This is the accepted manuscript made available via CHORUS. The article has been published as:

**Lepton-flavored electroweak baryogenesis**

Huai-Ke Guo, Ying-Ying Li, Tao Liu, Michael Ramsey-Musolf, and Jing Shu

Phys. Rev. D **96**, 115034 — Published 29 December 2017

DOI: [10.1103/PhysRevD.96.115034](https://doi.org/10.1103/PhysRevD.96.115034)
Lepton-Flavored Electroweak Baryogenesis

Huai-Ke Guo,1,2 Ying-Ying Li,3 Tao Liu,3 Michael Ramsey-Musolf,1,4 and Jing Shu2,5,6

1Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts Amherst, Amherst, MA 01003, USA
2CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
3Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong S.A.R., P.R.China
4Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125 USA
5CAS Center for Excellence in Particle Physics, Beijing 100049, China
6School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100190, P. R. China

We explore lepton-flavored electroweak baryogenesis, driven by CP-violation in leptonic Yukawa sector, using the $\tau - \mu$ system in the two Higgs doublet model as an example. This setup generically yields, together with the flavor-changing decay $h \rightarrow \mu\gamma$, a tree-level Jarlskog-invariant that can drive dynamical generation of baryon asymmetry during a first-order electroweak phase transition and results in CP-violating effect in the decay $h \rightarrow \tau\tau$. We find that the observed baryon asymmetry can be generated in parameter space compatible with current experimental results for the decays $h \rightarrow \tau\mu$, $h \rightarrow \tau\tau$ and $\tau \rightarrow \mu\gamma$, as well as the present bound on the electric dipole moment of the electron. The baryon asymmetry generated is intrinsically correlated with the CP-violating decay $h \rightarrow \tau\tau$ and the flavor-changing decay $h \rightarrow \tau\mu$, which thus may serve as “smoking guns” to test lepton-flavored electroweak baryogenesis.

Introduction. Explaining the origin of the baryon asymmetry of the universe (BAU) is a forefront challenge for fundamental physics. The BAU is characterized by the baryon density $n_B$ to entropy $s$ ratio $Y_B = \frac{n_B}{s} = (8.61 \pm 0.09) \times 10^{-11}$ [1]. According to Sakharov [2], generation of a non-vanishing $Y_B$ requires three ingredients in the particle physics of the early universe: non-conservation of baryon number (B); C- and CP-violation (CPV); and out of equilibrium dynamics (assuming CPT conservation). While the Standard Model (SM) of particle physics contains the first ingredient in the guise of electroweak sphalerons, it fails with regard to the remaining two. Physics beyond the SM is, thus, essential for successful baryogenesis.

Electroweak baryogenesis (EWBG) [3] is among the most theoretically well-motivated and experimentally testable scenarios, as it ties BAU generation to electroweak sphalerons, it fails with regard to the remaining two. Physics beyond the SM is, thus, essential for successful baryogenesis.

An extended Yukawa sector, e.g., the one involving leptons, may remedy this SM shortcoming. Phenomenologically, the report by the CMS collaboration of a signal for the charged lepton flavor violating (CLFV) Higgs boson decay $h \rightarrow \tau\mu$ (2.4 $\sigma$ significance) at $\sqrt{s} = 8$ TeV [5] hints at a possible richer leptonic Yukawa sector, despite no evidence for this decay mode has been observed in the ATLAS analysis at $\sqrt{s} = 8$ TeV [7], and in a preliminary CMS study at $\sqrt{s} = 14$ TeV [6]). Should an extended leptonic Yukawa sector exist, then the accompanying new CPV phases may provide sources for EWBG that do not suffer from the suppression associated with SM quark Yukawa sector.

Motivated by these considerations, we study the viability of “lepton flavored EWBG”, a scenario that relies on both CLFV and leptonic CPV. For concreteness, we use a variant of the type III two Higgs doublet model (2HDM) [8] with generic leptonic Yukawa textures [9] and focus on the $\tau - \mu$ families as an example. For a representative choice of Yukawa texture, we derive the CPV source for the EWBG quantum transport equations [10, 11] in terms of the relevant Jarlskog invariants $J_{\phi\gamma}$ and $\Im \frac{\sigma_{\phi\gamma}}{\mu\gamma} = 0$, parameterized by a CPV phase $\phi_\gamma$. Measurements of CPV asymmetries in $h \rightarrow \tau^+\tau^-$, as discussed in Ref. [12], would provide a test of this baryogenesis mechanism. Taking into account present constraints from measurements of $\Gamma(h \rightarrow \tau^+\tau^-)$ and limits on $\Gamma(\tau \rightarrow \mu\gamma)$ we find that a $\mathcal{O}(10^3)$ determination of $\phi_\gamma$ would probe this scenario at a significant level.

