Electroweak Baryogenesis with Lepton Flavor Violation

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Physics at the interface: Energy, Intensity, and Cosmic frontiers

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PLB 762 (2016) 315

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Outline :

1. Electroweak Baryogenesis

2. BAU in General Two Higgs doublet Model

3. Lepton Flavor Phenomenology

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

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Electroweak Baryogenesis

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

Baryon asymmetry is created during EW phase transition

✦ Since energy scale is O(100) GeV, collider physics can probe.

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

Sphaleron process

Manton, Phys. Rev. D28 (1983) 2019
Klinkhammer and Manton, Phys. Rev. D30 (1984)

(B + L) non-conserved process due to chiral anomaly

- Sphaleron transition rates (/time/volume) $\alpha_W = g_2^2/4\pi$

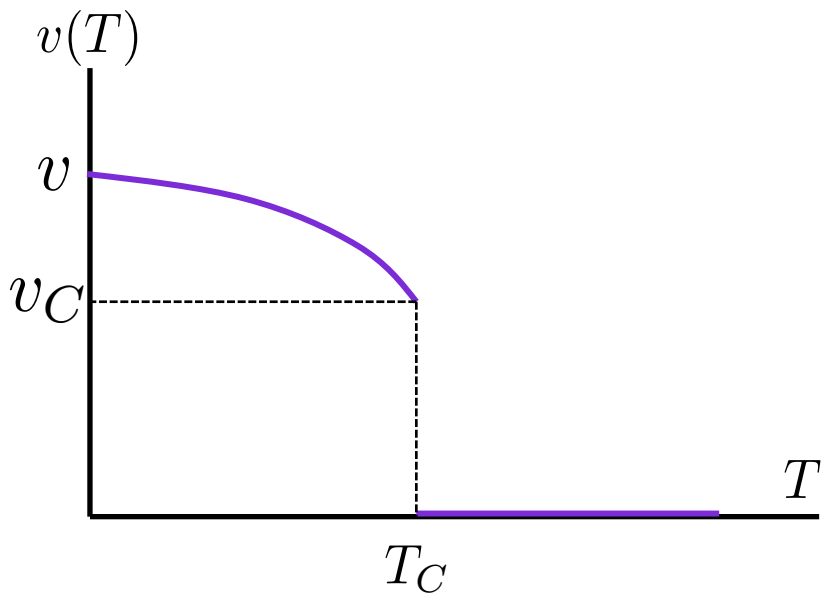
Symmetric phase : $\Gamma_B^{(s)} \simeq \kappa(\alpha_W T)^4$ $\kappa = 0.1 \sim 1.0$

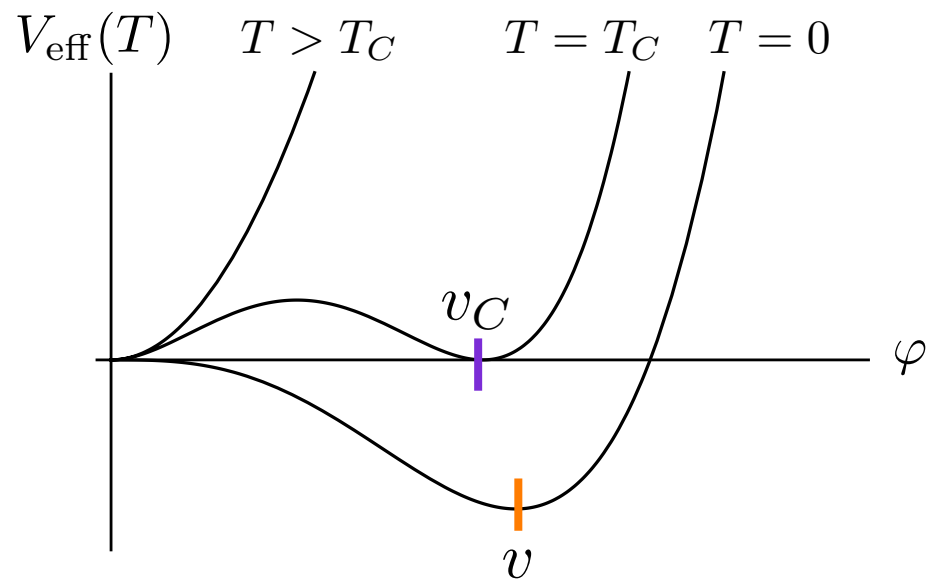
Broken phase : $\Gamma_B^{(b)} \simeq T^4 e^{-E_{\rm sph}/T}$ $E_{\rm sph}$: Energy of sphaleron

B-changing process is active at finite temperature but is suppressed at T=0.

1st order electroweak phase transition

The Higgs VEV discontinuously changes.



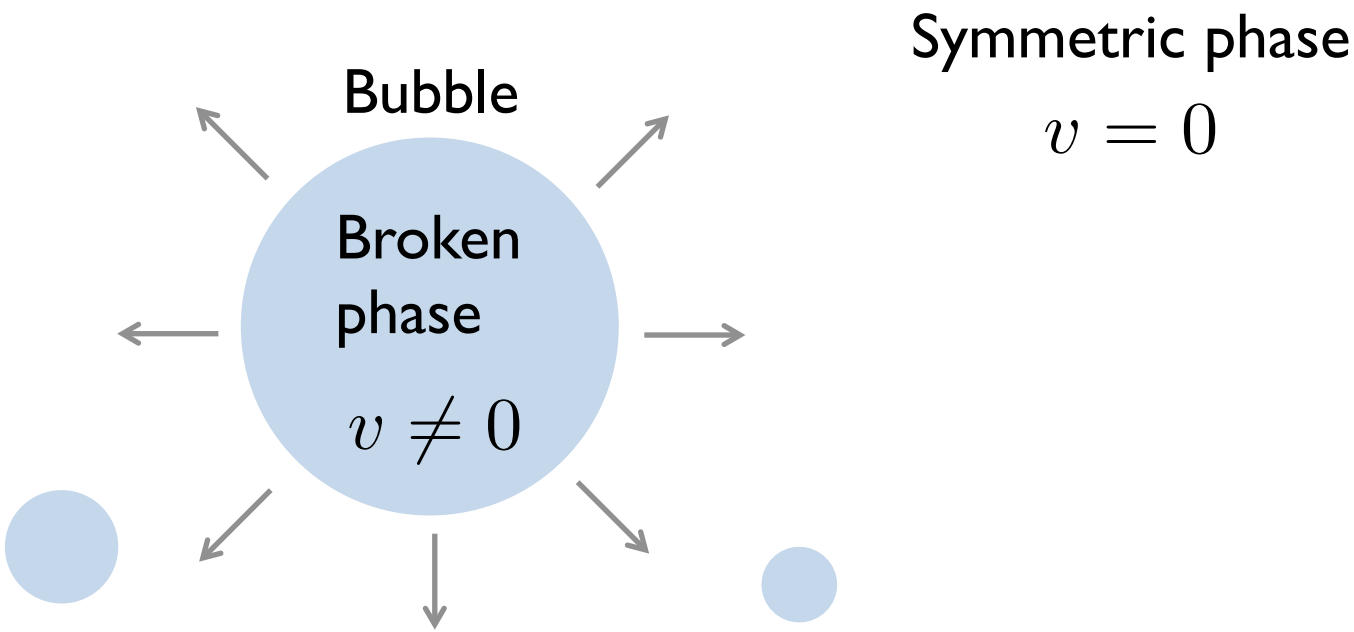


T_C : Critical temperature

v_C : Higgs VEV at T_C

Basic story

If the first order EWPT is achieved, bubbles can be nucleated around at T_C.



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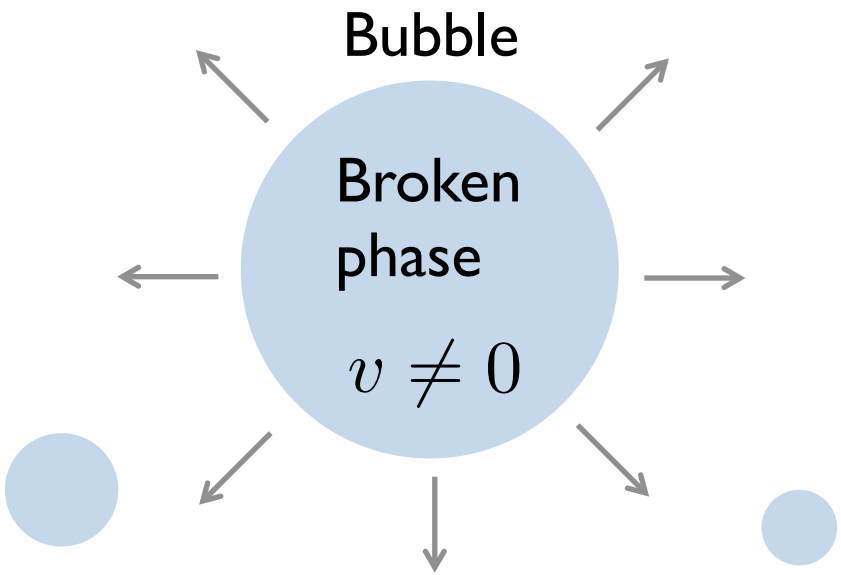


