Status and new ideas in electroweak baryogenesis

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KF, W-S. Hou, E. Senaha, PLB 776 (2018) 402
Electroweak baryogenesis driven by extra top Yukawa couplings

Outline :

1. Electroweak Baryogenesis

2. General Two Higgs doublet Model

3. Results of the BAU

4. Conclusion

Introduction

Baryon Asymmetry of the Universe : BAU

Cosmological observations show that our Universe is baryon-asymmetric.

$$Y_B \equiv \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5076

$n_B = n_b - n_{\bar{b}}$ s : Entropy density

$n_{b(\bar{b})}$: (Anti-) Baryon number density

Many possibilities

There are many scenarios for baryogenesis.

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44.Nonthermal leptogenesis.

M. Shaposhnikov, J. Phys. Conf. Ser. 171 012005

Many possibilities

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Electroweak Baryogenesis

Kuzmin, Rubakov, Shaposhnikov, PLB155, 36 (1985)

Baryon asymmetry is created during EW phase transition

- Energy scale is O(100) GeV, so high testability.

Sakharov's criteria

Sakharov's 3 conditions can be satisfied as follows:

(1) Baryon number violation

(2) C and CP violation

(3) Out of equilibrium

Sakharov's criteria

Sakharov's 3 conditions can be satisfied as follows:

(1) Baryon number violation

Sphaleron process

(2) C and CP violation

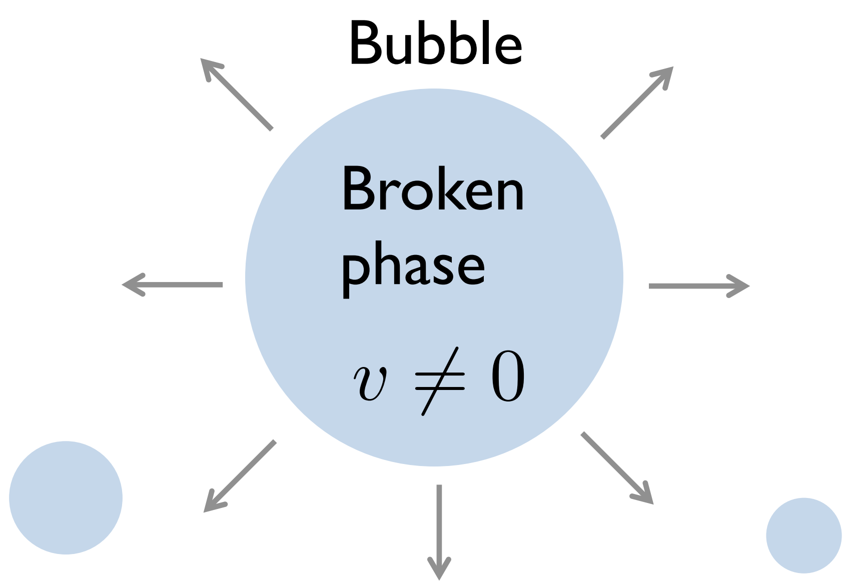
Chiral gauge theory and CP phase

(3) Out of equilibrium

1st order EW phase transition with expanding bubble walls

Basic story

If the first order EWPT is achieved, bubbles can be nucleated around at $T_{C.}$



Symmetric phase

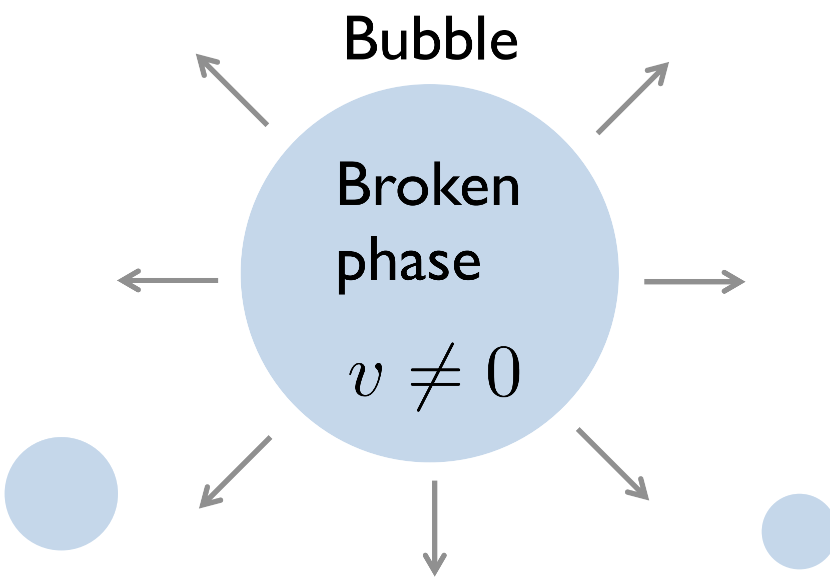
$v = 0$

v : Higgs VEV

T_C : Critical temperature

Basic story

If the first order EWPT is achieved, bubbles can be nucleated around at T_{C}.



