Electroweak baryogenesis in two Higgs doublet model without EDM cancellation

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Introduction

PDG (2022)

- **Baryon asymmetry of the Universe (BAU)** $\eta_B^{obs} = \dfrac{n_B - n_{\bar{B}}}{s} \simeq 8 \times 10^{-11}$

- **Sakharov conditions and electroweak baryogenesis (EWBG)**

Sakharov (1967)

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

Kuzmin, Rubakov and Shaposhnikov (1985)

① Sphaleron process
② EW interaction with CP phase
③ EW first order phase transition

・All are satisfied around EW scale -> Testable baryogenesis scenario!

・In the SM, CP violation is not enough
EW phase transition is crossover

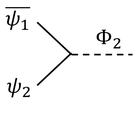
・Benchmark models： Singlet scalar extension, Two Higgs doublet model, …

- **Electric dipole moment (EDM): powerful tool to probe CPV**

EDMs	Current bounds	Expected limits
Electron	4.1×10^{-30} e cm JILA (2023)	$O(10^{-33})$ e cm Vutha, et al. (2018)
Neutron	1.8×10^{-26} e cm Abel, et al. (2020)	$O(10^{-28})$ e cm nEDM (2019)
Proton	2.1×10^{-25} e cm Sahoo (2017)	$O(10^{-29})$ e cm Alarcon, et al. (2022)

EDM in two Higgs doublet model (2HDM)

- **Two regimes to avoid FCNC** Discrete Z2 symmetry: $\Phi_2 \to -\Phi_2$

FCNC Yukawa 

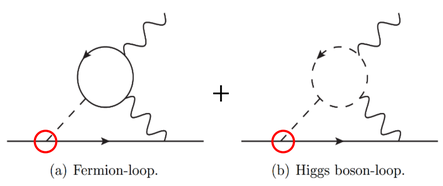
	Softly broken Z2 2HDM	General 2HDM
FCNC Yukawa	Forbidden	Assumed to be small
# of new CP phase	1	Many (more than 10)
eEDM to explain BAU	$O(10^{-28})$ e cm	Depends on Yukawa structure

Fromme et al. (2006); Dorsch et al. (2017); Basler et al. (2021), and more

Fuyuto, Hou, and Senaha (2019); Enomoto, Kanemura and YM (2021), (2022), and more

- **Do we really need cancellation b/w EDM diagrams?**

Fuyuto, Hou and Senaha (2019); Kanemura Kubota and Yagyu (2020); and more

$d_e \simeq$  +

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

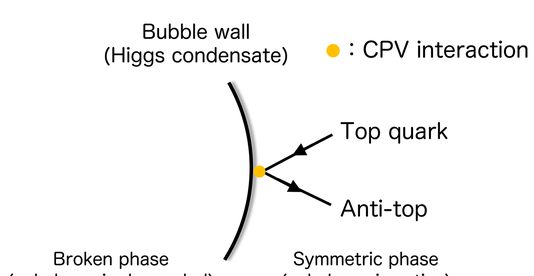
○ : electron-additional Higgs couplings

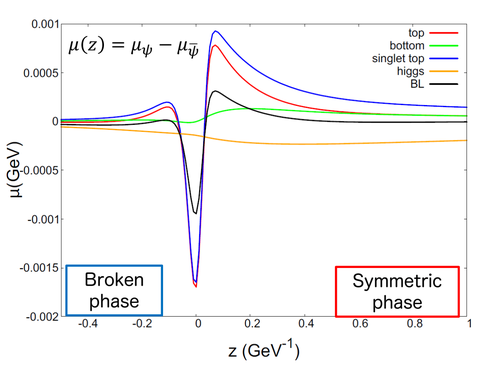
・This CPV coupling is not related to BAU (Why? -> see next)

・Can we consider a scenario, where only BAU-related-CPV is effective?

