Top-driven electroweak baryogenesis

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

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K. Fuyuto, WS. Hou, and E. Senaha, PLB 776 (2018) 402

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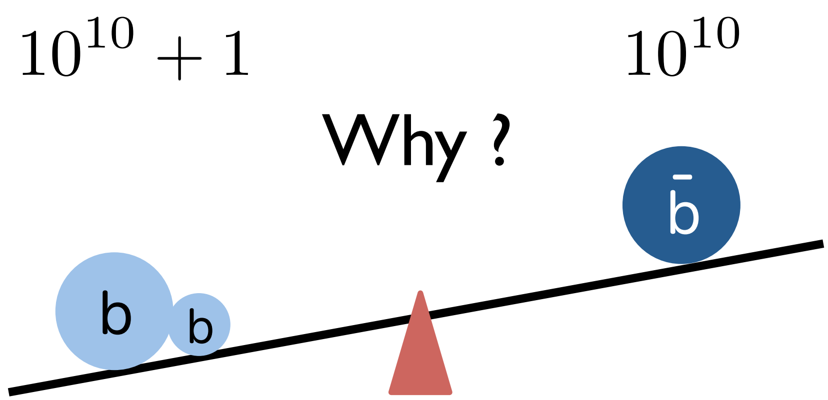
HPNP 2019 at Osaka U

Baryon Asymmetry of the Universe

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



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

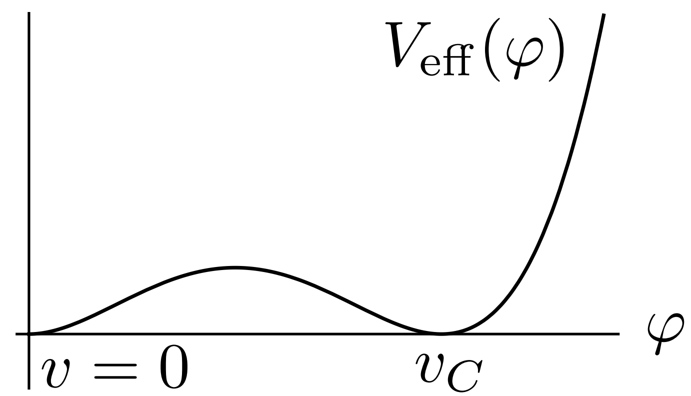
Baryon asymmetry is created during electroweak phase transition.

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

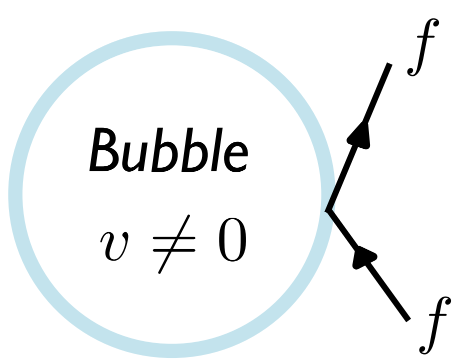
New Physics

The SM EWBG fails… so a successful scenario needs

✔ New Scalar for the 1st order PT



✔ New CP violation



New Physics

✦ *General Two Higgs Doublet Model*

✔ New Scalar for the 1st order PT

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

* Two doublets couple to fermions.

✔ New CP violation

Complex Yukawa couplings ← *Today's talk!*

Possibility of CPV Top Yukawa couplings

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

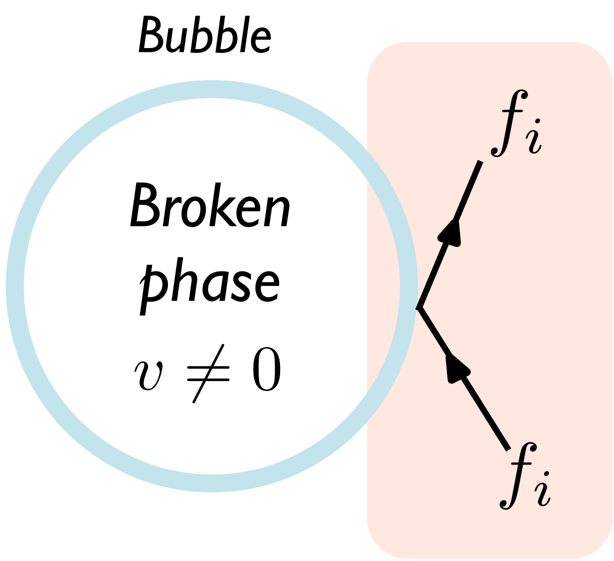
$$\Phi_{i=1,2} = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + ia_i) \end{pmatrix}$$