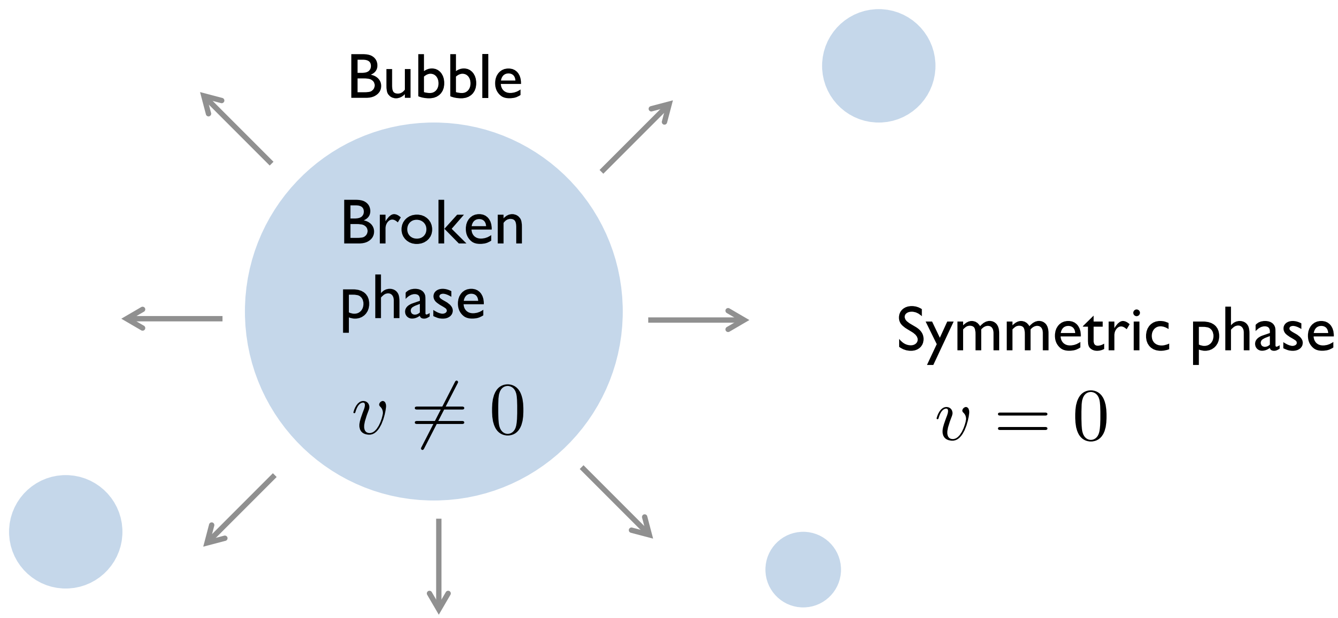
Symmetric phase

$$v = 0$$

Ex) Boiling water

Basic story

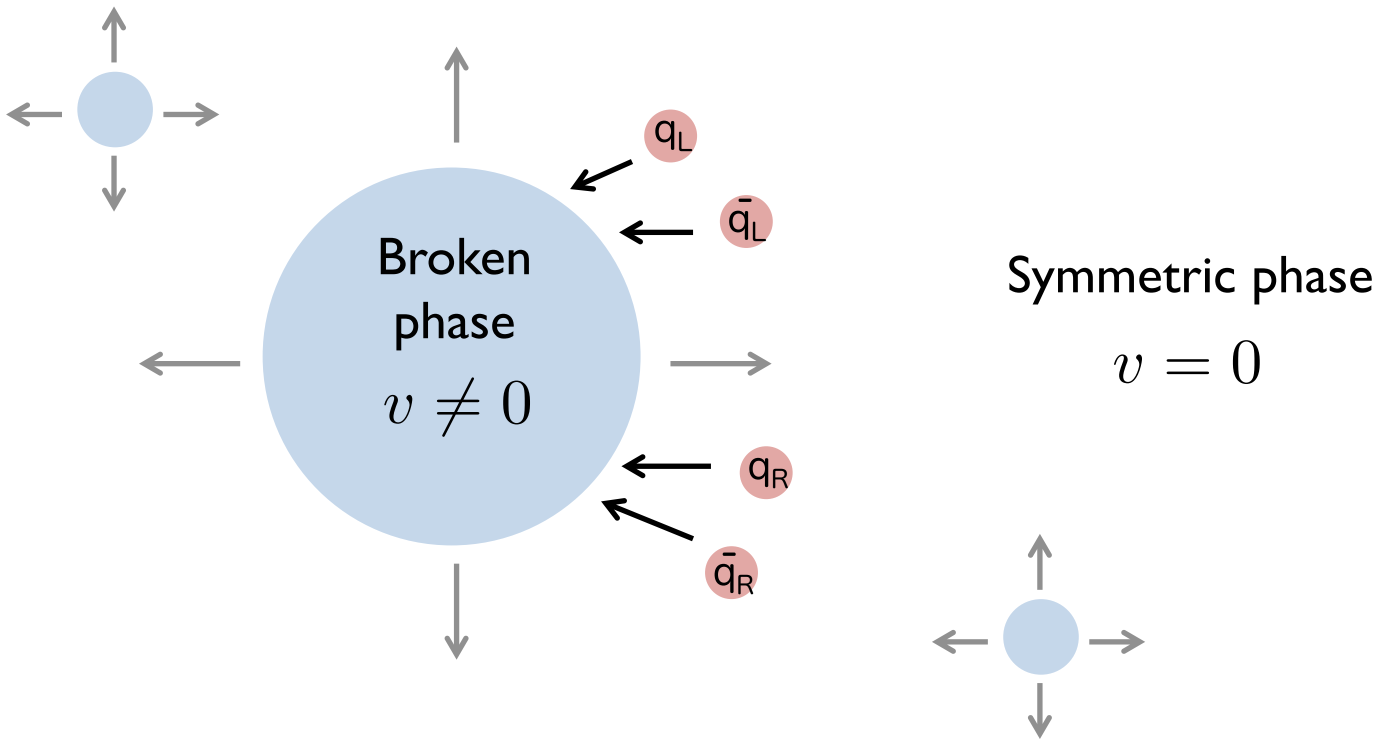
If the first order EWPT is achieved, bubbles can be nucleated around at $T_{C.}$



EWPT ends when the Universe is filled with bubbles.

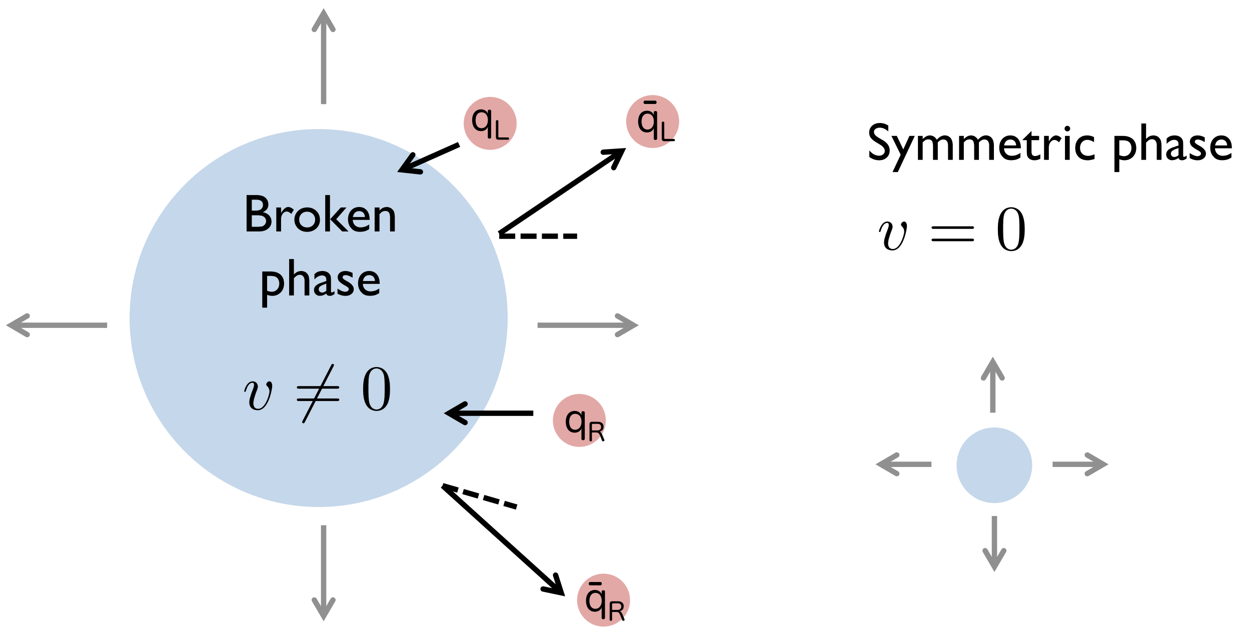
Basic story

(1) Particle and antiparticle interact with bubble wall.