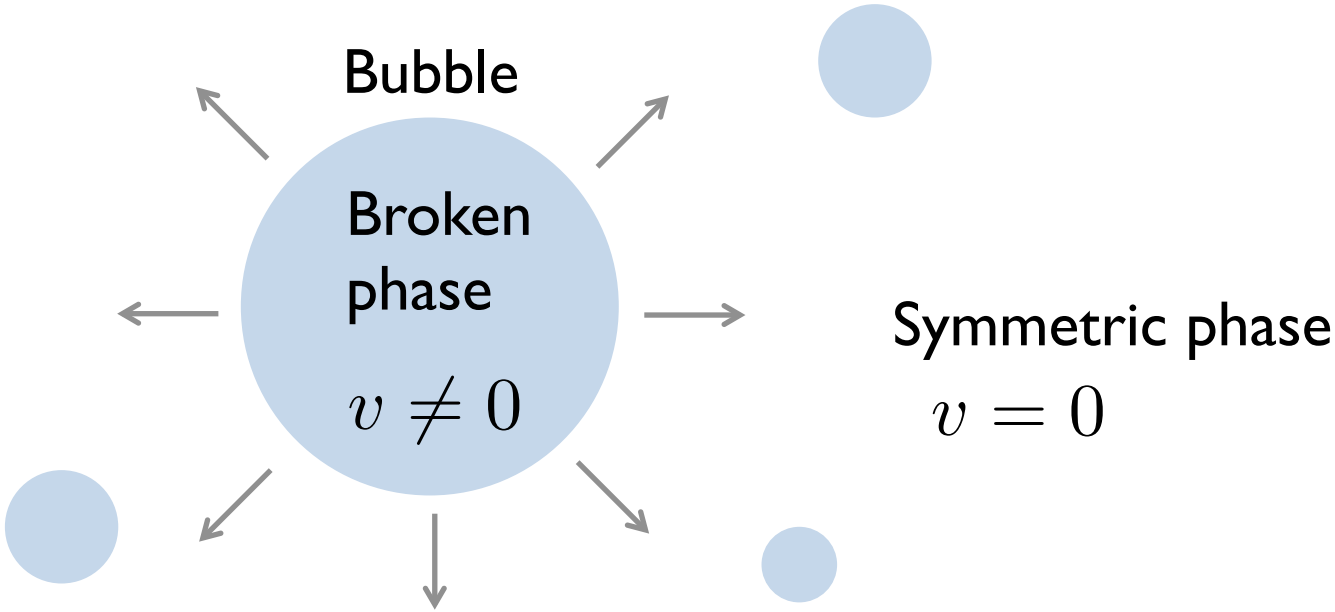
Symmetric phase

$$v = 0$$

Ex) Boiling water

Basic story

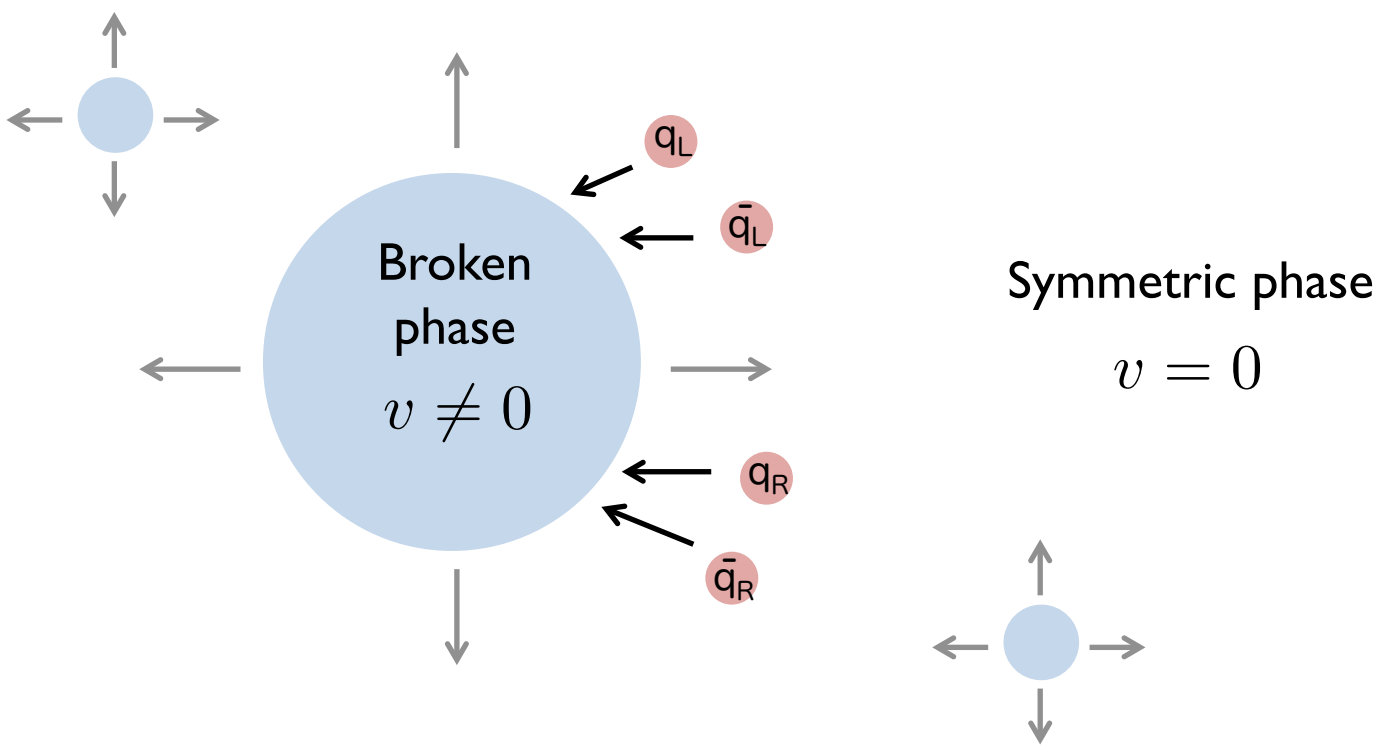
If the first order EWPT is achieved, bubbles can be nucleated around at T_C.



EWPT ends when the Universe is filled with bubbles.

Basic story

(1) Particle and antiparticle interact with bubble wall.



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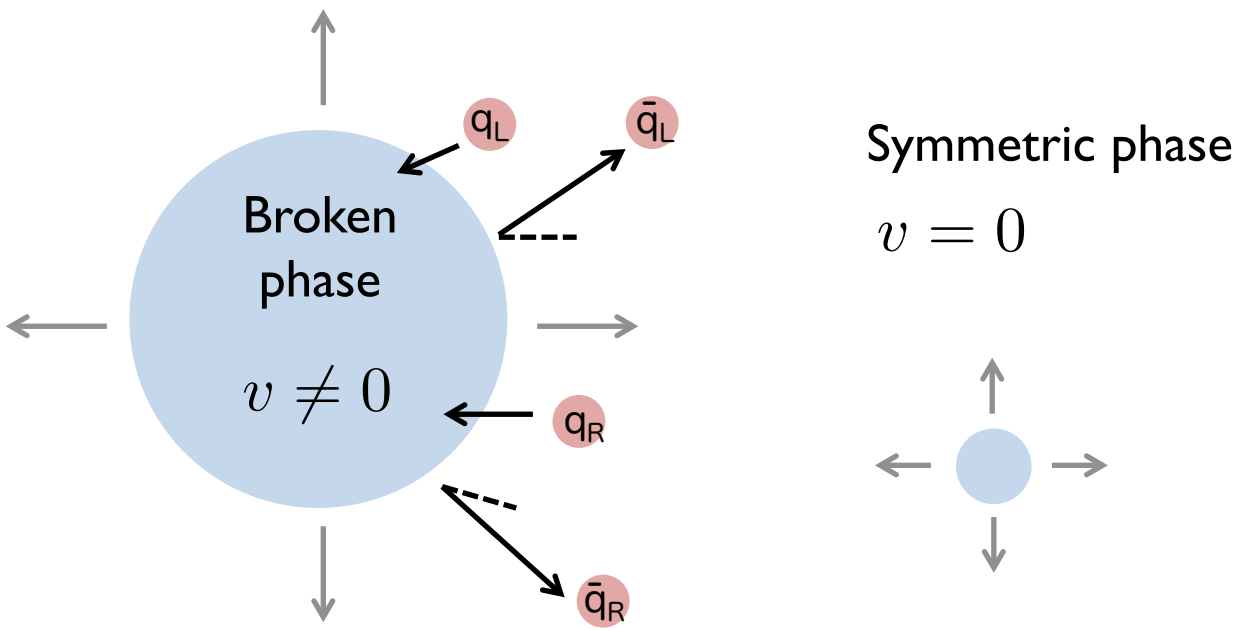
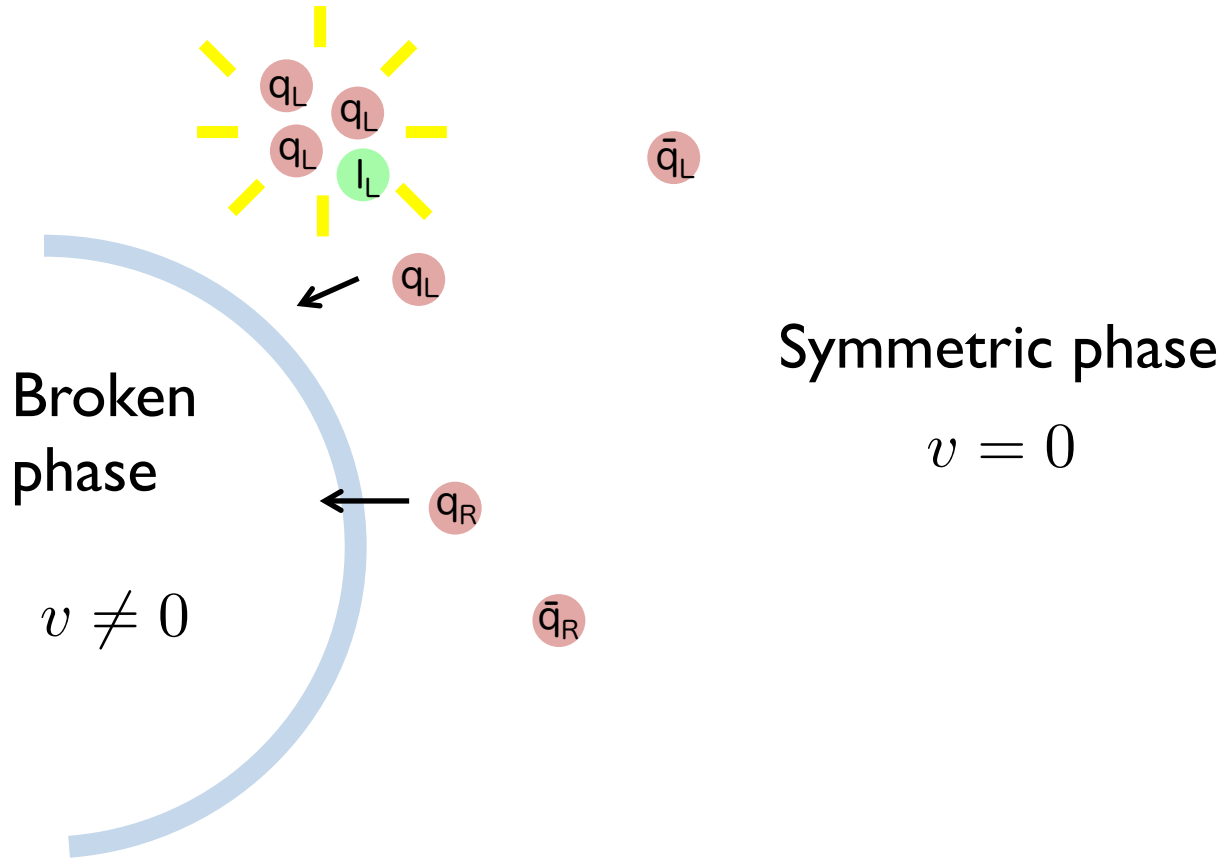


The transmission to bubbles is different between particles and antiparticles under CP violation.