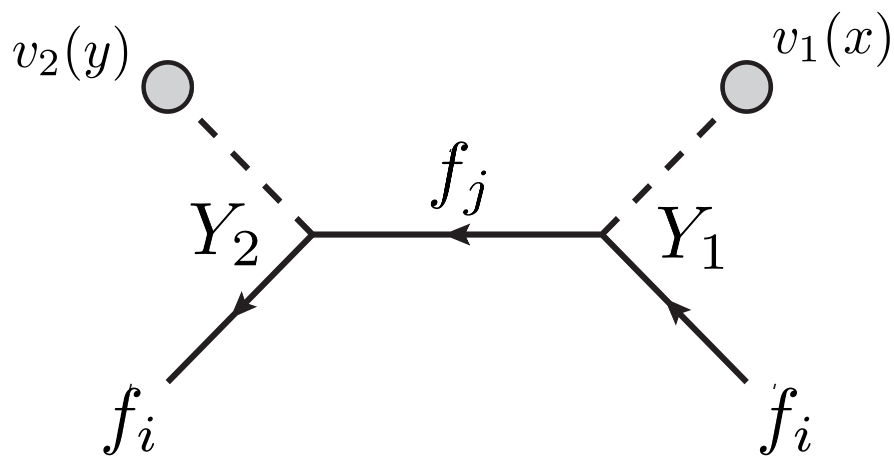
$$v_1 = v\cos\beta \qquad v_2 = v\sin\beta$$

General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

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





✔ We focus on top quark contribution.

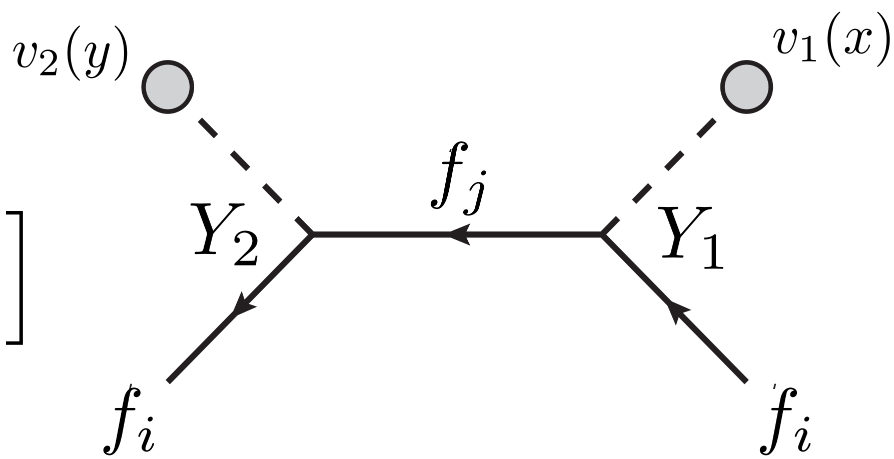
General Two Higgs Doublet Model

CP-violating interaction with expanding bubble:

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

Proportional to CP violation!

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



$\text{Im}\left[Y_1 Y_2^*\right]$ 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 : $\frac{m_u}{v}$

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

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, $Y_i \ (i = 1, 2)$ 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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Diagonalization:

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

Low-energy parameter:

$$V_L \left(-Y_1 s_\beta + Y_2 c_\beta \right) V_R = \rho_{ij}$$

Simplified case

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

BAU   Low energy

* Our numerical analyses take general structure of original Yukawa.

General Two Higgs Doublet Model

After diagonalizing mass matrices

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

Our setup :

ρ_{tt} : *CPV Top Yukawa*

ρ_{tc} : *CPV Flavor-changing top-charm Yukawa*

General Two Higgs Doublet Model

After diagonalizing mass matrices

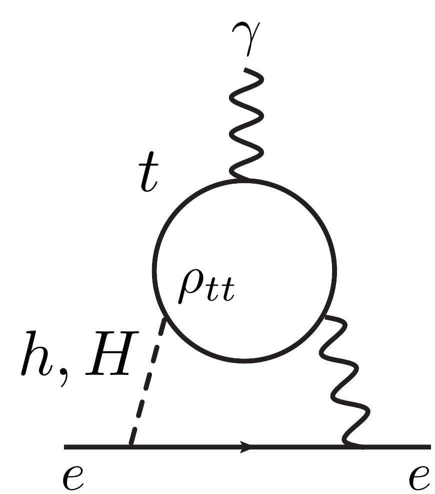
$$-\mathcal{L}_Y = \quad \bar{u}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right]u_{jR}h \quad +\text{h.c.}$$

Our setup :