Basic story

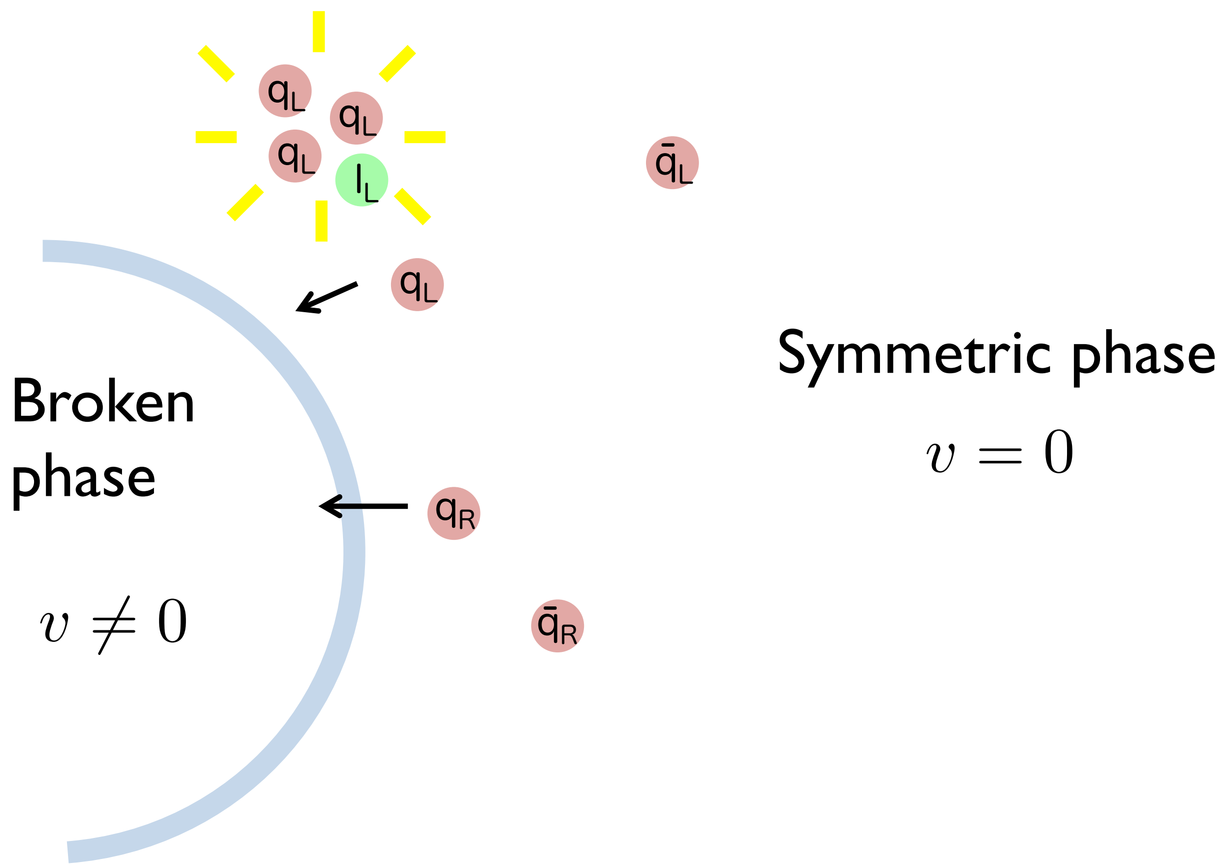
(1) Particle and antiparticle interact with bubble wall.



The transmission to bubbles is different between particles and antiparticles under CP violation.

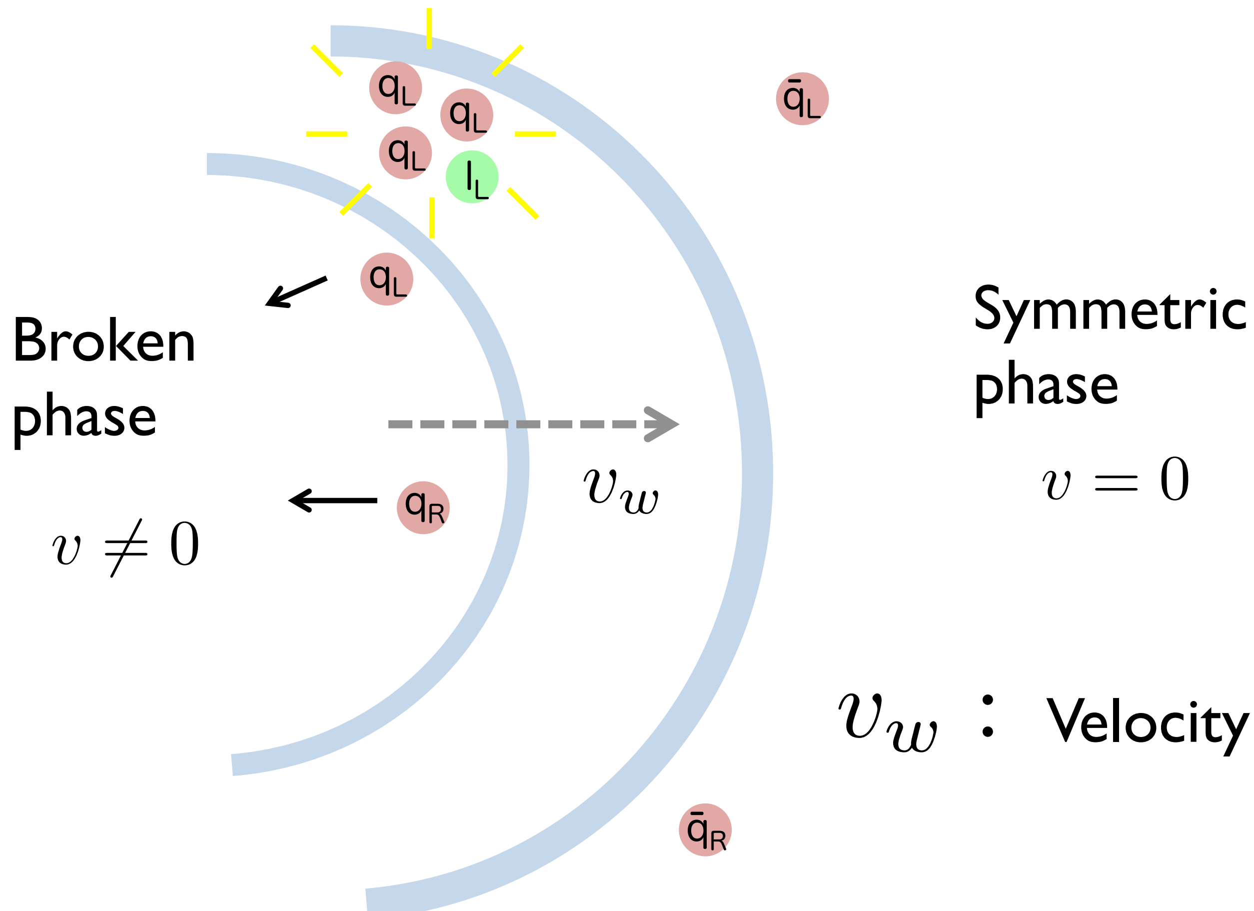
Basic story

(2) Sphaleron process changes the number of the left-handed particles.



Basic story

(3) With the expansion of bubble, $n_B \neq 0$ can be included in it.



v_w : Velocity of bubble

Possibility of EWBG

In the SM, 1st order PT and enough CPV are not obtained.

- Successful story needs

  1) New Scalar for the 1st order PT

  2) New CPV source

Possibility of EWBG

In the SM, 1st order PT and enough CPV are not obtained.

✔ *Higgs Physics*

Andrew's Talk

Successful story needs

1) New Scalar for the 1st order PT

- Singlet scalar

S. Profumo, et al, JHEP0708 (2007) 010
J. R. Espinosa, et al, JCAP01(2012)012
KF, E. Senaha, PRD90(2014)015015
S. Profumo, et al, PRD91(2015)035018
C-Y. Chen, J. Kozaczuk and I. Lewis, JHEP1708(2017)096

- 2 Higgs doublets

S. Kanemura, Y. Okada, E. Senaha, PLB606(2005)361
KF, E. Senaha, PLB747(2015)152
G.C. Dorsch, S.J. Huber, K. Mimasu, J.M. No, JHEP1712(2017)086

- Triplet scalar

H. Patel and M. Ramsey-Musolf, PRD88(2013)035013
N. Blinov, et al, PRD92(2015)035012
S. Inoue, G. Ovanesyan and M. Ramsey-Musolf, PRD93(2016)015013

Possibility of EWBG

In the SM, 1st order PT and enough CPV are not obtained.