Top-transport scenario

- **CPV force acting on top and anti-top ∝ y_t**

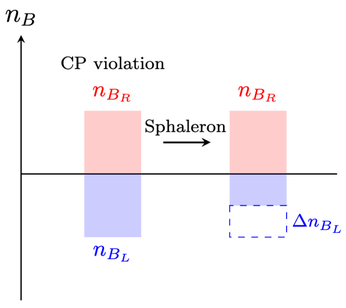




- **Inside bubbles, baryon # is conserved**

$\Gamma_{\rm sph}^{\rm brk} \propto e^{-v/T}$ Moore (1999)

$\Gamma_{\rm sph}^{\rm brk}(T_n) < H(T_n) \Longrightarrow v_n/T_n \gtrsim 1$ →Strongly first order PT



Lagrangian and minimal scenario

- **General 2HDM -> Minimal setup for EWBG**

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

Higgs basis
Davidson and Haber (2005)

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

Yukawa $\mathcal{L}_Y = -\sum_{k=1,2}\left(\overline{Q_L}Y_{k,u}^\dagger\tilde{\Phi}_k u_R + \overline{Q_L}Y_{k,d}\Phi_k d_R + \overline{L_L}Y_{k,l}\Phi_k e_R + \text{h.c.}\right)$

e.g.) Up type $Y_{1,u} = \text{diag}(y_u, y_c, y_t)$ $Y_{2,u} = \begin{pmatrix} \rho_{uu} & \rho_{cu} & \rho_{tu} \\ \rho_{uc} & \rho_{cc} & \rho_{tc} \\ \rho_{ut} & \rho_{ct} & \rho_{tt} \end{pmatrix}$

- **Rephasing invariants**

e.g.) hZZ coupling $\kappa_Z \simeq 1$ ➡ $|\lambda_6| \ll 1$ ➡ $\text{Im}[\lambda_5^*\lambda_7^2]$, $\text{Im}[\lambda_5\rho_{tt}^2]$, $\text{Im}[\lambda_7\rho_{tt}]$

・CPV force as a function of VEV φ

$$S_{\rm CPV} \propto \frac{y_t|\rho_{tt}|}{2}\{(\varphi_1\varphi_2' - \varphi_2\varphi_1')\sin(\arg[\rho_{tt}]) + (\varphi_3\varphi_1' - \varphi_1\varphi_3')\cos(\arg[\rho_{tt}])\}$$

・If $\lambda_6 \simeq \lambda_7 \simeq 0$, tree level potential has $\mathbb{Z}_2$ symmetry ($\boldsymbol{\Phi_2 \to -\Phi_2}$).
⇨ VEV of $\boldsymbol{\Phi_2}$ is suppressed, $\varphi_2, \varphi_3 \ll 1$.

・Essential rephasing invariant: $\text{Im}[\lambda_7\rho_{tt}]$

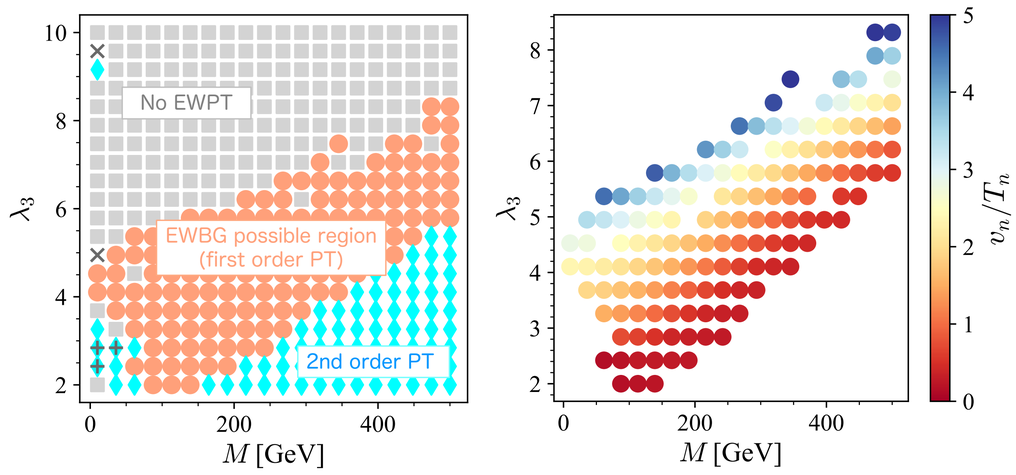
$\rho_{ij} = 0$ (except for ρ_{tt}) and $\lambda_4 = \lambda_5 = \lambda_6 = 0$