ρ_{tt} : Electron EDM d_e

Higgs decay to 2 gamma

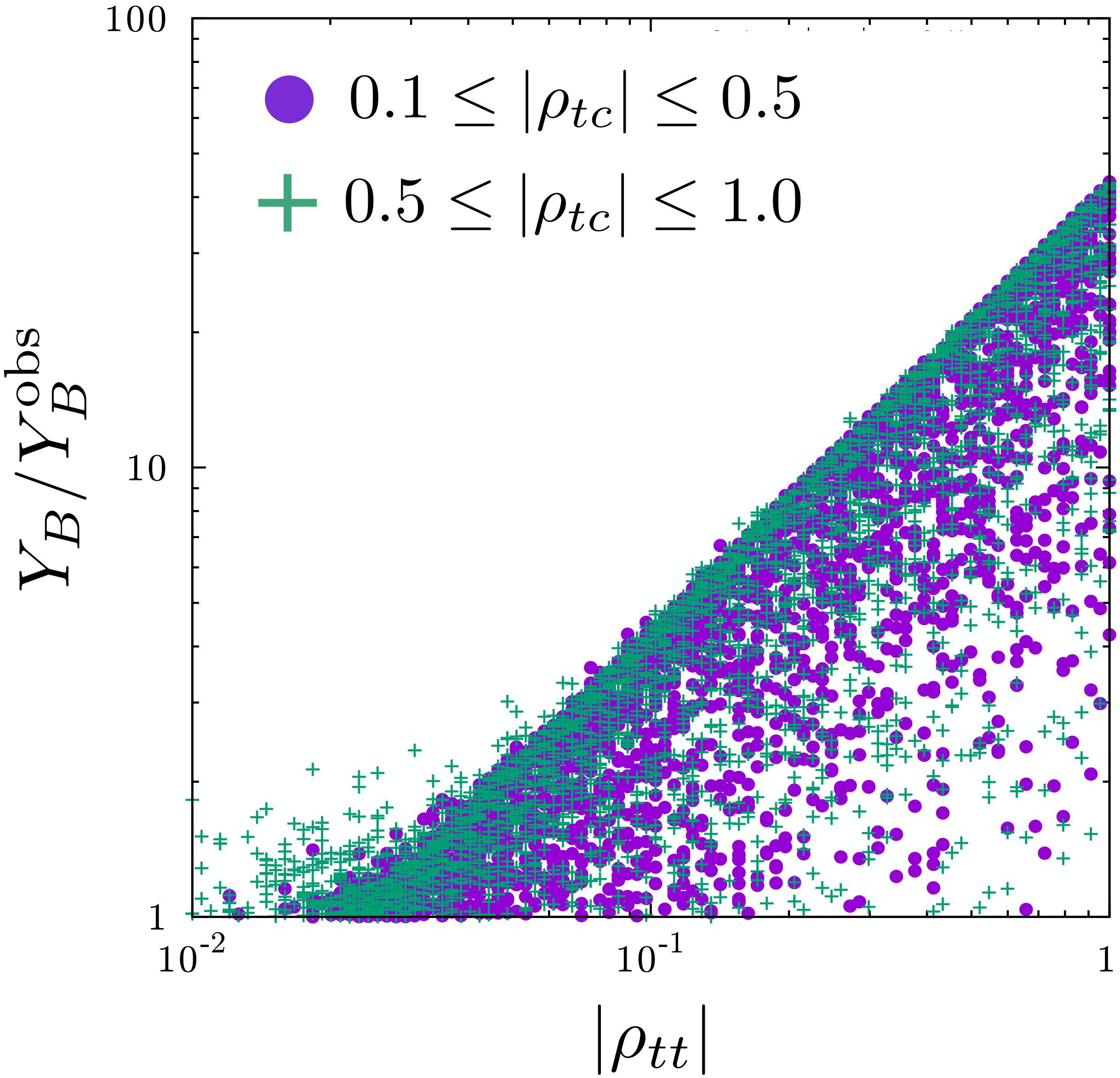
ρ_{tc} : $\text{Br}(t \to ch)$



✔ Can these couplings work for the BAU ?