✦ Successful story needs

1) New Scalar for the 1st order PT

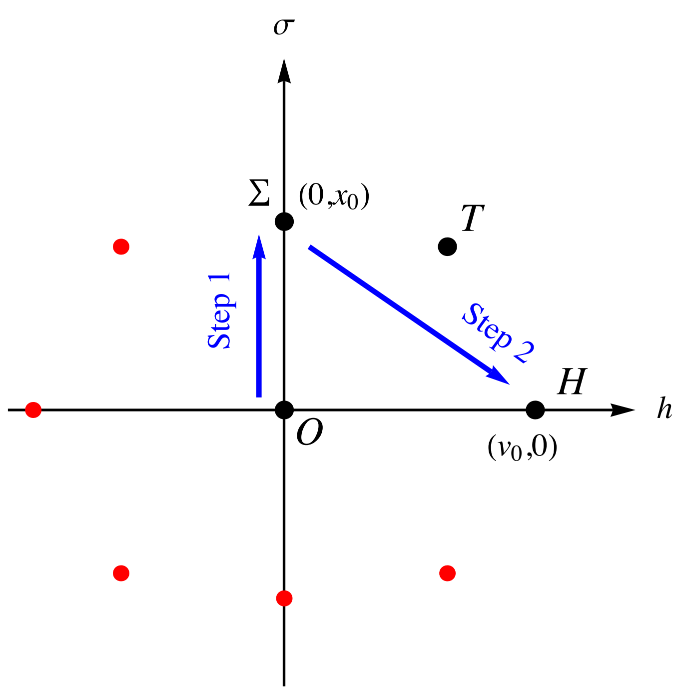
✔ Triplet case : Two step PT

Step 1 : $\langle \Sigma \rangle \neq 0 \quad \langle H \rangle = 0$

Triplet VEV

Step 2 : $\langle \Sigma \rangle = 0 \quad \langle H \rangle \neq 0$

Consistent with EW precision observables



General Two Higgs Doublet Model

+ B anomaly
Muon g-2

✦ *Enough ingredients for EWBG*

✔ 1st order PT : Two Higgs doublet $\Phi_{1,2}$

* Two doublets couple to fermions.

✔ CP violation : Complex Yukawa couplings

General Two Higgs Doublet Model

+ B anomaly
Muon g-2

✦ *Enough ingredients for EWBG*

✔ 1st order PT : Two Higgs doublet $\Phi_{1,2}$

* Two doublets couple to fermions.

✔ CP violation : Complex Yukawa couplings

Possibility of CPV Top Yukawa couplings

- Sensitive to New Physics due to the large Yukawa
- Can be tested by low- and high-energy frontiers

General Two Higgs Doublet Model

General Two Higgs Doublet Model

Yukawa interactions : $i, \ j$: Flavor indices

$$-\mathcal{L}_Y = \bar{q}_{iL} \left(Y_{1ij} \tilde{\Phi}_1 + Y_{2ij} \tilde{\Phi}_2 \right) u_{jR} + \text{h.c.}$$

$Y_1, \ Y_2$: Complex numbers

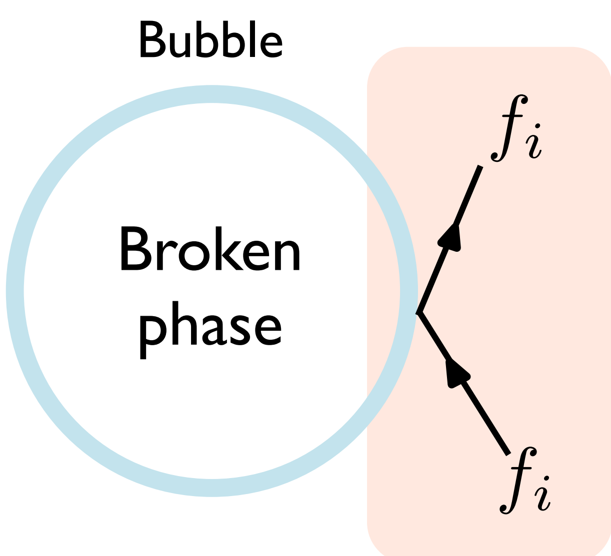
$$\Phi_{i=1,2} = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i a_i) \end{pmatrix}$$

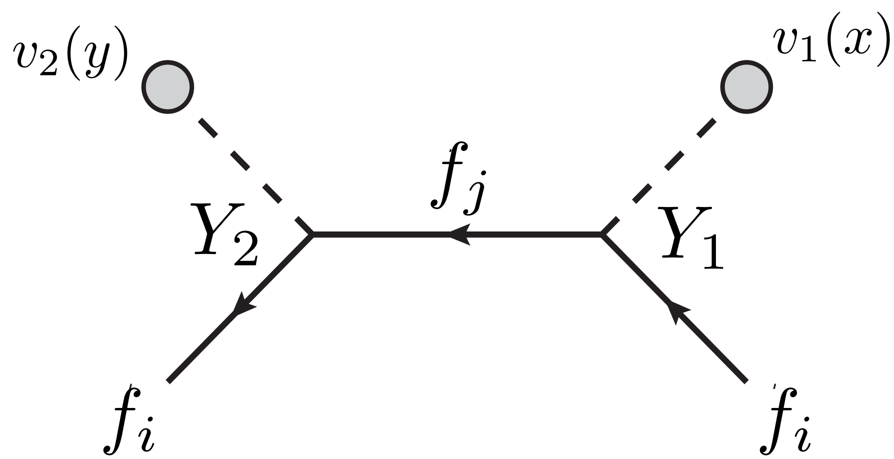
$$v_1 = v \cos\beta \qquad v_2 = v \sin\beta$$

General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

$$-\mathcal{L}_Y = \bar{q}_{iL}\left(Y_{1ij}\,v_1 + Y_{2ij}\,v_2\right)u_{jR} + \mathrm{h.c.}$$





✔ We focus on top quark contribution.

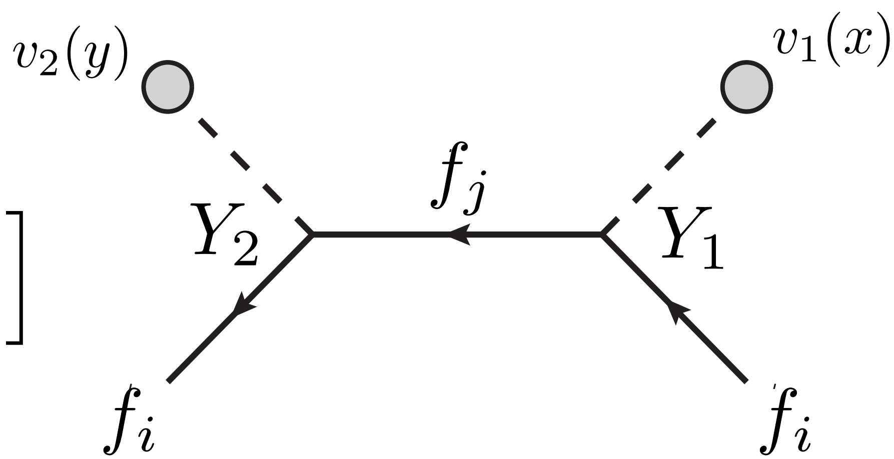
General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

$$-\mathcal{L}_Y = \bar{q}_{iL}\left(Y_{1ij}\, v_1 + Y_{2ij}\, v_2\right) u_{jR} + \text{h.c.}$$

Sakharov's 2nd condition:

$$n_B \propto \text{Im}\left[(Y_1)_{ij}\,(Y_2)^*_{ij}\right]$$



$\text{Im}\left[Y_1 Y_2^*\right]$ leads to the nonzero baryon number.

General Two Higgs Doublet Model

After diagonalizing mass matrices

$$-\mathcal{L}_Y = \quad \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right]u_{jR}h \quad +\text{h.c.}$$

Yukawa : $\dfrac{m_u}{v}$ Complex : $|\rho_{ij}|e^{\phi_{ij}}$

$s_{\beta-\alpha} = \sin(\beta - \alpha)$ * SM limit is $s_{\beta-\alpha} = 1$

α : Mixing angle between h and H

with 125 GeV

General Two Higgs Doublet Model

After diagonalizing mass matrices

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right]u_{jR}h \quad +\text{h.c.}$$

Relationship :

$$Y_1 = V_L^\dagger \left[c_\beta y - s_\beta \rho\right] V_R^\dagger \qquad\qquad u_L \to V_L^\dagger u_L$$

$$Y_2 = V_L^\dagger \left[s_\beta y + c_\beta \rho\right] V_R^\dagger \qquad\qquad u_R \to V_R u_R$$

Nonzero ρ can be induced by the nonzero Y_1 and Y_2.