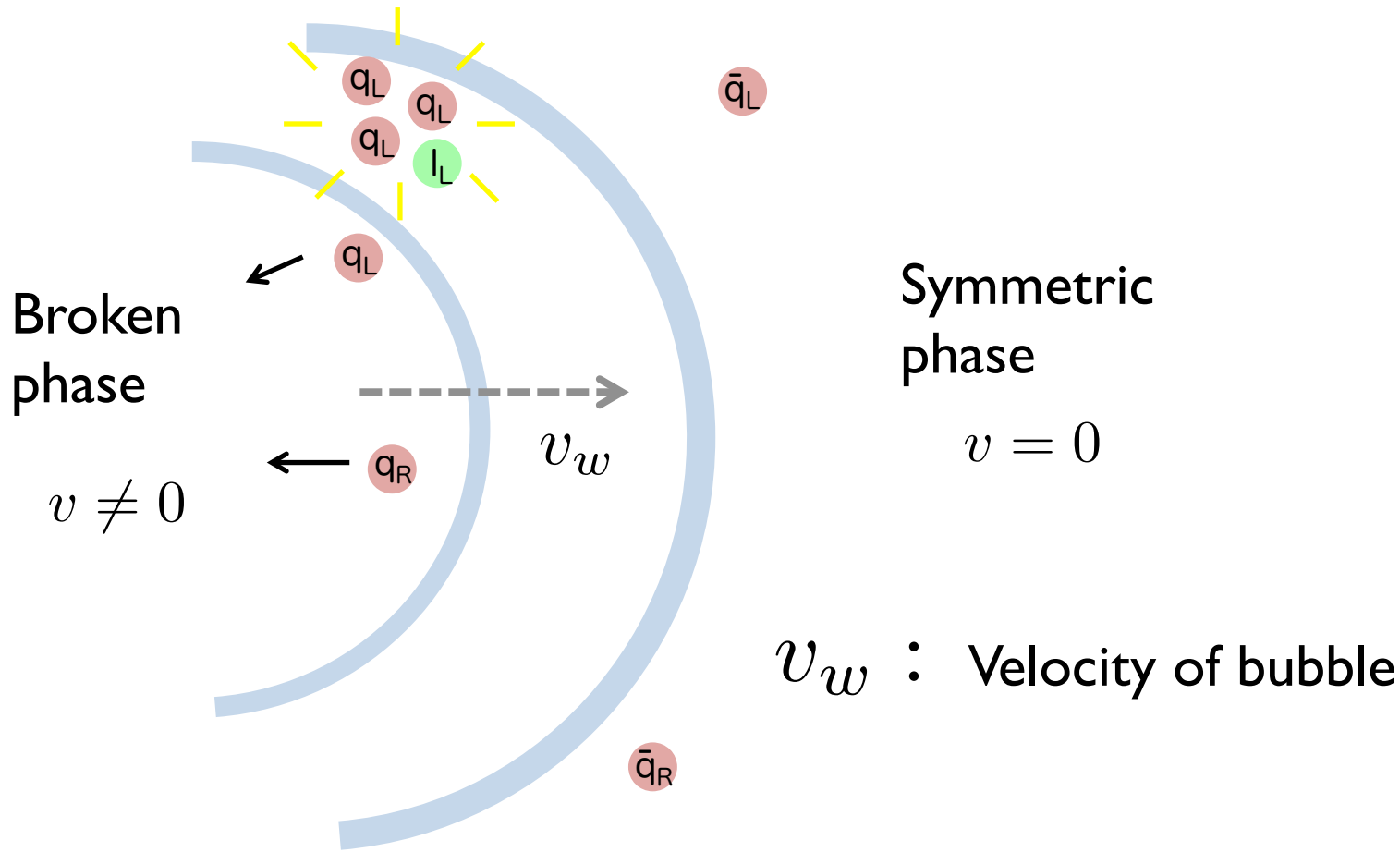
Basic story

(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.



Possibility of EWBG

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

- Successful scenario for EWBG needs

  1) New Scalar for the 1st order PT

  2) New CP violation

Possibility of EWBG

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

✦ General Two Higgs Doublet Model

1) New Scalar for the 1st order PT

Two Higgs doublet : $\Phi_{1,2}$

* Two doublets couple to fermions.

2) New CP violation

✔ Complex Yukawa couplings

General Two Higgs Doublet Model

General Two Higgs Doublet Model

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

$$-\mathcal{L}_Y = \bar{l}_{iL}\left(Y_1\Phi_1 + Y_2\Phi_2\right)_{ij} e_{jR} + \text{h.c.}$$

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

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

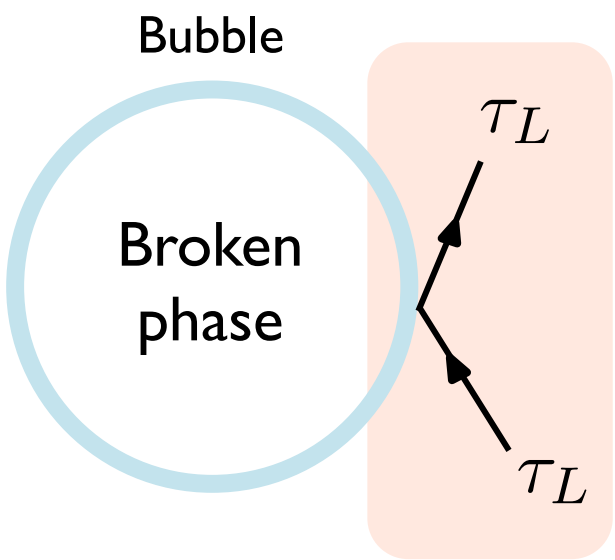
We take $t_\beta = 1\,.$

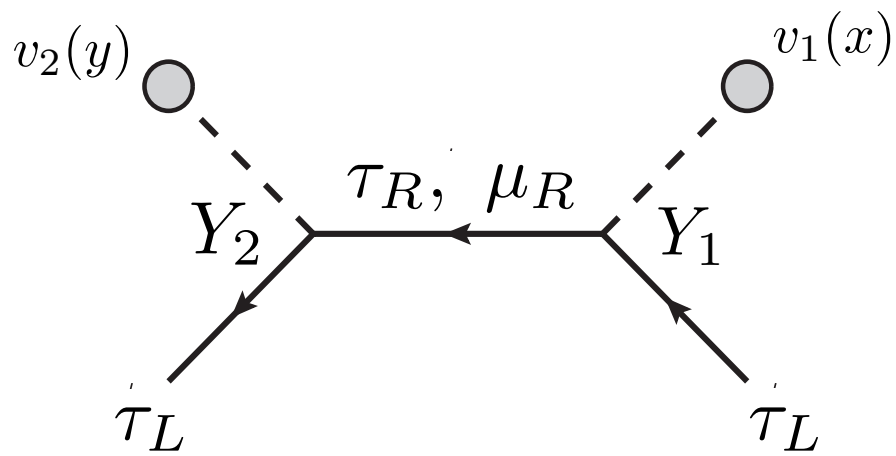
$Y_1,\ Y_2$: Complex numbers ✦ Important couplings!

General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

$$-\mathcal{L}_Y = \bar{l}_{iL}\,(Y_1\,v_1 + Y_2\,v_2)_{ij}\,e_{jR} + \text{h.c.}$$





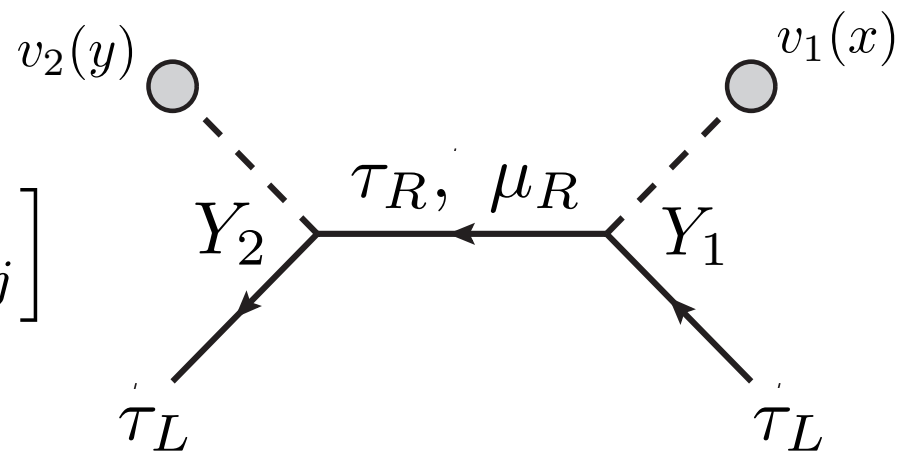
General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

$$-\mathcal{L}_Y = \bar{l}_{iL}\,(Y_1\,v_1 + Y_2\,v_2)_{ij}\,e_{jR} + \text{h.c.}$$

Sakharov's 2nd condition:

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



Imaginary parts in Yukawa interactions lead to the BAU.