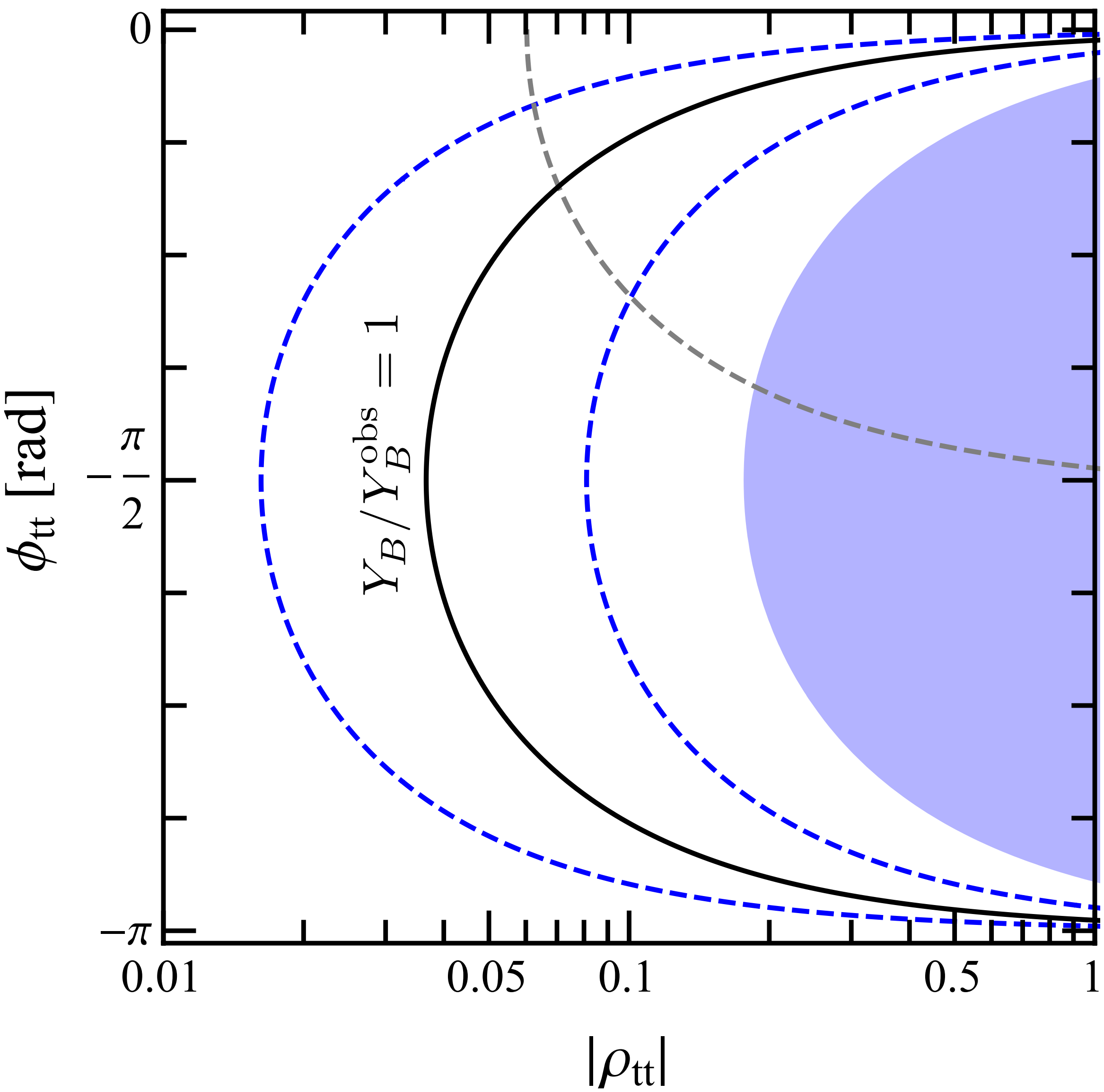
Random scan

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



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

Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4) \quad c_{\beta-\alpha} = 0.01$



Top decay :

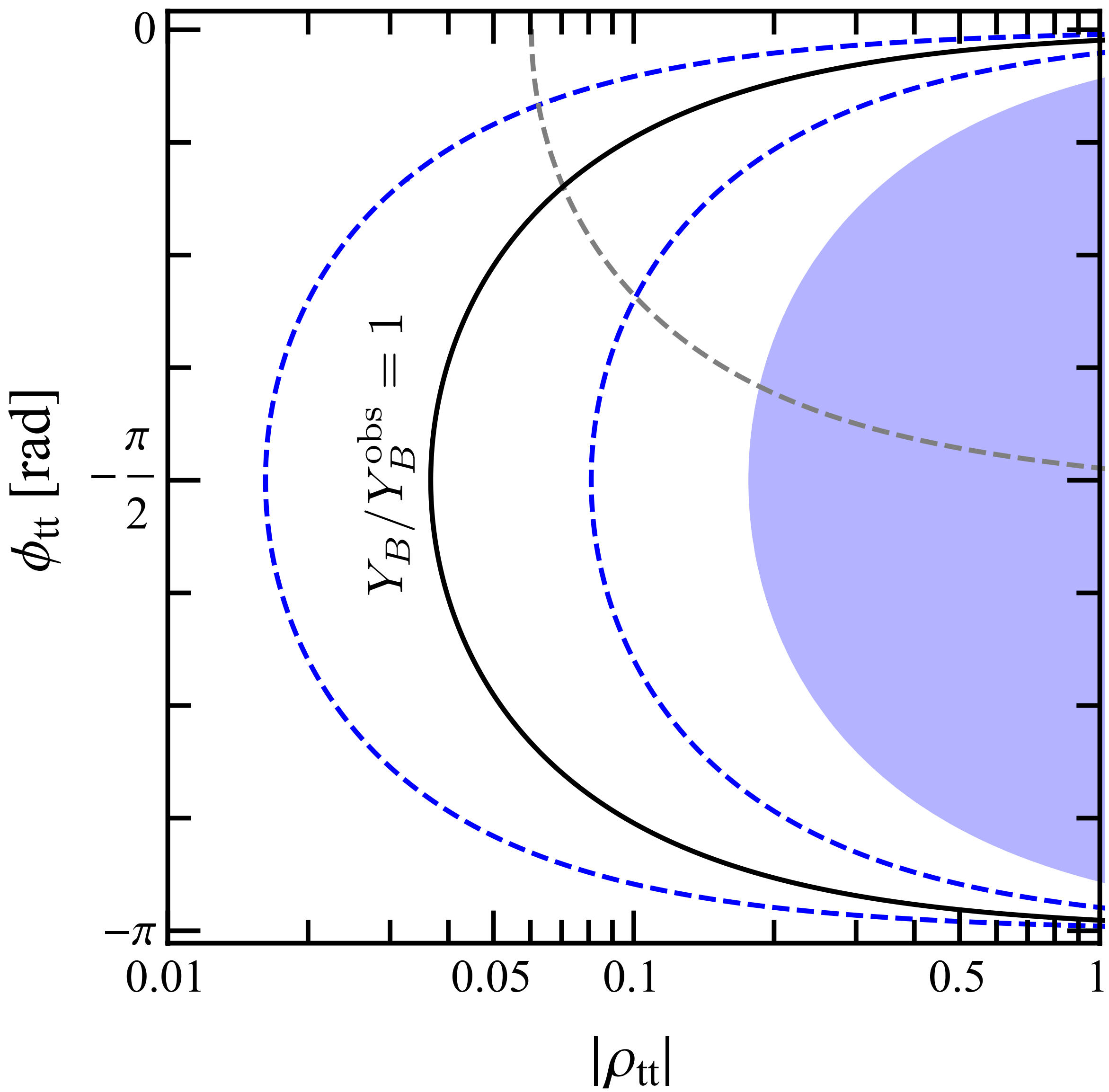
$$\mathrm{Br}(t \to ch) < \begin{matrix} 0.22\% \ \mathrm{(ATLAS)} \\ 0.40\% \ \mathrm{(CMS)} \end{matrix}$$