Simplified case

T. Liu, et al, PRL108(2012)221301
HK Guo, et al, PRD96(2017)115034
KF, et al, PLB 776 (2018) 402

In general, $Y_i \ (i = 1, 2)$ can have all components.

Let us assume

$$Y_i = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & (Y_i)_{32} & (Y_i)_{33} \end{pmatrix} \quad \text{and} \quad (Y_1)_{33} = (Y_2)_{33}$$

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Low-energy top Yukawa is obtained after diagonalization.

$$V_L\left(Y_1 c_\beta + Y_2 s_\beta\right) V_R = \mathrm{dia}\left(0,0,y_t\right) \quad \text{with} \;\; V_L = 1$$

$$\mathrm{Im}\left[(Y_1)_{32}(Y_2)^*_{32}\right] = -y_t \mathrm{Im}\left(\rho_{tt}\right)$$

BAU

Low energy

General Two Higgs Doublet Model

After diagonalizing mass matrices

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right]u_{jR}h \quad +\text{h.c.}$$

Our setup :

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \rho_{tc} & \rho_{tt} \end{pmatrix}$$

ρ_{tt} : Electron EDM d_e

Higgs decay to 2 gamma

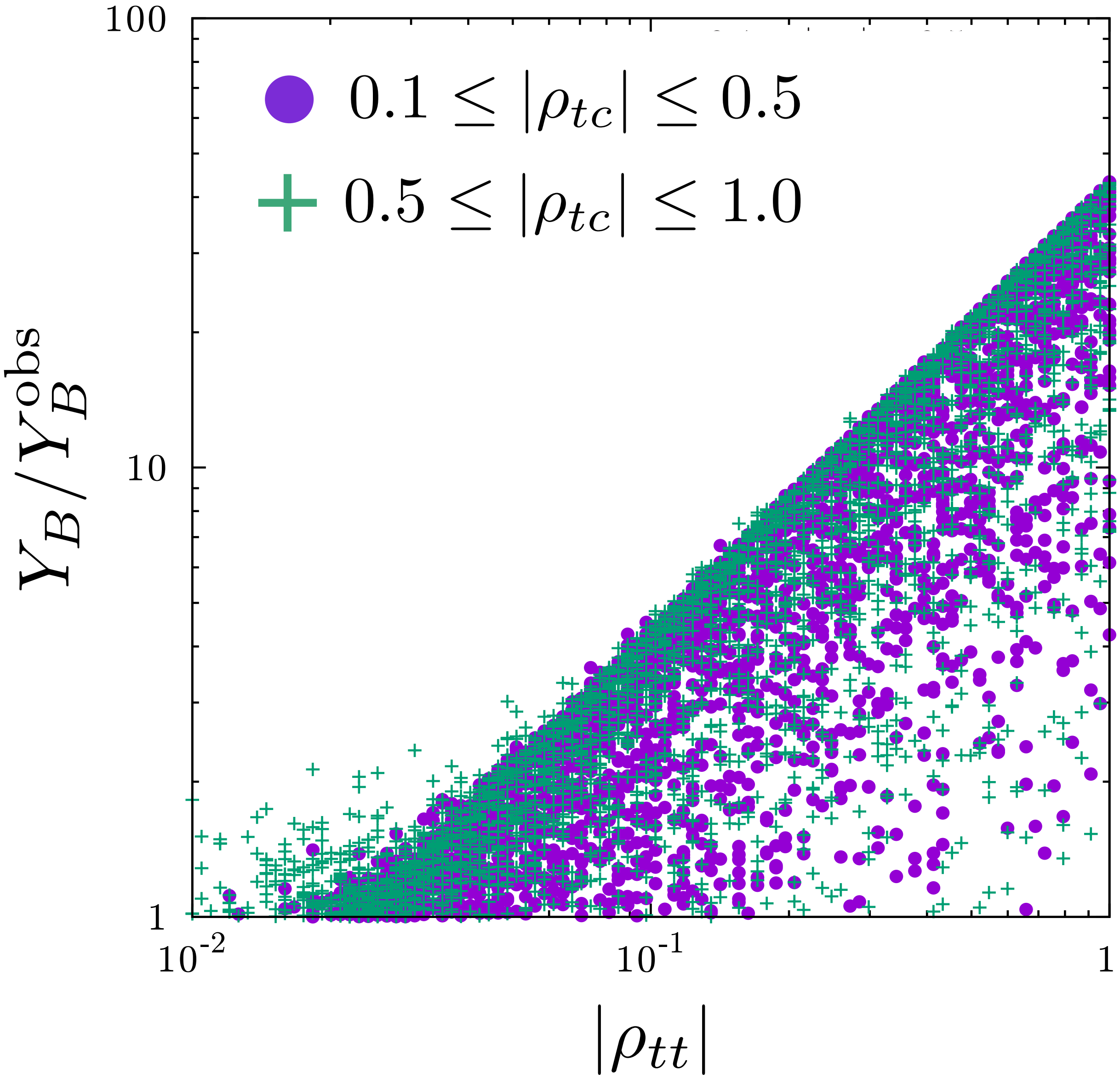
ρ_{tc} : $\mathrm{Br}(t \to ch)$

✔ Can these couplings work for the BAU ?