Model Setup. We focus on CPV in the $\mu - \tau$ sector of type III 2HDM, assuming a CP-conserving scalar potential. The $SU(2)_L \times U(1)_Y$ invariant weak eigenbasis lepton Yukawa interaction is

$$L_{\text{Yukawa}}^{\text{Lepton}} = -\mathcal{L} \left[ Y_{1,ij} \Phi_1 + Y_{2,ij} \Phi_2 \right] e_R^i + h.c.,$$

where $\Phi_{1,2}$ are the two Higgs doublets with the same hypercharge, $L^i$ and $e_R^i$ are left-handed lepton doublet and right-handed lepton singlet in weak basis, with the
family index \(i, j = 2, 3\). Then we can uniquely define a Jarkovsky invariant as the imaginary part of \([13, 14]\):

\[
J_A = \frac{1}{v^2\mu_{12}^{\overline{H}B}} \sum_{a,b,c=1}^2 v_a v_b^* \mu_{bc} \text{Tr} \{Y_a Y_b^*\},
\]

(2)

with the power of Yukawa coupling (or mass parameter of fermions) product being two. Here \(v_a = \sqrt{2} \langle \Phi_a^0 \rangle\) is vacuum expectation value (vev) of neutral Higgs fields, \(\mu_{bc}\) is the coefficient of \(\Phi_a^0 \Phi_b^0\) in the potential, and the trace is taken over flavor space. \(J_A\) is normalized to be a dimensionless quantity by dividing a factor \(v^2\mu_{12}^{\overline{H}B}\), where \(\mu_{12}^{\overline{H}B} = \frac{1}{2}(\mu_{22} - \mu_{11})\sin 2\beta + \mu_{12}\cos 2\beta\) is a quadratic Higgs coupling defined in “Higgs basis” \([8, 14]\): \(H_1 = \cos \beta \Phi_1 + \sin \beta \Phi_2; H_2 = -\sin \beta \Phi_1 + \cos \beta \Phi_2\); \(\langle H_1^0 \rangle = v/\sqrt{2} = 174\text{ GeV}\) and \(\langle H_2^0 \rangle = 0\).

The mass matrix for fermions is defined as \(M = (v_1 Y_1 + v_2 Y_2)/\sqrt{2}\) in the weak basis, with a determinant of \(M^\dagger M\) or \(M\) close to zero (since \(m_{\nu_\alpha} \approx 0\)). For illustration, we choose a texture with \(Y_{1,22} = Y_{1,23} = 0\), with \(j = 1, 2\). This immediately yields \(\text{Im}(J_A) = -\text{Im}(Y_{1,32} Y_{2,32} + Y_{1,33} Y_{2,33})\) or

\[
\text{Im}(J_A) = -\text{Im}(Y_{1,32} Y_{2,32}),
\]

(3)

with a further assumption \(Y_{1,33} = Y_{2,33}\). The diagonalization condition \(|M_{32}|^2 + |M_{33}|^2 = m_2^2\) immediately gives \(|M_{32}| \leq m_\tau\), and fixes the value of \(|Y_{1,33}| = |Y_{2,33}|\). Since the proposed mass matrix is not invariant under basis transformation of \(\Phi_1\) and \(\Phi_2\), \(\tan \beta = v_2/v_1\) becomes an independent parameter (similar to what happens in type II 2HDM). Thus this setup contains five relevant and independent parameters: \(\tan \beta, \alpha\) (the mixing angle in the CP-even Higgs sector), \(|Y_{2,32}|\), \(r_{32} = |Y_{1,32}|/|Y_{2,32}|\) and \(\text{Im}(J_A)\). Noticed that a strongly first order EWPT, necessary for successful EWBG, strongly favors \(\tan \beta \sim 1\) in the Higgs alignment limit \([15]\), where we choose to work below. This realization is less sensitive to the other three parameters, which contribute to the effective Higgs potential at finite temperature at quantum level only.