General Two Higgs Doublet Model

After diagonalizing mass matrices

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

Yukawa : $\frac{m_{e_i}}{v}$ 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

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

Relationship :

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

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

$$e_L \to V_L e_L$$

$$e_R \to V_R e_R$$

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

Approximate diagonalization

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

Assumption: $i = 1, 2$

$$Y_i = \begin{pmatrix} (Y_i)_{ee} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & (Y_i)_{\tau\mu} & (Y_i)_{\tau\tau} \end{pmatrix} \text{ and } (Y_1)_{\tau\tau} = (Y_2)_{\tau\tau}$$

In this case,

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

$$\underbrace{\mathrm{Im}\left[(Y_1)_{\tau\mu}(Y_2)^*_{\tau\mu}\right]}_{\text{BAU}} = -y_\tau \underbrace{\mathrm{Im}(\rho_{\tau\tau})}_{\text{Low energy}}$$

BAU parameters can be related to low-energy parameters.

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✔ How large low-energy parameter is necessary for BAU ?

Lepton flavor phenomenology

Lepton flavor structure

Yukawa interactions at low energy:

$$-\mathcal{L}_Y \ni \bar{e}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right]e_{jR}h$$

Off-diagonal parts cause flavor-changing process

Lepton flavor structure

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Off-diagonal parts cause flavor-changing process

Our setup:

$$\rho = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_{\mu\tau} \\ 0 & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix} \qquad |\rho_{\mu\tau}| = |\rho_{\tau\mu}|$$

✔ We discuss the possibility of creating BAU and lepton flavor processes.

Lepton flavor

Y-F Zhou, Y-L Wu, EPJ C27(2003)577
Y. Omura. Eibun Senaha, K. Tobe,
JHEP05(2015)028, PRD94,055019(2016)

Off-diagonal components : $\rho_{\mu\tau}$ $\rho_{\tau\mu}$

1) Lepton flavor violating decay of the Higgs

$$\mathrm{Br}(h \to \mu\tau) < 0.25\%$$

CMS Collaboration, CMS-PAS-HIG-17-001.

$$\mathrm{Br}(h \to \mu\tau) < 1.43\%$$

ATLAS Collaboration., EPJC77 no2 70 (2017)

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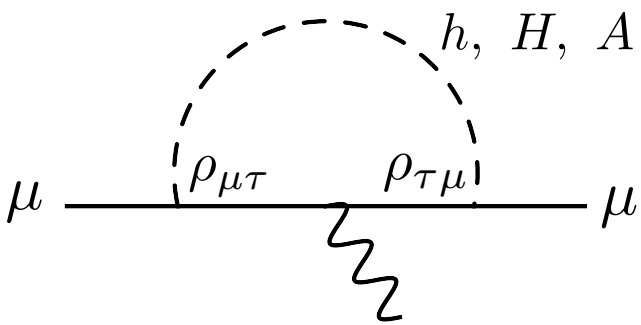


2) Muon EDM and g-2

$$|d_\mu| < 1.9 \times 10^{-19}\ e\ \mathrm{cm}$$

G.W.Bennett et al. PRD80,052008(2009)

$$\delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \times 10^{-10}$$

K. Hagiwara, et al, J. Phys. G38(2011)085003.

Lepton flavor

Diagonal component : $\rho_{\tau\tau}$

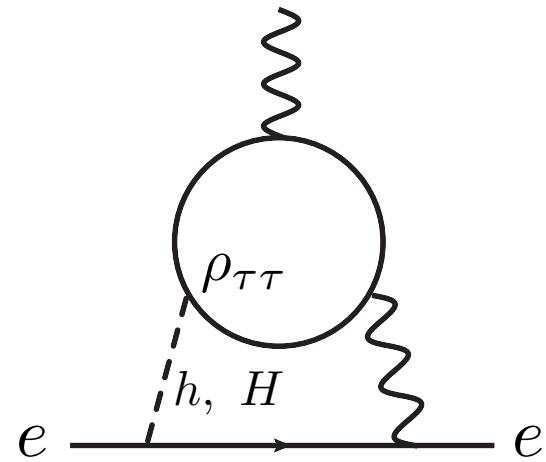
$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$

ACME Collaboration, Science 343 (2014) 269

$$|d_e| < 1.3 \times 10^{-28}\ e\ \mathrm{cm}$$

W. B. Cairncross et al., PRL.119, no.15,153001(2017)

Electron EDM



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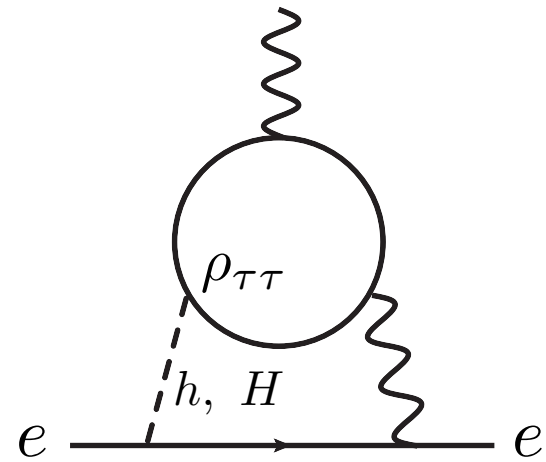
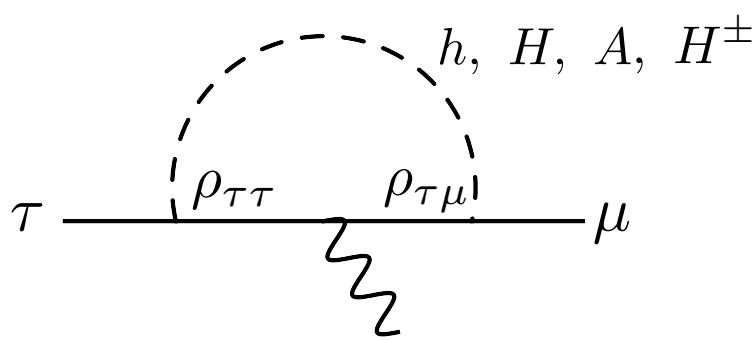
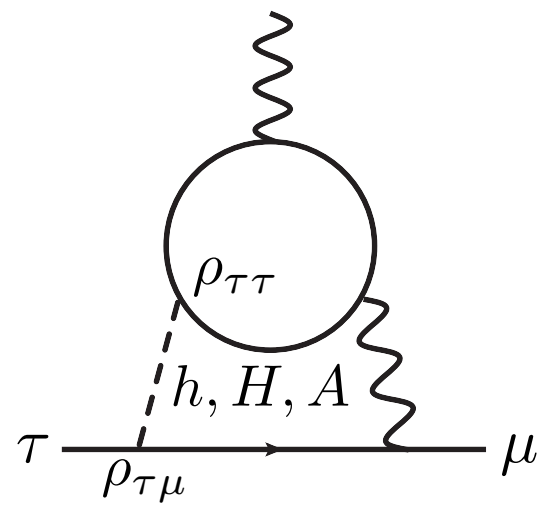


All components : $\rho_{\mu\tau}\ \ \rho_{\tau\mu}\ \ \rho_{\tau\tau}$

$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

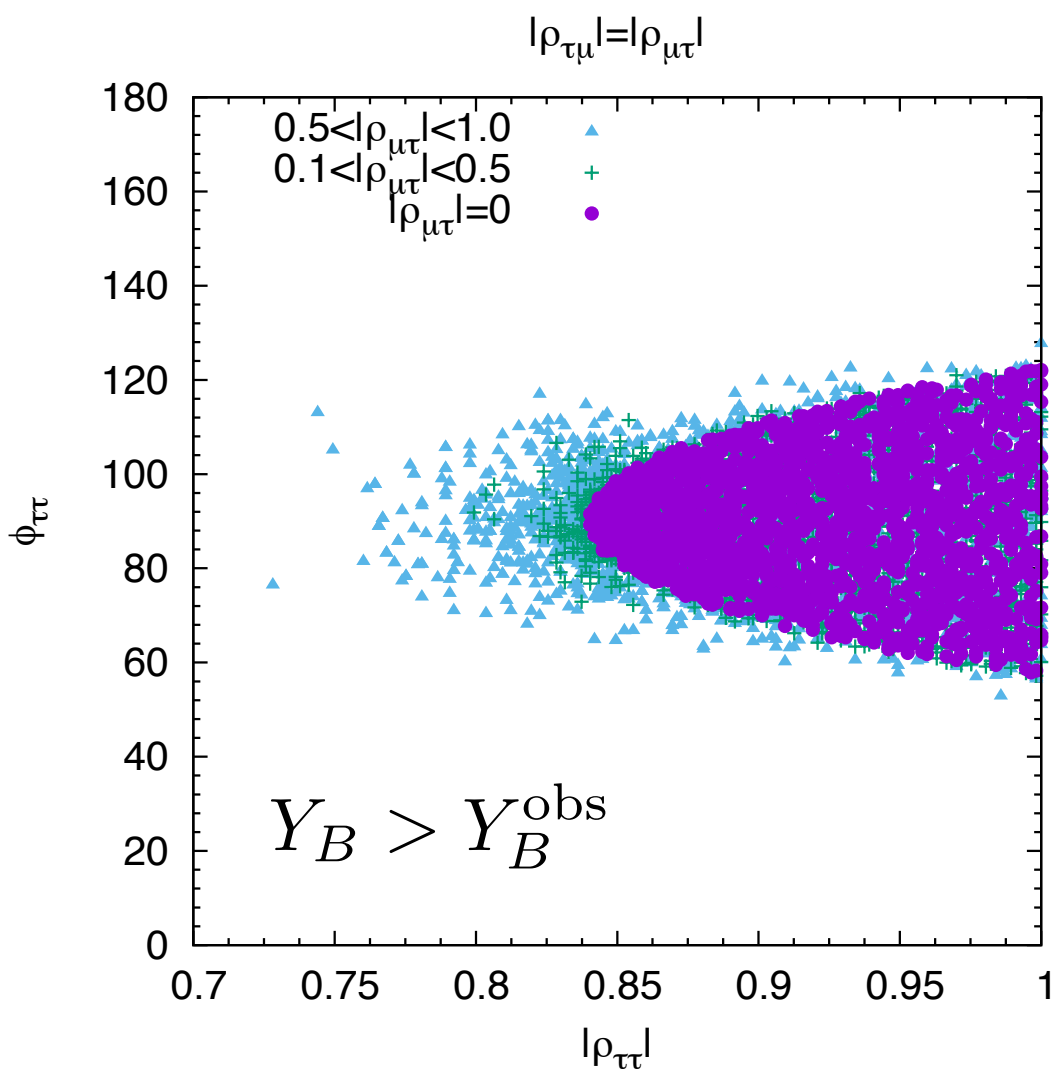
K. Hayasaka et al. [Belle Collaboration], PLB666 (2008) 16;
B. Aubert et al. [BaBar Collaboration], PRL104 (2010) 021802





