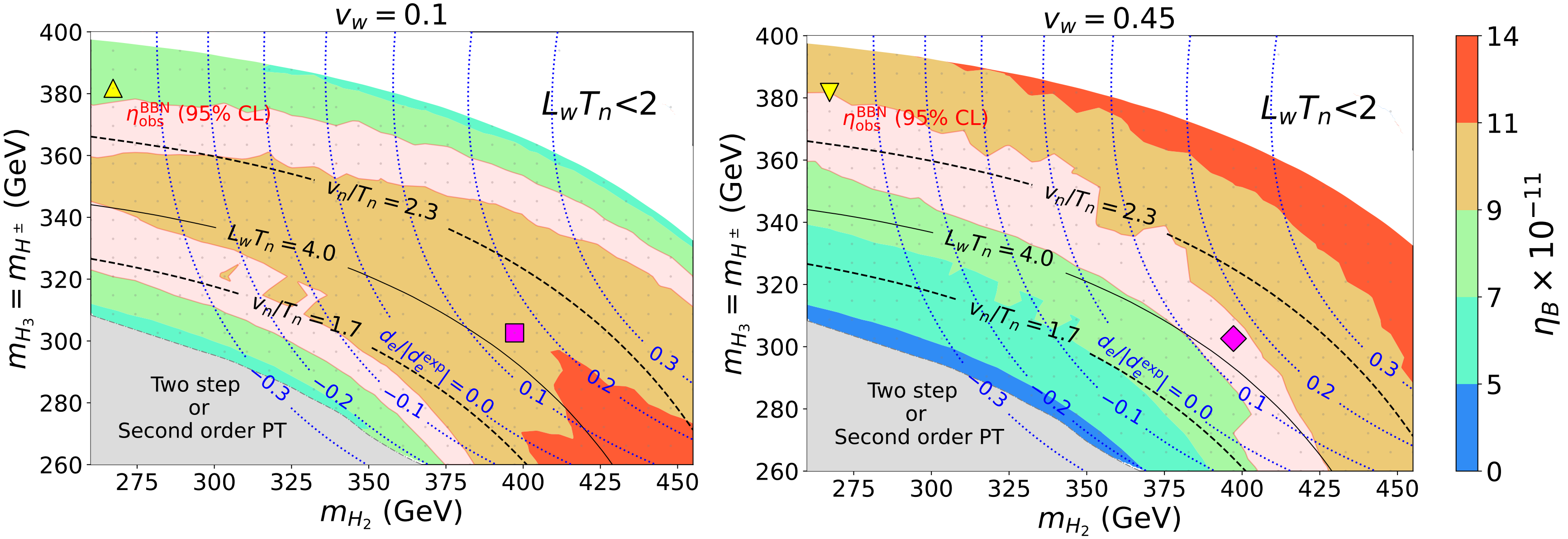
Other constraints

Experimental neutron EDM, STU parameters
Theoretical perturbative unitarity, vacuum stability

Baryogenesis

Baryon asymmetry in the relativistic bubble wall velocity J. M. Cline and K. Kainulainen (2020)

Assuming the velocity as a free parameter



Strongly first order PT (except for gray region)

$$M = 30\ \mathrm{GeV},\ \ \lambda_2 = 0.1,\ \ |\lambda_7| = 0.8,\ \ \theta_7 = -0.9,$$

$$|\zeta_u| = |\zeta_d| = |\zeta_e| = 0.18,\ \ \theta_u = -2.7,\ \ \delta_d = 0,\ \ \delta_e = -0.04.$$

The observed BAU (pink) $\eta_{obs}^{\rm BBN} \equiv \frac{n_B}{s} = 8.2\text{–}9.2 \times 10^{-11}$

Electron EDM (blue dotted) $|d_e^{\rm exp}| < 1.1{\times}10^{-29} e$ cm ACME (2018)

green: relate to the BAU
blue: relate to the eEDM
purple: relate to the both

We set four benchmarks :

△ BP1a: small velo. + strongly PT
▽ BP1b: large velo. + strongly PT
■ BP2a: small velo. + weakly PT
◆ BP2b: large velo. + weakly PT

Triple Higgs coupling

Strongly PT
- small velo. △
- large velo. ▽

Weakly PT
- small velo. ■
- large velo. ◆

	v_w	m_{H_2}	$m_{H_3,H^\pm}$	M	v_n/T_n	L_wT_n	η_B	ΔR
BP1a	0.1	267 GeV	381 GeV	30 GeV	2.4	2.6	7.8×10^{-11}	0.61
BP1b	0.45						9.1×10^{-11}	
BP2a	0.1	397 GeV	302 GeV	30 GeV	2.0	4.1	10.8×10^{-11}	0.44
BP2b	0.45						9.0×10^{-11}	

BP1b and BP2b can explain observed BAU.