In the mass basis for both fermions and Higgs bosons, the \(\tau\) Yukawa interaction is then parameterized as

\[
\begin{align*}
-\frac{1}{v} \tau H [m_\tau \beta - \alpha + N_{\tau\tau} c_{\beta - \alpha}] \\
+ H (m_\tau \beta - \alpha - N_{\tau\tau} s_{\beta - \alpha}) + i AN_{\tau\tau} \rangle + \text{h.c.},
\end{align*}
\]

(4)

where \(\beta - \alpha\) is invariant under the basis transformation in Higgs family space \([16]\). The SM-like Higgs boson \(h\) receives two contributions to its coupling. The first one results from its \(H_2^0\) component which is aligned with the \(\tau\) mass. Another one is related to its \(H_2^0\) component which is proportional to \(N_{\tau\tau}\), the Yukawa coupling of \(H_2^0\) with \(\tau\) leptons, with

\[
\begin{align*}
\text{Re}(N_{\tau\tau}) &= \frac{v^2 \mu_{12}^{\overline{H}B} \text{Re}(J_A) - 2 \mu_{11}^{\overline{H}B} m_\tau^2}{2 \mu_{12}^{\overline{H}B} m_\tau}, \\
\text{Im}(N_{\tau\tau}) &= \frac{v^2 \text{Im}(J_A)}{2 m_\tau}.
\end{align*}
\]

(5)

The CLFV interactions are completely controlled by the Yukawa coupling of \(H_2^0\), \(N_{\tau\mu}\),

\[
-\frac{N_{\tau\mu}}{v} \tau H [(\beta - \alpha) h - s_{\beta - \alpha} H + i A] + \text{h.c.},
\]

(6)

With \(\tan \beta = 1\), the expression in terms of weak basis parameters is given by

\[
N_{\tau\mu} = e^{i\delta} \frac{N_{\tau\tau} M_{33}}{M_{22}}.
\]

(7)

Here \(\delta\) is an un-physical phase undetermined in the diagonalization procedure which can be removed by field redefinition. For later convenience, we also have for \(\tan \beta = 1\)

\[
\text{Re}(J_A) = \frac{1}{2} (|Y_{2,32}|^2 - |Y_{1,32}|^2) + \frac{2 m_\tau^2 \mu_{12}^{\overline{H}B}}{v^2 \mu_{12}^{\overline{H}B}}.
\]

(8)

Finally the charged Higgs Yukawa interactions are governed by \(-\sqrt{2}/vHH^* Y_{2,32}^* Y_{1,32} + \text{h.c.}\).

Given the four free parameters left for describing tree-level Yukawa interactions of the \(\nu - \tau\) system, we present various phenomenological results (e.g., \(h \to \tau\tau\), \(\tau\mu\)) and the BAU analysis in terms of the effective \(h\tau\tau\) coupling \([17]\) (see Fig. 1)

\[
\frac{-m_{\tau}}{v} [\text{Re}(y_{\tau}) \bar{\tau} + \text{Im}(y_{\tau}) \bar{\tau} i \gamma_5 \tau] h
\]

(9)

with benchmark values assigned to \(r_{32}\) and \(\beta - \alpha\). Here

\[
\begin{align*}
\text{Re}(y_{\tau}) &= s_{\beta - \alpha} + \frac{c_{\beta - \alpha}}{m_\tau} \text{Re}(N_{\tau\tau}), \\
\text{Im}(y_{\tau}) &= \frac{c_{\beta - \alpha}}{m_\tau} \text{Im}(N_{\tau\tau}).
\end{align*}
\]

(10)

Then, the condition \(|M_{32}| \leq m_\tau\) imposes a constraint at the \((\text{Re}(y_{\tau}), \text{Im}(y_{\tau}))\) plane, allowing only a circular region centered at \((\text{Re}(y_{\tau}) = s_{\beta - \alpha} + c_{\beta - \alpha}(1 + r_{32}^2)/(1 - r_{32}^2), \text{Im}(y_{\tau}) = 0)\) with a radius \(2|c_{\beta - \alpha} r_{32}/(1 - r_{32}^2)|\). At its boundary, we have \(M_{33} = 0\) and hence \(N_{\tau\tau} = 0\).

For \(r_{32} = 1, N_{\tau\tau}\) is purely imaginary, yielding a vertical line at \(\text{Re}(y_{\tau}) = s_{\beta - \alpha}\). In Fig. 1, we present results in two representative cases: \(r_{32} = 0.9\) and \(r_{32} = 1.1\), with \(\beta - \alpha - \frac{\pi}{2} = 0.05\).