Results

Results : BAU



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

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

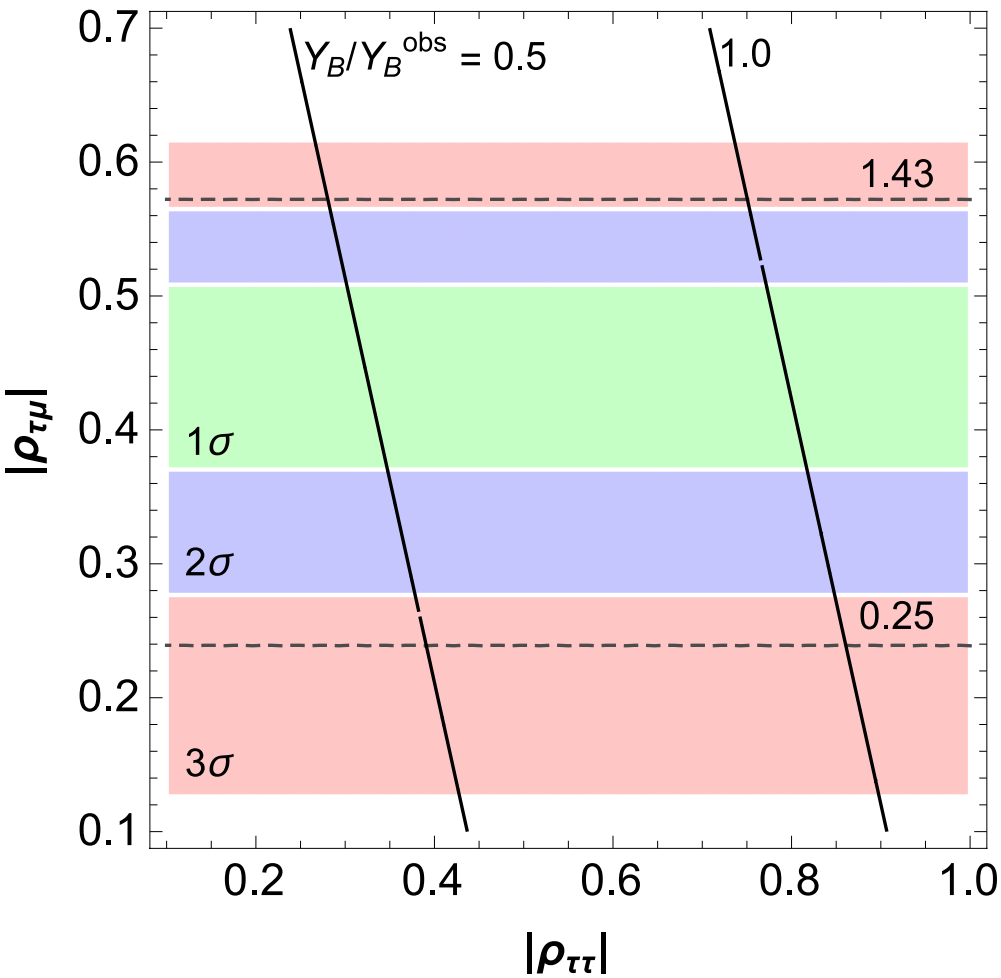
Nonzero $\rho_{\tau\tau}$ and $\rho_{\tau\mu}$ can produce the BAU.

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

Results : BAU at benchmark point

$$m_H = 350 \text{ GeV} \quad m_A = m_{H^\pm} = 400 \text{ GeV} \quad c_{\beta-\alpha} = 0.006$$

$$\phi_{\tau\mu} + \phi_{\mu\tau} = \pi/4, \ \phi_{\tau\tau} = \pi/2$$



Black lines :

$$Y_B/Y_B^{\rm obs} = 0.5, \ 1.0$$

Colored region (G,B,R) :

δa_μ within 1,2,3 sigma

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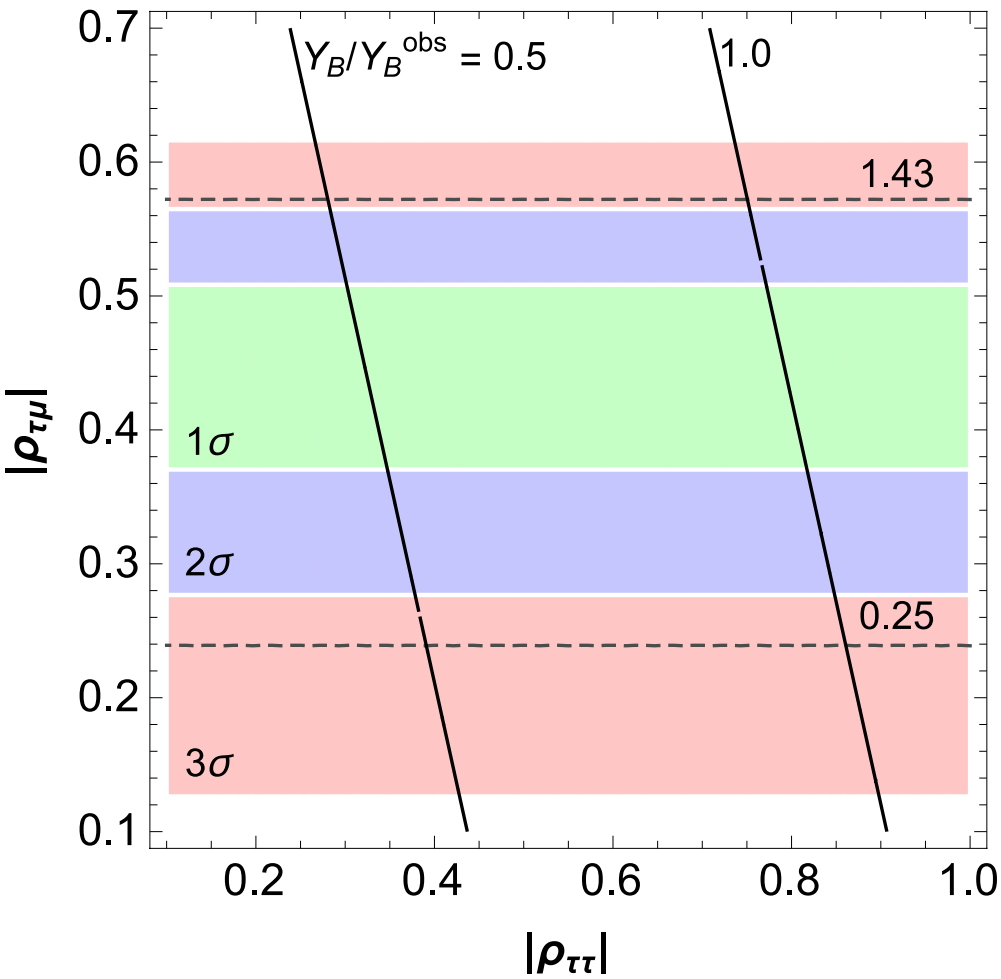

Black lines :

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Muon EDM:

$$d_\mu = -\frac{e\tan(\phi_{\tau\mu} + \phi_{\mu\tau})}{2m_\mu}\delta a_\mu$$

$$\sim 10^{-22} \ e \text{ cm}$$

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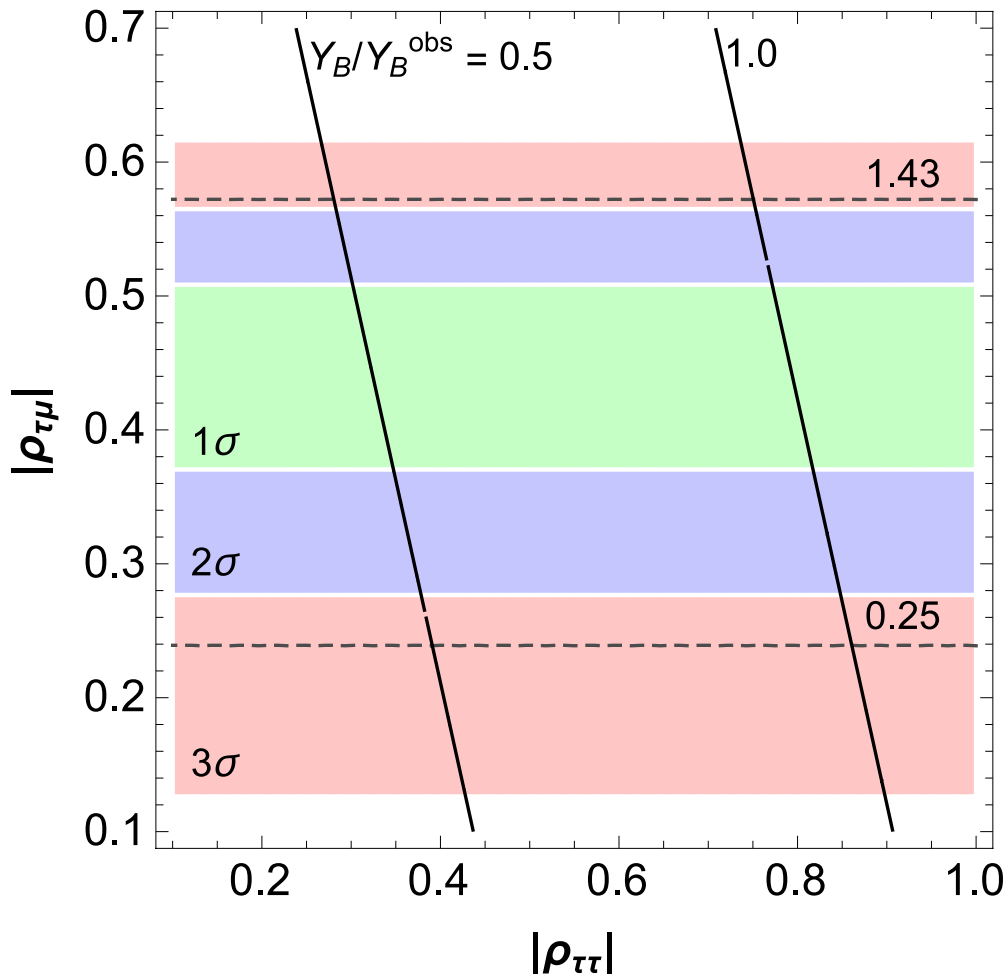