Results

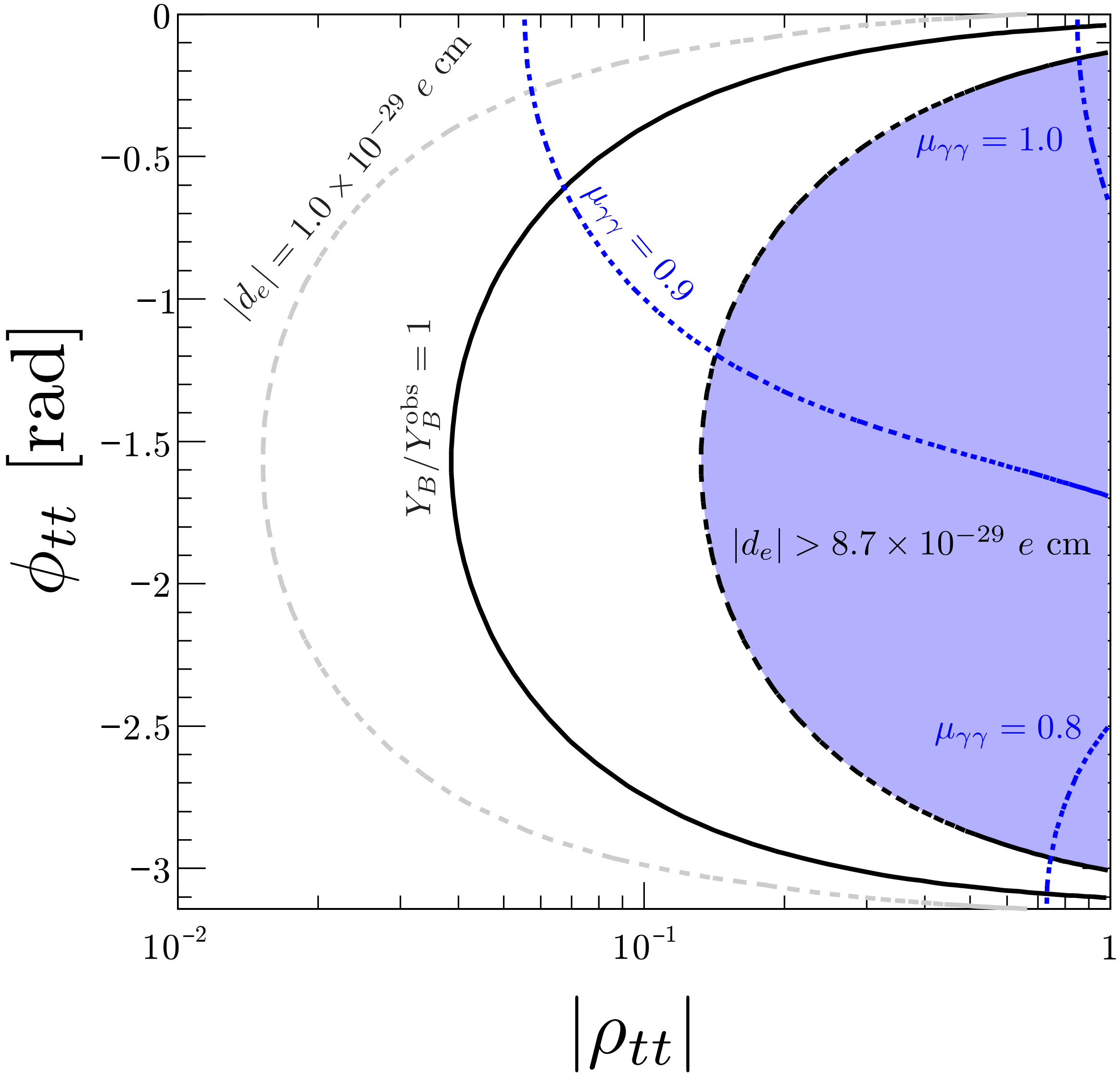
Random scan

$m_H = m_A = m_{H^\pm} = 500\ \text{GeV}$



- ✔ Enough BAU is produced by ρ_{tt} and ρ_{tc} .
- ✔ Large ρ_{tt} yields more BAU.

Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4)$ $c_{\beta-\alpha} = 0.1$



Black line :

$Y_B/Y_B^{\rm obs} = 1$

Benchmark value :

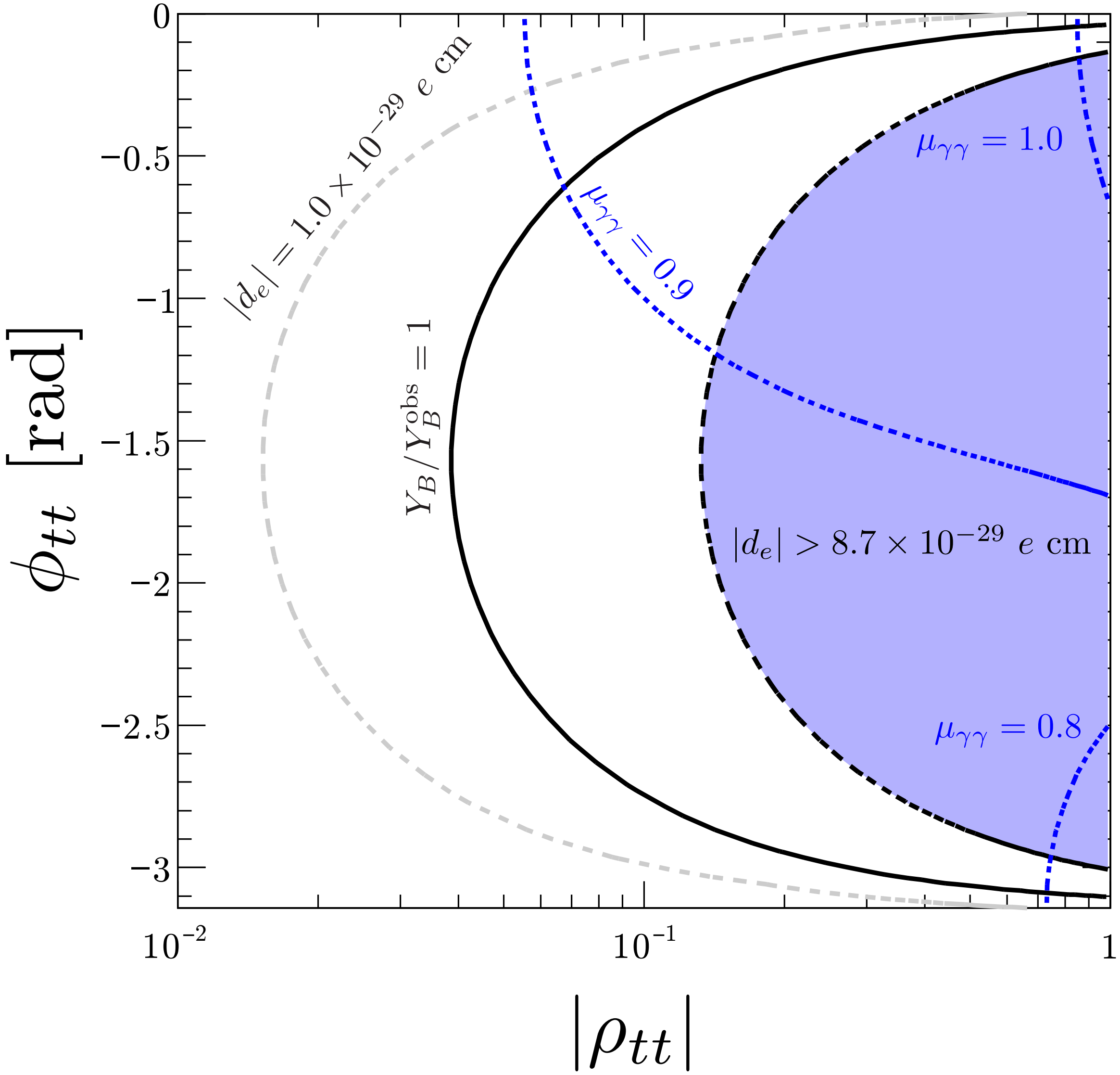
$\mathrm{Br}(t \to ch) \simeq 0.15\%$

$\mathrm{Br}(t \to ch)$

$< \begin{array}{l} 0.22\% \text{ (ATLAS)} \\ 0.40\% \text{ (CMS)} \end{array}$

ATLAS, JHEP1710(2017)129
CMS , JHEP1702(2017)079

Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4)$ $c_{\beta-\alpha} = 0.1$



Black line :

$$Y_B/Y_B^{\rm obs} = 1$$

Electron EDM :