➡ $m_{H_2} = m_{H_3} = m_{H^\pm} \equiv m_\Phi$ ($\lambda_4 = \lambda_5$ is for T parameter)

Electroweak phase transition

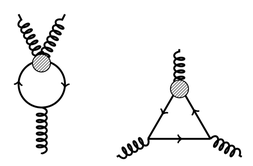
- **Several fates of the vacuum**

c.f.) $m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$
$m_{H_2} = m_{H_3} = m_{H^\pm}$



Two-loop top (C)EDM and BAU

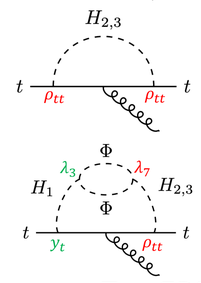
Weinberg operator (low energy side)



RGE flow

Kamenik et al. (2012); Hisano et al (2012); Kaneta et al. (2023);

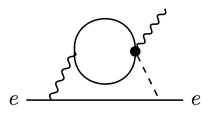
Top chromo EDM



$\propto \text{Im}[\lambda_5\rho_{tt}^2] = 0$ (minimal setup)

$\propto \text{Im}[\lambda_7\rho_{tt}]$

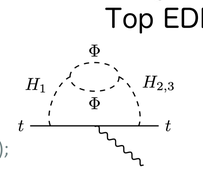
Electron EDM (low energy side)



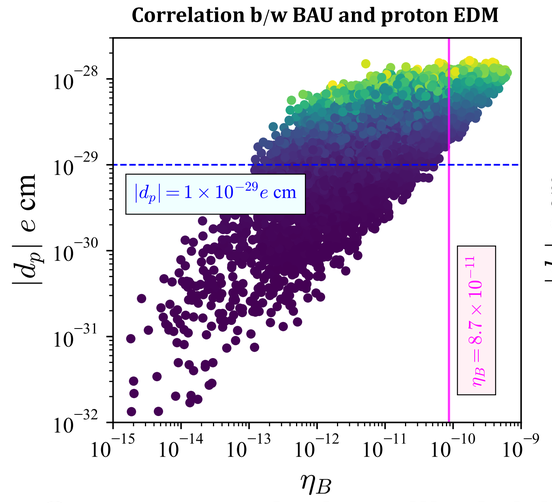
RGE flow

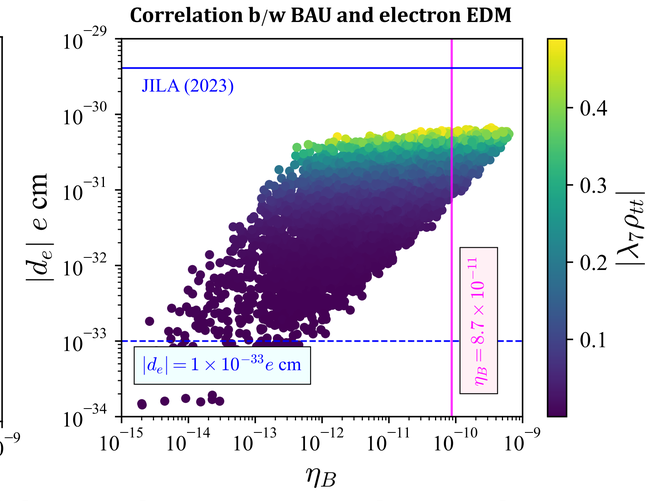
Cirigliano et al. (2016); Fuyuto and Ramsey (2017);

Top EDM



$\propto \text{Im}[\lambda_7\rho_{tt}]$





- **Our scenario is still viable under current bound, but would be tested in the future.**

- **Null results in the future**

⇨ **need a cancellation mechanism**