Strongly first order PT → Non-decoupling situation $(m_\Phi^2 \sim \lambda v^2)$

Deviation of triple Higgs coupling $\Delta R \equiv \delta\lambda_{hhh}/\lambda_{hhh}^{SM}$

S. Kanemura et. al. (2005)

PT is

relatively strong (BP1) $\Delta R = 61\%$

relatively weak (BP2) $\Delta R = 44\%$

$\Longrightarrow$ Detectable in the future colliders

Ex)

HL-LHC : 50%
ILC (500 GeV) : 27%
ILC (1 TeV) : 10%

Gravitational waves from EWPT

Strongly PT
- small velo. ▲
- large velo. ▼

Weakly PT
- small velo. ■
- large velo. ◆

	v_w	m_{H_2}	$m_{H_3,H^\pm}$	M	v_n/T_n	L_wT_n	η_B	ΔR
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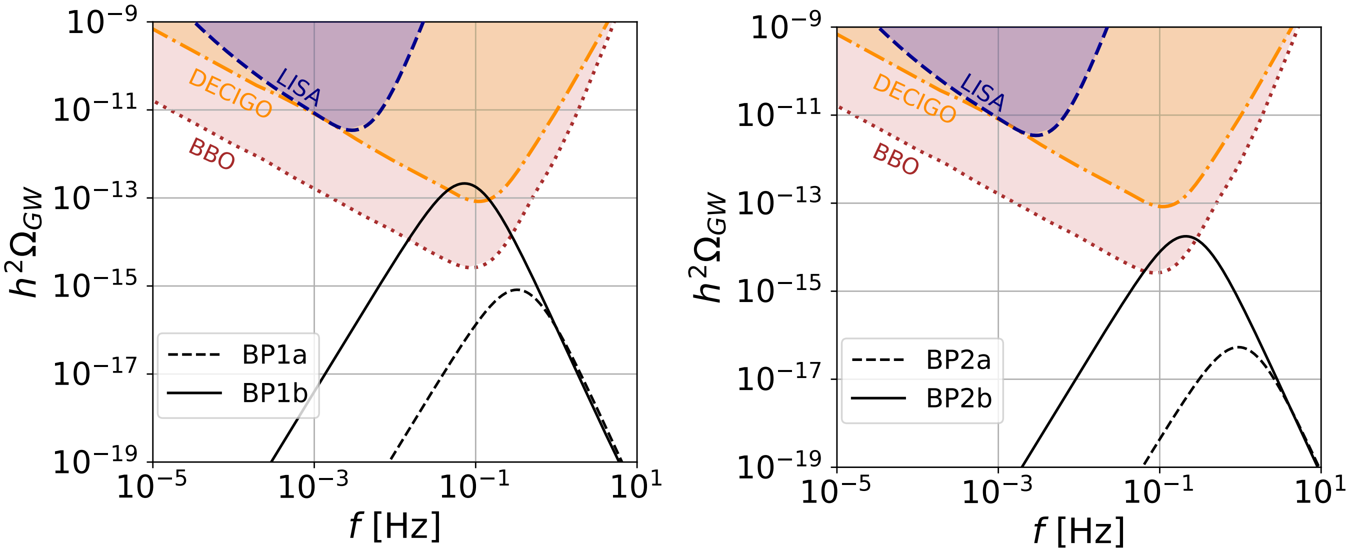
Gravitational wave spectrum

C. Caprini et al (2016), J. R. Espinosa et al (2010), and more



⇒ **Strong PT and large velocity are needed.**

Fisher matrix analysis

K. Hashino et al (2019)

Summary

◆ **SM cannot explain the Baryon asymmetry of the universe**

EWBG as the solution of BAU is Higgs physics thus it is testable.

◆ **Aligned Two Higgs Doublet Model**

- SM like 125 GeV Higgs boson
- We showed the BAU can be explained under current data.
- Additionally, some of BPs can be tested using GW signal.

◆ **Phenomenology**

- Higgs triple coupling ⇨ HL-LHC, ILC (500GeV, 1TeV)
- Gravitational waves ⇨ LISA, DECIGO, BBO