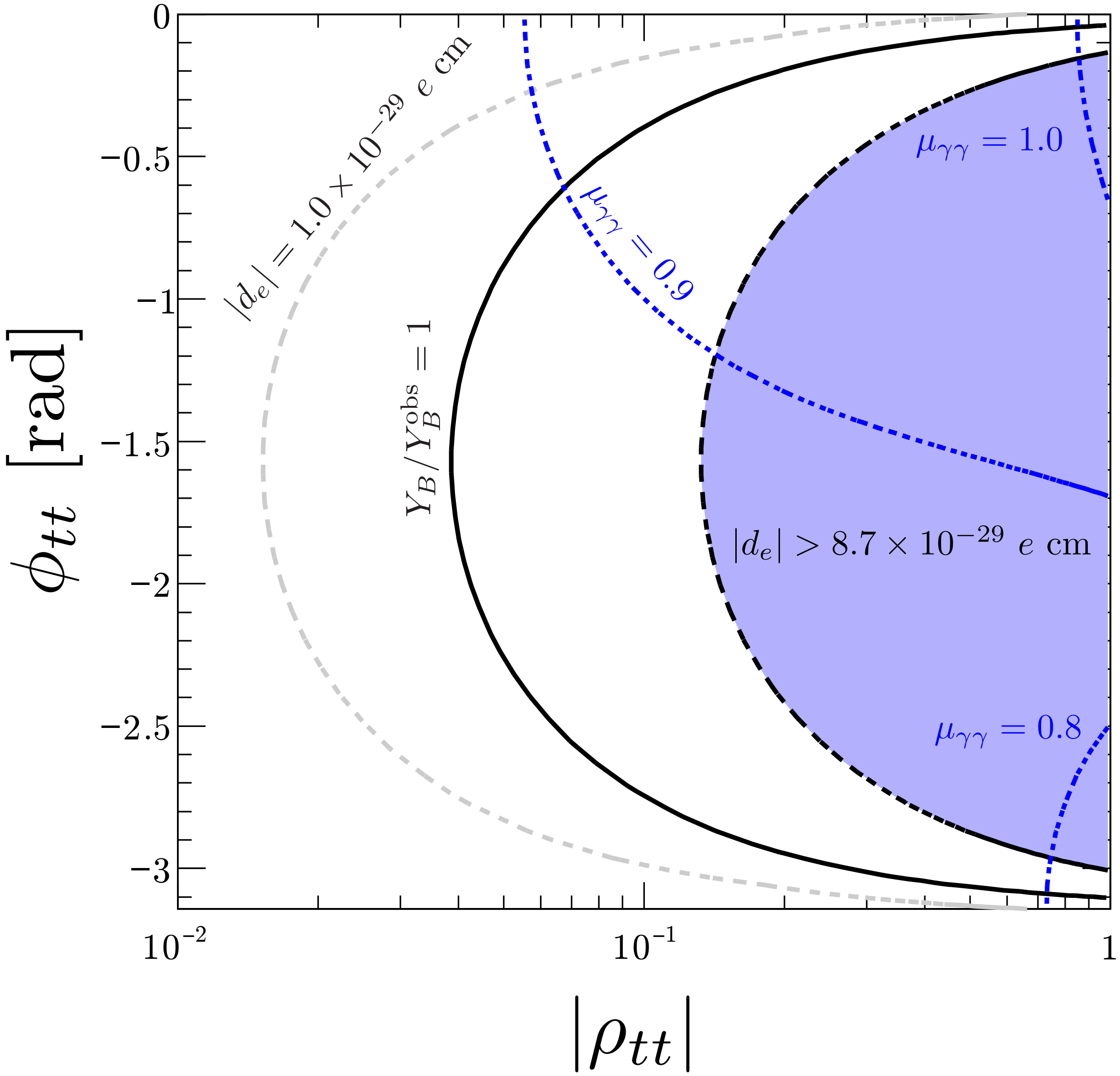
- **Blue region**

$$|d_e| < 8.7 \times 10^{-29}\ e\ \text{cm}$$

- **Gray dashed line**

$$|d_e| = 1.0 \times 10^{-29}\ e\ \text{cm}$$

Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4)$ $c_{\beta-\alpha} = 0.1$



Black line :

$$Y_B/Y_B^{\rm obs} = 1$$

Higgs signal strength :

$$\mu_{\gamma\gamma} = 1.14^{+0.19}_{-0.18}$$

ATLAS, CMS Collaboration, JHEP1608(2016)045

- Blue dotted line

$$\mu_{\gamma\gamma} = 1.0,\ 0.9,\ 0.8$$

Conclusion

✔ EWBG has high testability.

New scalar

CP phase

- *Search for new scalar*
- *Higgs coupling measurement*
- *Precision measurement of EDM*

✔ General 2HDM is one successful scenario for EWBG.

CPV Top Yukawa : $c_{\beta-\alpha}\bar{t}_L\left(\rho_{tt}t_R+\rho_{tc}c_R\right)h$

✦ *Can be probed by EDM and Higgs physics.*

For lepton sector, see C-W. Chiang, KF, E. Senaha, PLB 762 (2016) 315
HK Guo, et al, PRD96(2017)115034

Backup Slide

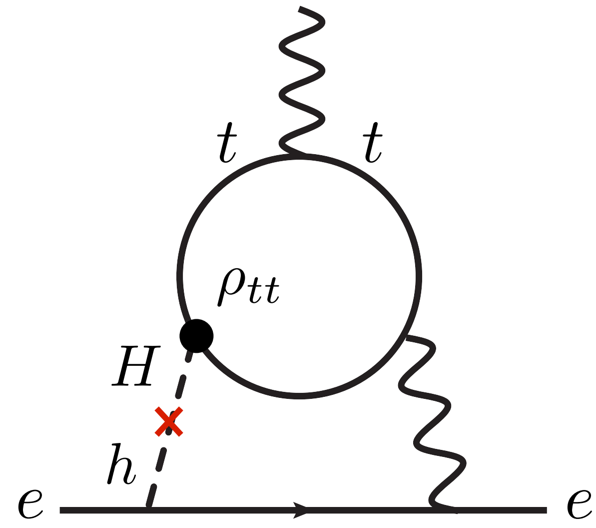
General Two Higgs Doublet Model

$$
\begin{aligned}
-\mathcal{L}_Y = \quad & \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho^u_{ij}c_{\beta-\alpha}\right]u_{jR}h \\
& +\bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}c_{\beta-\alpha} - \frac{1}{\sqrt{2}}\rho^u_{ij}s_{\beta-\alpha}\right]u_{jR}H \\
& -\frac{i}{\sqrt{2}}\bar{u}_{iL}\rho^u_{ij}u_{jR}A \\
& -\bar{d}_{iL}\left(V^\dagger_{\mathrm{CKM}}\rho^u\right)_{ij}u_{jR}H^-
\end{aligned}
$$

Phenomenology

- Electron EDM:

$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm} \quad (90\%\ \mathrm{CL})$$



- Signal strength of $h \to 2\gamma$:

* Top quark and charged scalars can contribute

$$\mu_{\gamma\gamma} = 1.14^{+0.19}_{-0.18}$$

Combined Run I limit from ATLAS and CMS
JHEP08(2016)045

- B physics constraint : $|\rho_{33}| < 1$ at $m_H = 500\ \mathrm{GeV}$

B. Altunkaynak, et al PLB751(2015)135

For estimate of the BAU, we use CTP formalism with VEV insertion.

Simplified case

Assumption:

$$Y_1 = \begin{pmatrix} 0 & 0 \\ (Y_1)_{21} & (Y_1)_{22} \end{pmatrix} \qquad Y_2 = \begin{pmatrix} 0 & 0 \\ (Y_2)_{21} & (Y_2)_{22} \end{pmatrix}$$