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

At benchmark:

$$\sim O(10^{-3})\%$$

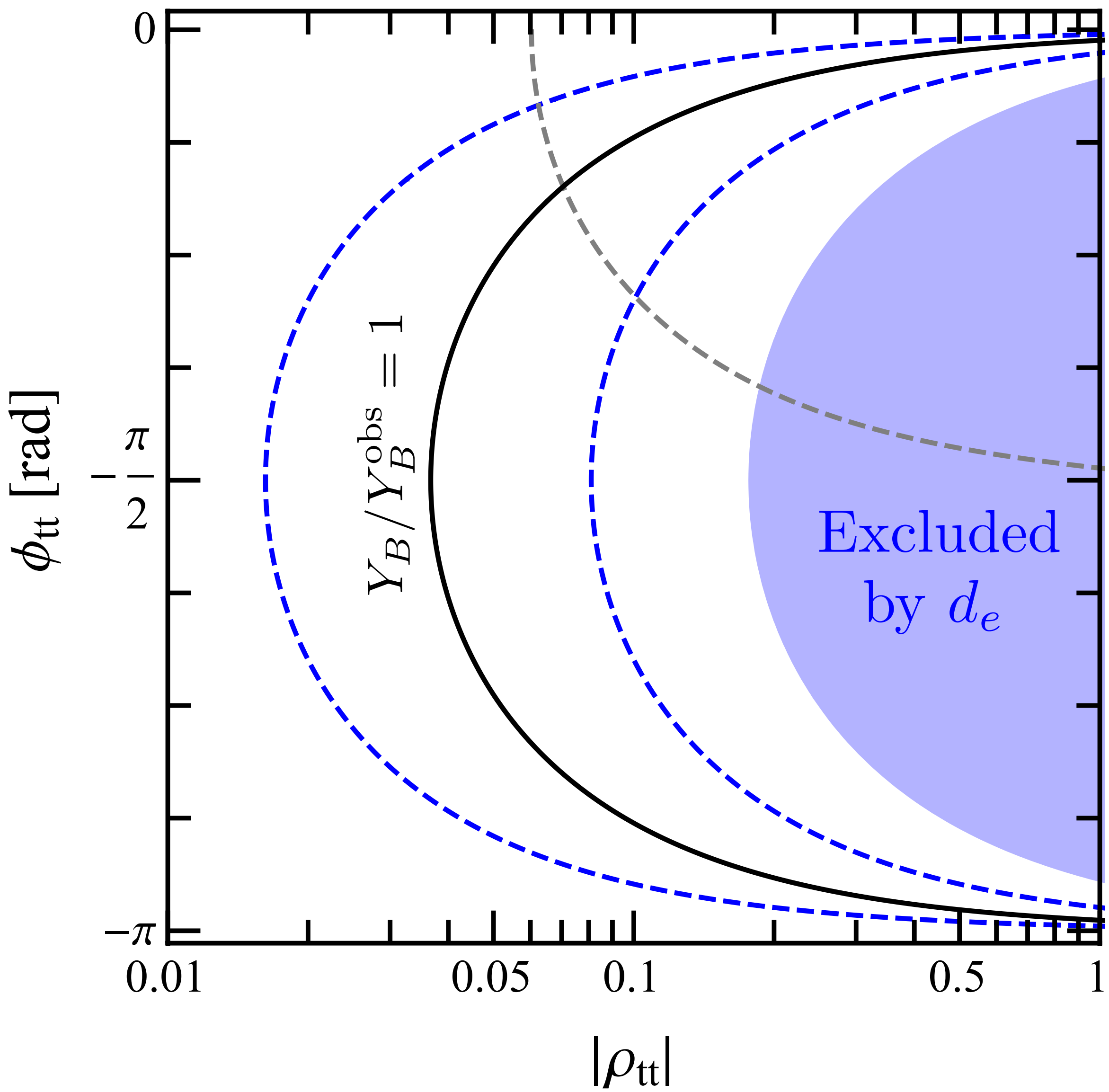
Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4)$ $c_{\beta-\alpha} = 0.01$