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Colored region (G,B,R) :

δa_μ within 1,2,3 sigma

Dashed line :

$$\text{Br}(h \to \mu\tau) = 1.43, \ 0.25\%$$

Results : BAU at benchmark point

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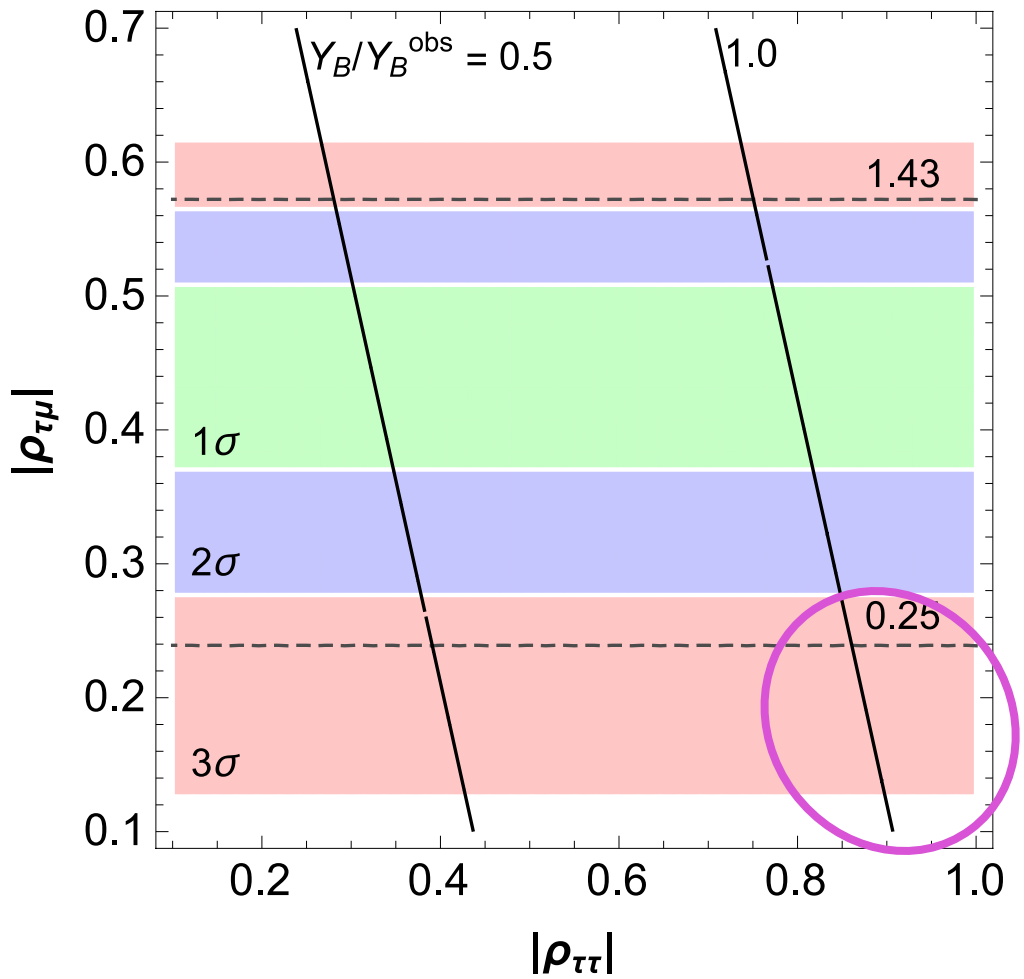
$$\phi_{\tau\mu} + \phi_{\mu\tau} = \pi/4, \ \phi_{\tau\tau} = \pi/2$$



Black lines :

$$Y_B/Y_B^{\rm obs} = 0.5, \ 1.0$$

Colored region (G,B,R) :

δa_μ within 1,2,3 sigma

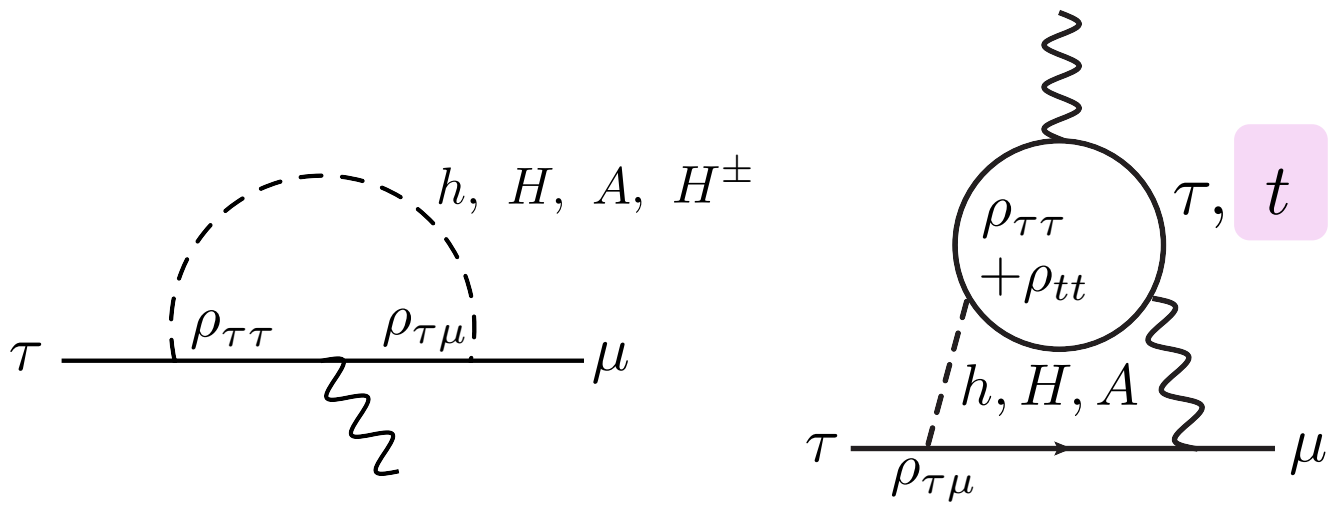
$$|\rho_{\tau\mu}| = 0.1 \sim 0.2$$

$$|\rho_{\tau\tau}| = 0.8 \sim 0.9$$

Tau decay

$\mathrm{Br}(\tau \to \mu\gamma)$ for $|\rho_{\tau\tau}| \gtrsim 0.1$ exceeds the current limit.

New top coupling ρ_{tt} cause an accidental cancellation between 1- and 2-loops.



Y. Omura. Eibun Senaha, K. Tobe,
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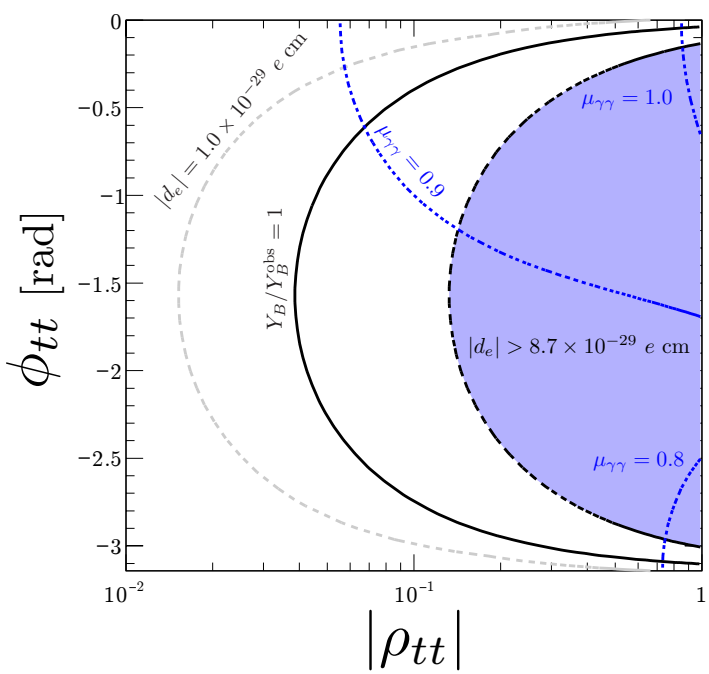
PLB776(2018)402 :

ρ_{tt} can produce enough BAU.