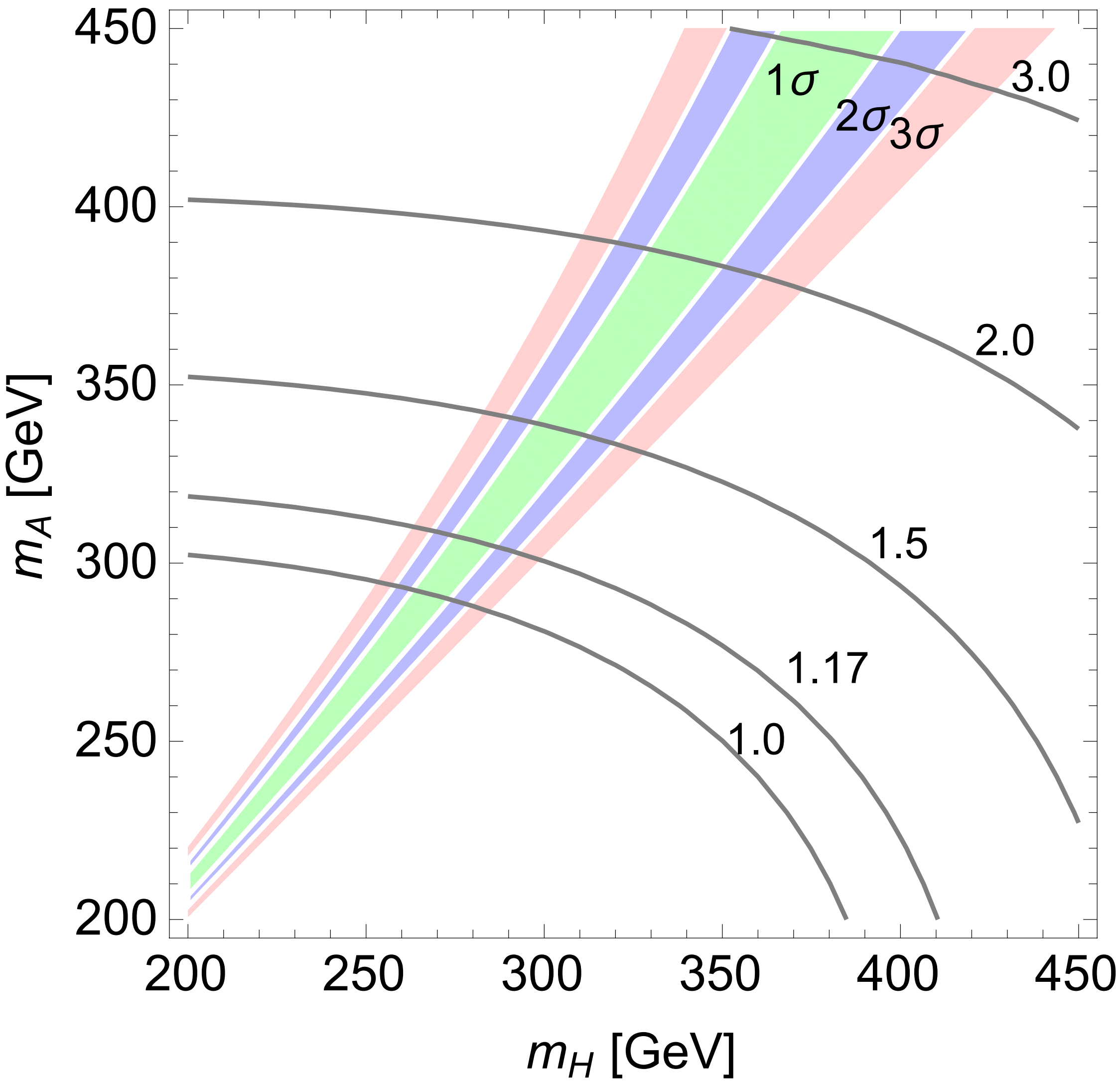
with $(Y_1)_{22} = (Y_2)_{22}$

$$\mathrm{Re}(\rho_{22}) = \frac{1}{y_2}\left[- |(Y_1)_{21}|^2 + |(Y_2)_{21}|^2 \right]$$

$$\mathrm{Im}(\rho_{22}) = -\frac{1}{y_2}\mathrm{Im}\left[(Y_1)_{21}(Y_2)^*_{21}\right]$$

$$\rho_{21} = -\rho_{22}\frac{Y_{22}}{|Y_{21}|}$$

Electroweak Phase Transition



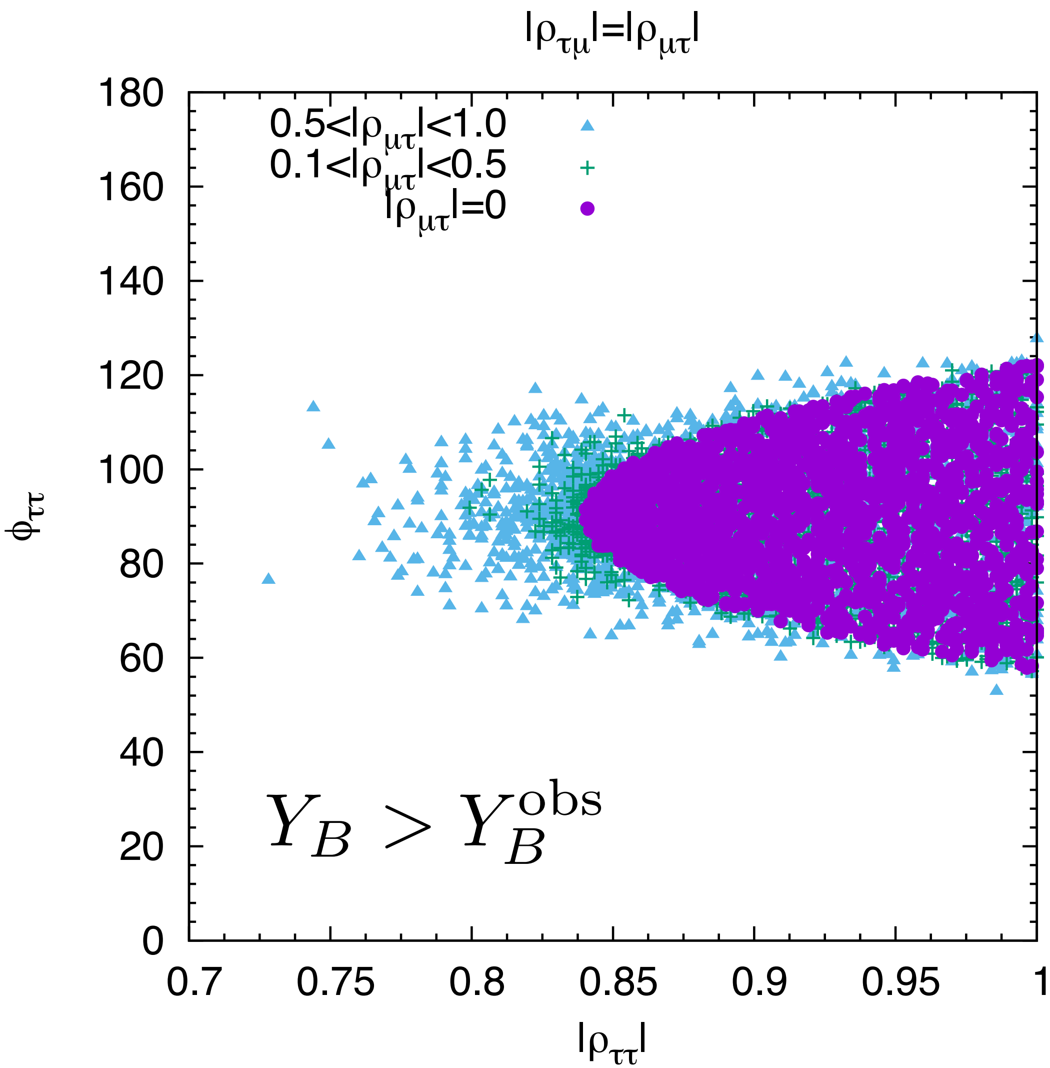
$$m_A = m_{H^\pm}$$

$$c_{\beta-\alpha} = 0.006$$

Contour :

$$v_C/T_C$$

Lepton-driven case



Random scan in $(|\rho_{\tau\tau}|,\ \phi_{\tau\tau})$ plane

- $|\rho_{\mu\tau}| = 0$
- $0.1 < |\rho_{\mu\tau}| < 0.5$
- $0.5 < |\rho_{\mu\tau}| < 1$

Nonzero $\rho_{\tau\tau}$ and $\rho_{\tau\mu}$ can produce the BAU.

$$|\rho_{\tau\tau}| \gtrsim 0.75$$