Black line :

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

Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4) \quad c_{\beta-\alpha} = 0.01$



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Electron EDM :

- Blue region

$$|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm}$$

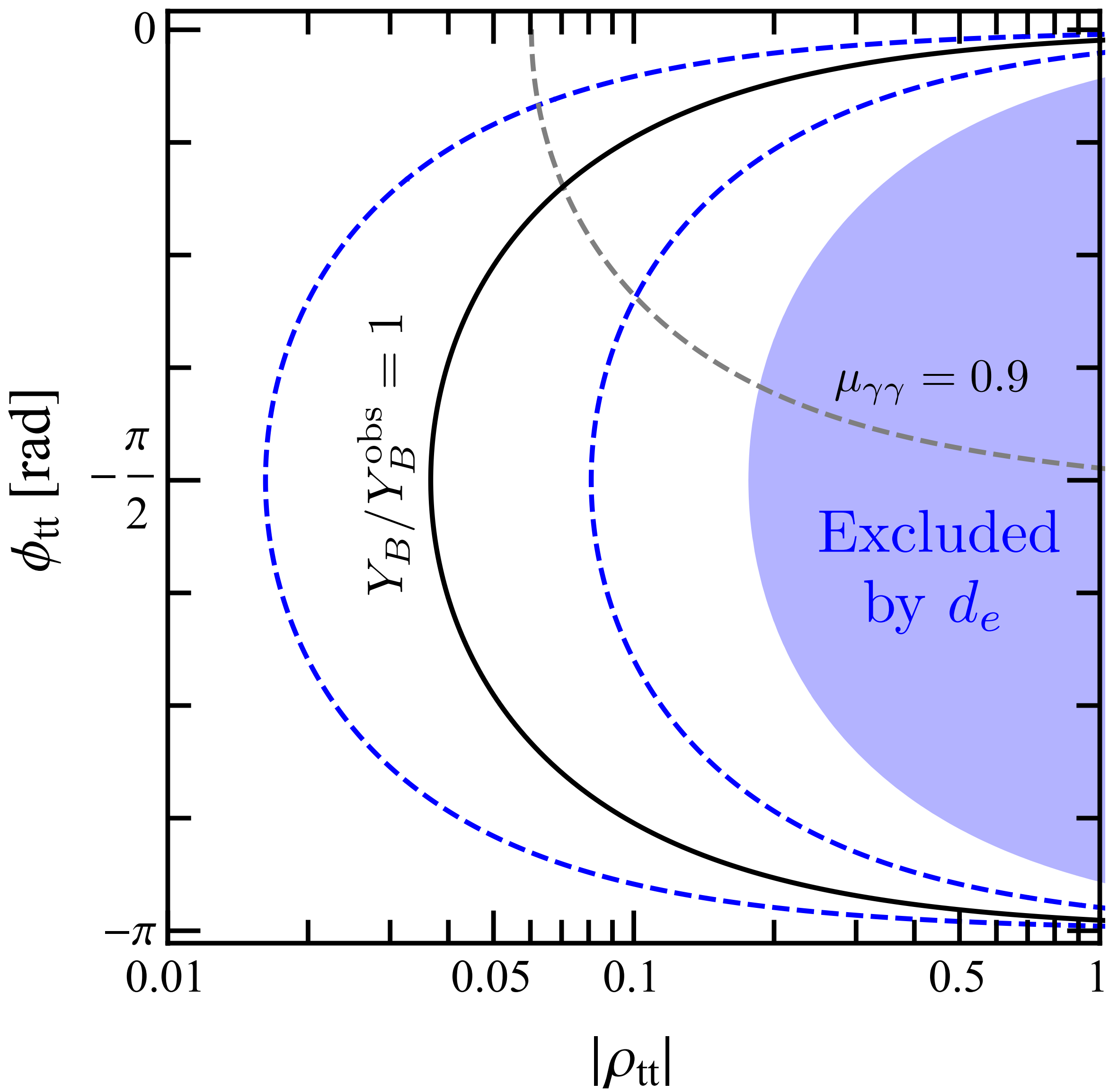
ACME Collaboration
Nature 562(2018)7727 355