Successful region :

$$|\rho_{tt}| \gtrsim O(10^{-2})$$



Tau decay

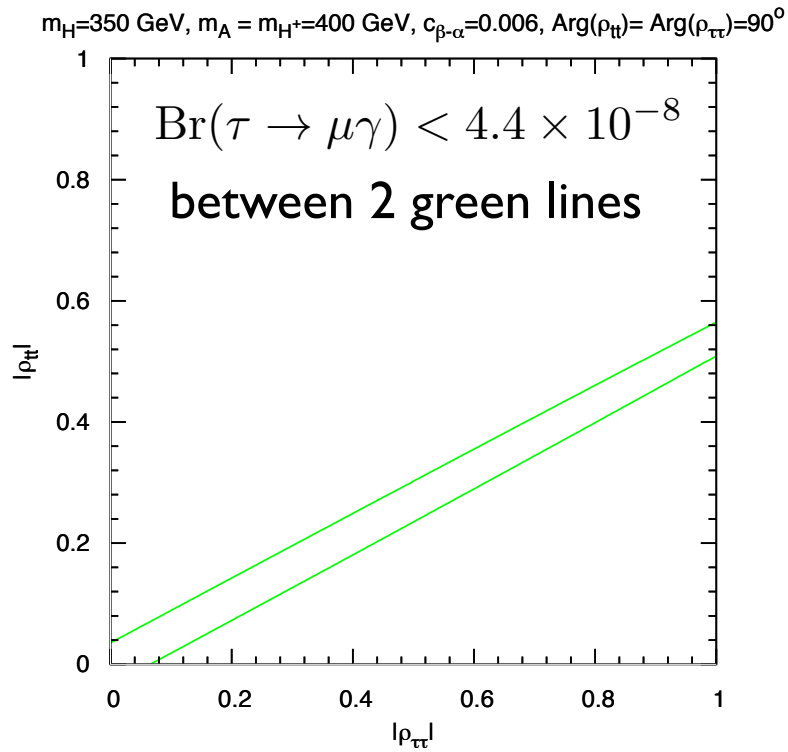
$\mathrm{Br}(\tau \to \mu\gamma)$ for $|\rho_{\tau\tau}| \gtrsim 0.1$ exceeds the current limit.

New top coupling ρ_{tt} cause an accidental cancellation between 1- and 2-loops.

For $|\rho_{tt}| \simeq 0.5$ and $|\rho_{\tau\tau}| \simeq 1$,

$$\mathrm{Br}\,(\tau \to \mu\gamma) \simeq 2 \times 10^{-8}$$

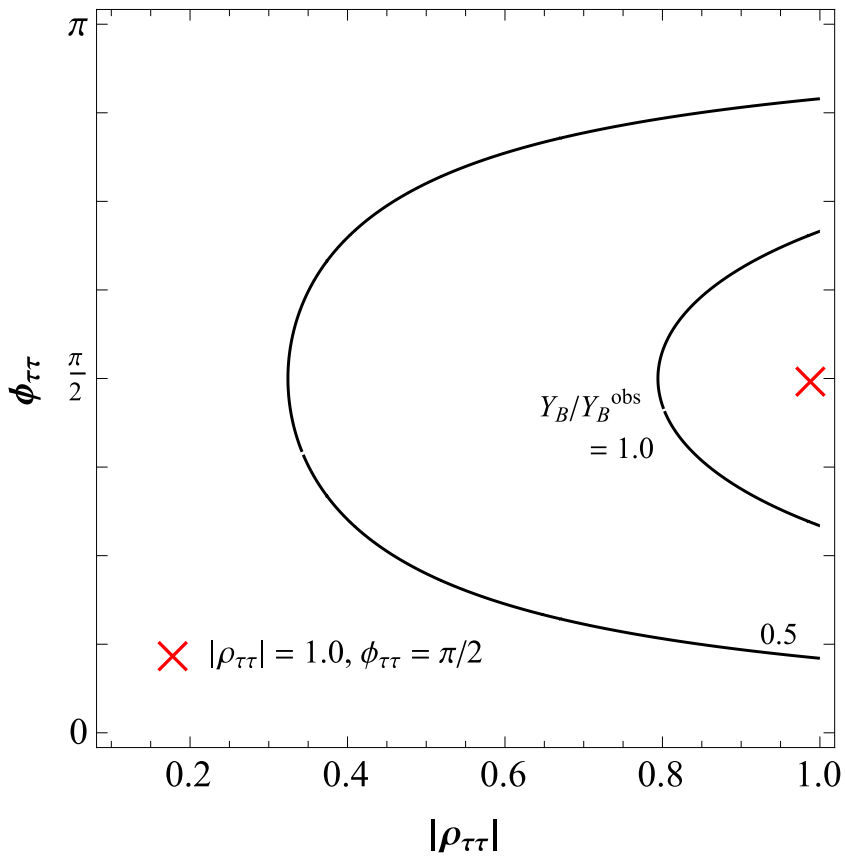
This setup can be examined by the tau decay.



Electron EDM

$m_H = 350\ \mathrm{GeV} \quad |\rho_{tt}| = 0.5 \quad \phi_{tt} = \pi/2$

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



Black lines :

$$Y_B/Y_B^{\rm obs} = 0.5,\ 1.0$$

Current limit :

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

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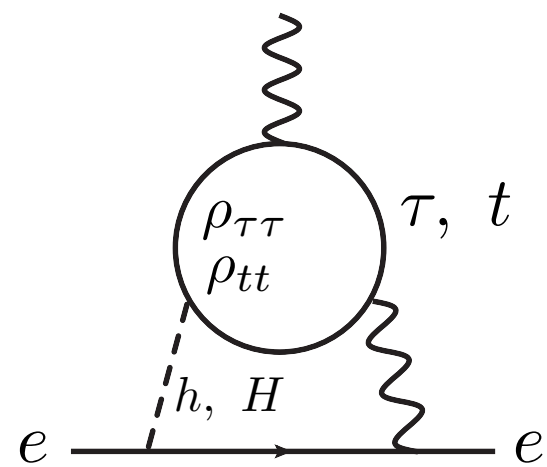
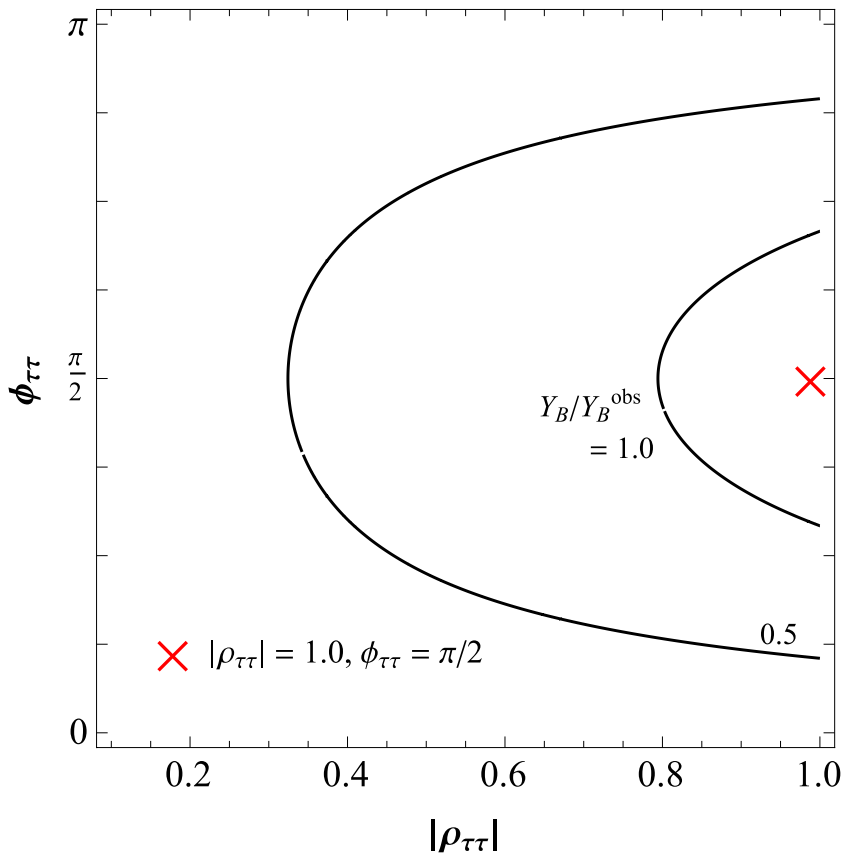


Current electron EDM constraint is avoided.

Electron EDM

$m_H = 350\ \mathrm{GeV} \quad |\rho_{tt}| = 0.5 \quad \phi_{tt} = \pi/2$

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



Black lines :

$$Y_B/Y_B^{\rm obs} = 0.5,\ 1.0$$

Current limit :

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

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× $(|\rho_{\tau\tau}|,\ \phi_{\tau\tau}) = (1.0,\ \pi/2)$

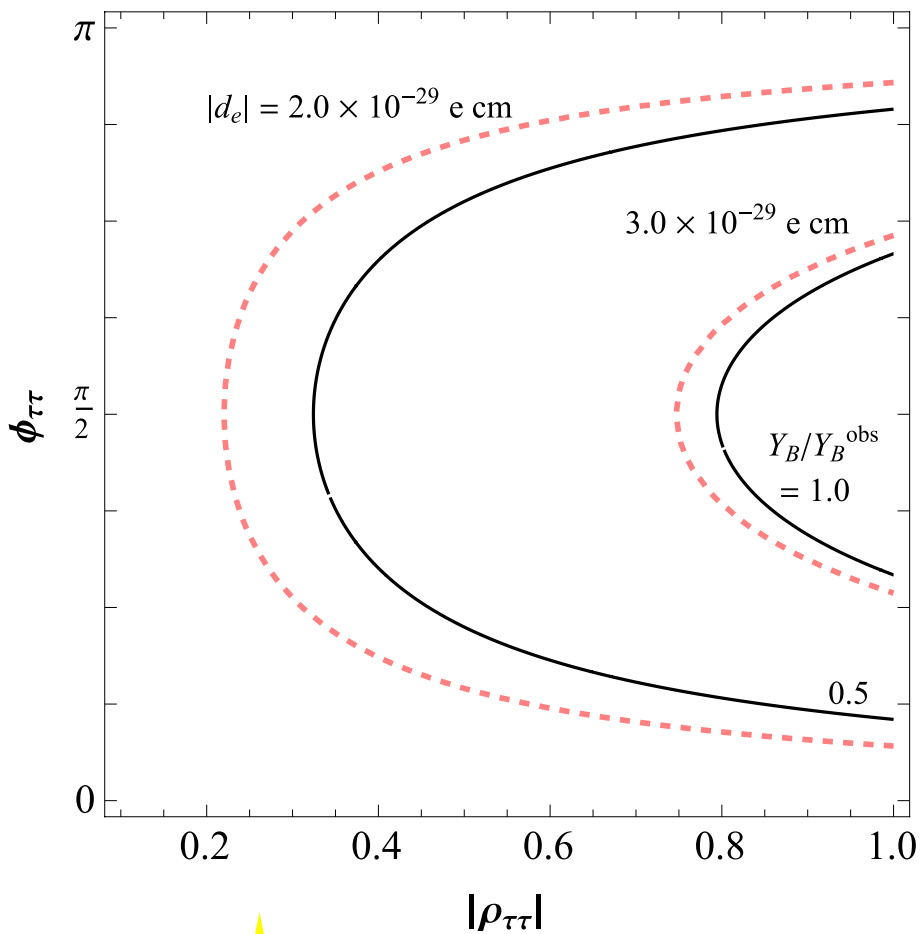
$$d_e = 3.5 \times 10^{-29}\ e\ \mathrm{cm}$$

Current electron EDM constraint is avoided.