\(h \to \tau\tau\) constraints. The decay width for \(h \to \tau\tau\) is given by

\[
\Gamma^{\tau\tau} = \frac{\sqrt{2} G_F m_\tau h^2}{8\pi} |y_{\tau}|^2.
\]

(11)

Experimentally, the ATLAS signal strength is \(\mu_{\text{ATLAS}} = 1.43^{+0.33}_{-0.37} [18]\) while CMS favors a smaller one \(\mu_{\text{CMS}} = 0.78 \pm 0.27 [19]\). We take a \(\chi^2\) analysis at 95% C.L. for these two measurements, assuming a Gaussian distribution for both and neglecting their correlations. Apparently, the allowed parameter region should be a circular band at the \((\text{Re}(y_{\tau}), \text{Im}(y_{\tau}))\) plane, as is indicated by two green dashed curves in Fig. 1. A future determination of this coupling that agrees with the SM value within \(\pm 10\%) is plotted as a curved blue band.
FIG. 1. Theoretical and phenomenological constraints on the Higgs-τ Yukawa couplings in Eq. (9). The inner parts of circular regions satisfy the diagonalization constraint $|M_{32}| \leq m_τ$ for two representative choices of $r_{32}$, with the outer boundaries giving vanishing $\text{Br}(τ \rightarrow μγ)$ and $Γ(h \rightarrow τμ)$. The $r_{32} = 0.9$ and $r_{32} = 1.1$ regions are separated by the vertical dashed line at $\text{Re}(y_τ) = \sin(0.05 + \frac{π}{2}) \approx 1$. Brown regions correspond to non-vanishing $Γ(h \rightarrow τμ)$, with different representative values (1%, 0.5% and 0%) denoted by circular dashed lines. For $r_{32} = 1.1$, the ATLAS 95% C.L. upper bound of 1.43% is shown, while for $r_{32} = 0.9$ a maximum BR of 1.41% can be achieved within the theoretically allowed region. The preliminary CMS upper limit 0.25% is indicated by a thick dashed blue circle in both cases. Upper limits on $Γ(h \rightarrow ττ)$ (95% C.L.) and $\text{Br}(τ \rightarrow μγ)$ (90% CL) are given by the green and grey regions, respectively. The region inside the green dashed lines gives the Higgs signal strength $r_{32} = 1$, the ATLAS 95% C.L. upper bound of 1.43% is shown, while for $r_{32} = 0.9$ and $r_{32} = 1.1$ regions are denoted in gray in Fig. 1. There exists a positive correlation between new physics contributions to $\text{Br}(h \rightarrow τμ)$ and $Γ(h \rightarrow ττ)$, without assuming a specific Yukawa texture. The inner light-blue band labelled $|y_τ| = 1 \pm 0.1$ corresponds to the region with a more SM-like $hτ$ coupling. The region giving the observed BAU is indicated by the horizontal pink bands assuming $|Δβ| \leq 0.4$ for $β - α - \frac{π}{2} = 0.05$ as discussed in the text. The other relevant parameters are fixed to be $m_μ = m_A = m_{h±} = 500\text{GeV}$, $v_μ = 0.05 \{4, 30, 31\}$, $L_W = \frac{2}{7}T$, $D_q = \frac{6}{7}T$, $D_{1L} = \frac{100}{T}$ [32] and $T = 100\text{GeV}$. To guide the eye, the argument of $y_τ$ is denoted by red-dotted lines. Note, the calculation of baryon asymmetry outside the circular regions could be unreliable due to the breaking of perturbative “mass insertion”.

$h \rightarrow τμ$ constraints. The lepton flavor-changing decay width is given by

$$Γ_{τμ} = \frac{\sqrt{2}β_3 α G_F m_h}{8π}|N_{τμ}|^2.$$ (12)

Theoretically, a sizable $\text{Br}(h \rightarrow τμ)$ requires a small $|M_{32}|$ (see Eq. (7)). At 8 TeV, ATLAS sets an upper limit on its branching ratio, $\text{Br}(h \rightarrow τμ) < 1.43\%$, at 95% C.L. [7], while CMS gives a best fit $\text{Br}(h \rightarrow τμ) = 0.84^{+0.37}_{−0.29} \%$ as well as an upper limit $\text{Br}(h \rightarrow τμ) < 1.51\%$ at 95% C.L. [5]. At 14 TeV, a preliminary CMS sets an upper limit of $\text{Br}(h \rightarrow τμ) < 0.25\%$ at 95% C.L. [6]. In Fig. 1, the current ATLAS limit 1.43% and the preliminary CMS limit 0.25% are both shown in the two cases with $r_{32} = 0.9$ and 1.1. The circular boundaries of the brown regions correspond to vanishing $M_{33}$ or $N_{τμ}$, yielding $\text{Br}(h \rightarrow τμ) = 0$.