- Blue dashed lines

(R) $5.0 \times 10^{-30}\ e\ \mathrm{cm}$

(L) $1.0 \times 10^{-30}\ e\ \mathrm{cm}$

Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4)$ $c_{\beta-\alpha} = 0.01$



Black line :

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

Higgs signal strength :

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

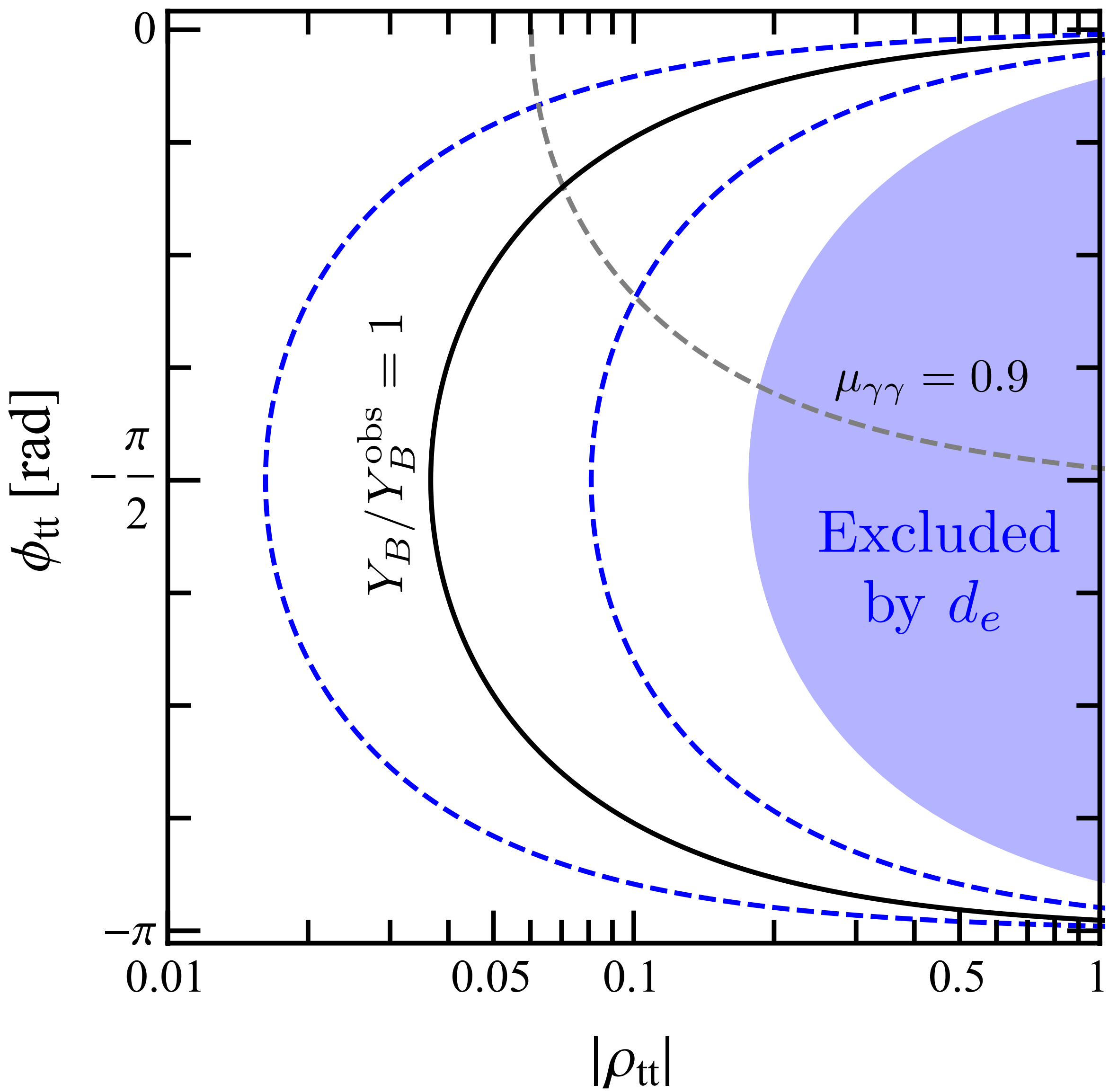
ATLAS, CMS Collaboration, JHEP1608(2016)045

- Gray dashed line

$$\mu_{\gamma\gamma} = 0.9$$

~ within 2 sigma

Benchmark point $(|\rho_{tc}|, \phi_{tc}) = (1.0, \pi/4) \quad c_{\beta-\alpha} = 0.01$



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ATLAS, CMS Collaboration, JHEP1608(2016)045

Successful and Testable scenario!