Electron EDM

$m_H = 350\ \mathrm{GeV} \quad |\rho_{tt}| = 0.5 \quad \phi_{tt} = \pi/2$

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



Black lines :

$$Y_B/Y_B^{\rm obs} = 0.5,\ 1.0$$

Red dashed lines :

(Right)

$$d_e = 3.0 \times 10^{-29}\ e\ \mathrm{cm}$$

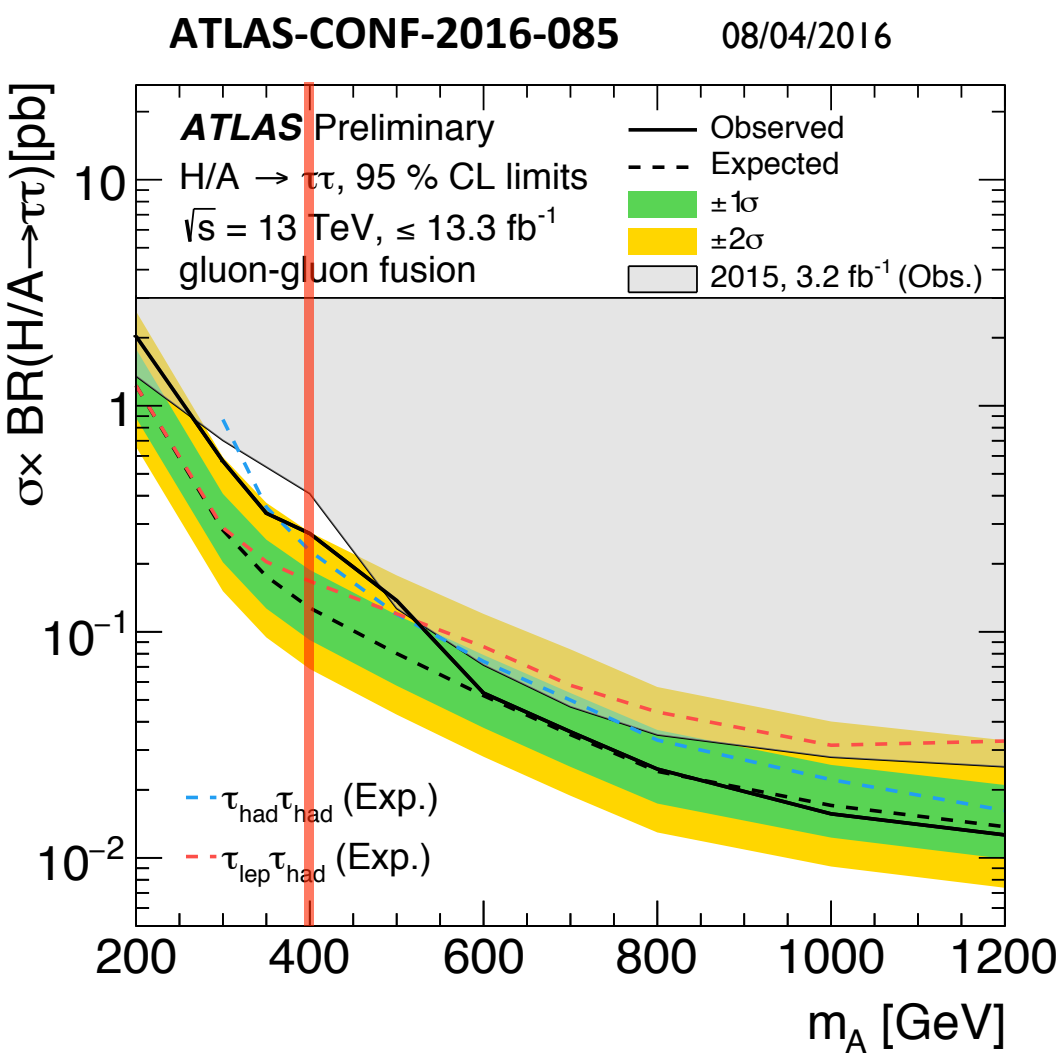
(Left)

$$d_e = 2.0 \times 10^{-29}\ e\ \mathrm{cm}$$

This benchmark point can be tested by the eEDM.

LHC constraint

$\sigma(gg \to A) \times \mathrm{Br}(A \to \tau\tau)$ gives a severe constraint on $\rho_{\tau\tau}$.



The current setup

$$|\rho_{\tau\tau}| \sim 0.9$$

$$|\rho_{\tau\mu}| = |\rho_{\mu\tau}| \sim 0.2$$

$$|\rho_{tt}| = 0.5$$

$$\sigma_{gg\to A} \times \mathrm{Br}(A \to \tau\tau) \sim 1.0 \text{ pb}$$

Other ρ couplings are needed!

Conclusion

- General 2HDM is one successful scenario for EWBG.

Yukawa : $-\mathcal{L}_Y \ni \bar{e}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right]e_{jR}h$

- We have discussed the possibility with $\rho_{\tau\tau},\ \rho_{\tau\mu},\ \rho_{\mu\tau}$.

  BAU can be explained if

$$|\rho_{\tau\tau}| = 0.8 \sim 1.0 \quad |\rho_{\tau\mu}| = 0.1 \sim 0.2 \quad |\rho_{tt}| = 0.5$$

- Extended setup with other ρ couplings can reduce $\mathrm{Br}(A \to \tau\tau)$. Ex) Coupling to neutrino

Thank you very much for your attention :)

Backup Slide

General Two Higgs Doublet Model

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

Approximate diagonalization

Assumption:

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

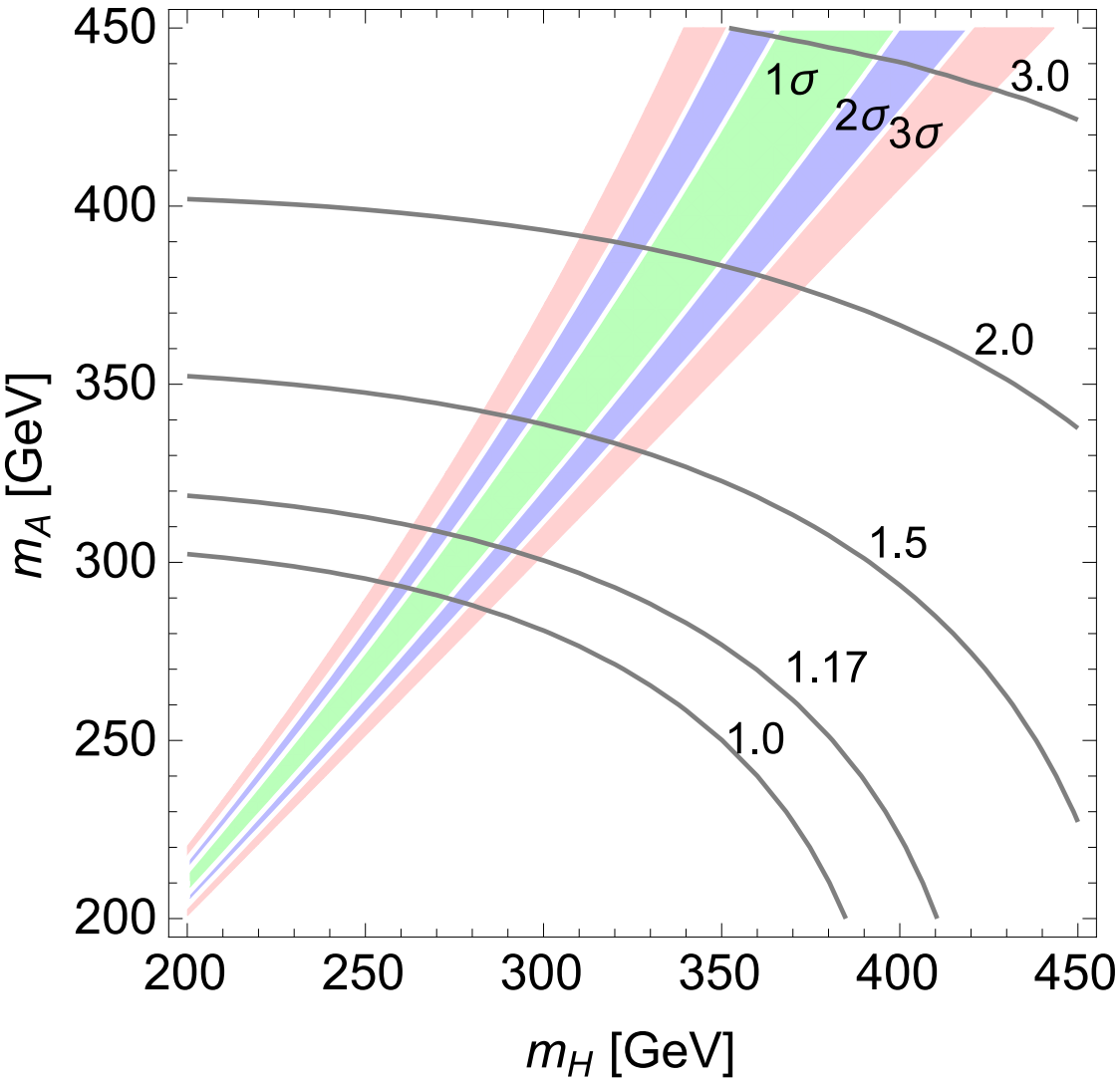
with $(Y_1)_{22} = (Y_2)_{22}$

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

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

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

Electroweak Phase Transition



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

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

Contour :

$$v_C/T_C$$