Conclusion

- EWBG is a testable scenario for explaining BAU.

- One possible extension of the SM is G2HDM.

Yukawa : $\bar{q}_L \left(Y_1 \tilde{\Phi}_1 + Y_2 \tilde{\Phi}_2 \right) u_R$

CPV interactions with bubble

- CPV Top coupling can produce enough asymmetry.

Top Yukawa : $\rho_{tt} \bar{t} t h$ $\quad 0.04 \lesssim \rho_{tt}$

Probed by the electron EDM and Higgs Physics

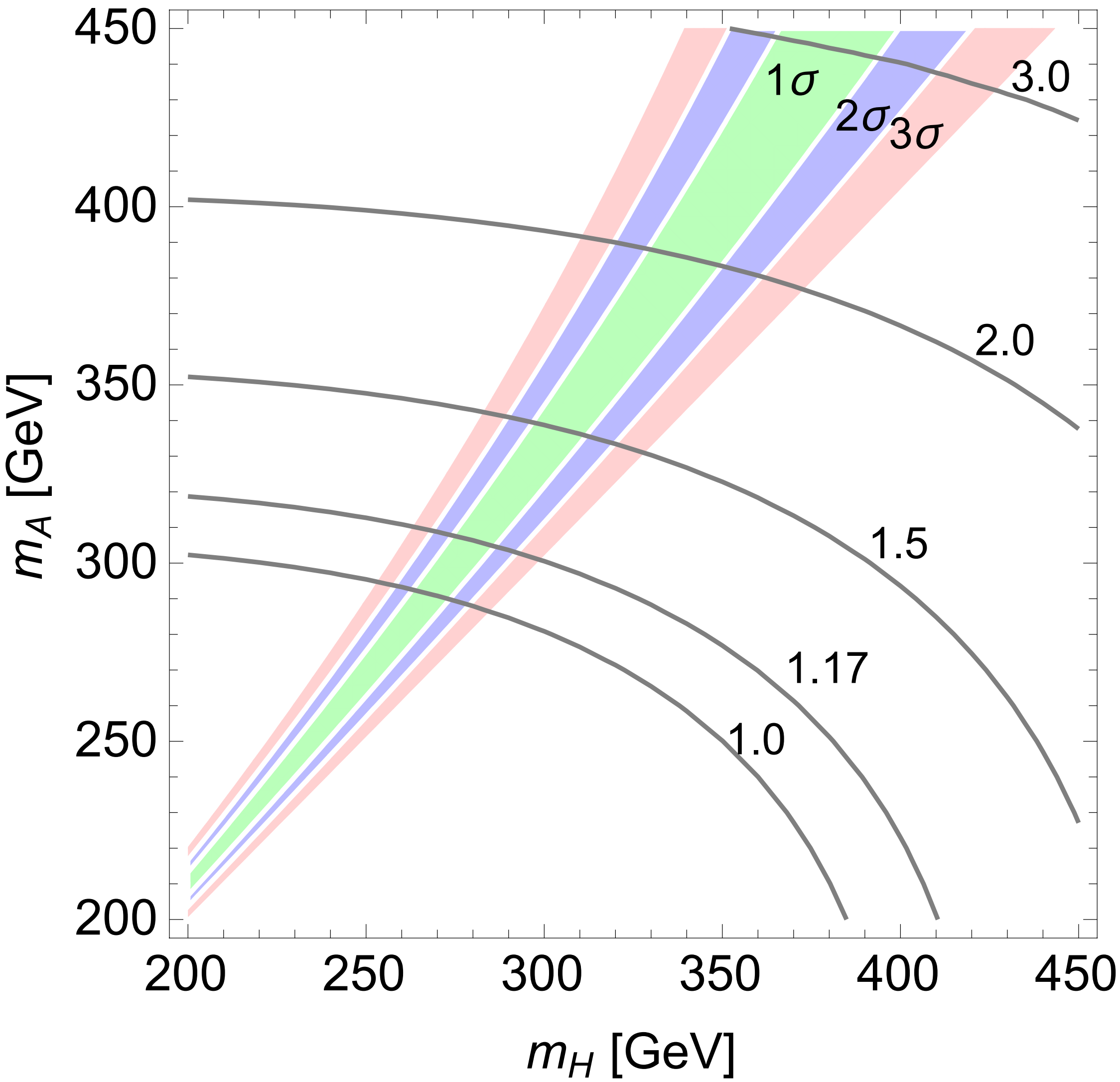
Thank you very much for your attention :)

Backup Slide

General Two Higgs Doublet Model

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

Electroweak Phase Transition



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

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

Contour :

$$v_C/T_C$$