$τ \rightarrow μγ$ constraints. Non-vanishing $N_{τμ}$ may also contribute to the rare decay $τ \rightarrow μγ$, via one-loop neutral and charged Higgs mediated diagrams and two-loop Barr-Zee type diagrams [20, 21]. Explicitly, one has

$$\text{Br}(τ \rightarrow μγ) = \frac{τ_τ α G_F^2 m_τ^5}{32π^4} |(C_{7L})^2 + (C_{7R})^2|,$$ (13)

where $τ_τ = (290.3 \pm 0.5) \times 10^{−15} s$ [22] is the $τ$ lifetime and $C_{7L/R}$ are the Wilson coefficients of the dipole operators $Q_{τ/μ}^L/R = e m_τ σ^{μν}(1 ± γ^5)τ F_{μν}/8π^2$ in the Hamiltonian $−G_F |C_{7L} Q_{τ/μ}^L + C_{7R} Q_{τ/μ}^R|/\sqrt{2}$ [23]. In our setup, $C_{7L}$ and $C_{7R}$ are proportional to $N_{τμ}^∗$ and $N_{τμ}$, respectively, yielding a vanishing $C_{7R}$. The current experimental limit is $\text{Br}(τ \rightarrow μγ) < 4.4 \times 10^{−8}$ (90% C.L.) [24]. The allowed parameter regions are denoted in gray in Fig. 1. There exists a positive correlation between new physics contributions to $\text{Br}(h \rightarrow τμ)$ and $Γ(h \rightarrow ττ)$. To make it more explicit, we project experimental constraints in Fig. 1 to the $\text{Br}(h \rightarrow τμ)−\text{Br}(τ \rightarrow μγ)$ plane (see Fig. 2). It is easy to see that the flavor-violating Higgs decay $\text{Br}(h \rightarrow τμ)$ of percent level is possible, without violating the experimental constraints for $\text{Br}(τ \rightarrow μγ)$. This is due to the fact that in type III 2HDM, new physics contributions to $\text{Br}(h \rightarrow τμ)$ and $\text{Br}(τ \rightarrow μγ)$ result from tree- and loop-levels respectively.

Electric dipole moments. Null results from experimental searches for the electric dipole moments (EDMs) of the neutron, neutral atoms, and molecules in general place stringent limits on new sources of CPV. In the present instance, the electron EDM ($d_e$) provides the most significant probe of $\text{Im}(J_A)$ or $\text{Im} y_τ$, given the bound obtained by the ACME collaboration using ThO[25]. In our setup, the dominant contribution to electron EDM results from $h$–mediated Barr-Zee diagram.
with a $\tau$ lepton loop, because of non-vanishing $\text{Im} \, y_\tau$. We find $|d_{\ell}\gamma/e| \approx 1.66 \times 10^{-29} \text{[Im } y_\tau]_{\text{cm}}$, yielding a bound of $|\text{Im} y_\tau| < 5.2$. As indicated in Fig. 1, this bound is an order of magnitude larger than what is required to account for the observed BAU (see below). We also note in passing that CPV in the scalar potential, will lead to mixing between the CP-even and CP-odd scalars. The resulting EDM can be considerably larger (see, e.g., [26–28]).

**Electroweak baryogenesis.** The CPV scattering from the bubble walls generates a left-handed fermion density $n_L$, which converts into a baryon number density $n_B$ through the electroweak sphaleron transitions $\Gamma_{\text{ew}}$ during a first order EWPT. As with earlier work, we will employ the “vev insertion approximation” to estimate the CPV sources [4], in the fermion weak basis, and compute $n_B$ from quantum transport equations (see Ref. [11] for pedagogical discussions). Here we neglect bubble wall curvature [29], so that all relevant quantities depend only on the coordinate in the bubble wall rest frame $\bar{z} = z + v_w t$ with $v_w$ being the wall velocity, $\bar{z} > 0 (< 0)$ corresponding to (un)broken phase. Since non-zero densities for the first and second generation quarks as well as for the bottom quark are generated only by strong sphaleron processes, the following relations hold: $Q_1 = Q_2 = -2 U = -2 D = -2 C = -2 S = -2 B$, where $Q_k$ denotes the density of left-handed quarks of generation $k$ and $U$, $D$, etc. denote the corresponding right-handed quark densities. In addition, $L_1 = L_2 = e_\mu \approx 0$ for negligible leptonic Yukawa interactions. Local baryon number density is also approximately conserved so $\sum_{a=1}^3 (Q_a + U_i + L_i) = 0$.

The resulting transport equations are

$$
\begin{align*}
\partial_\mu Q_{\beta}^\mu &= \Gamma_{\text{mt}}(\xi_T - \xi_{Q_\beta}) + \Gamma_{\text{t}}(\xi_T - \xi_H - \xi_{Q_\beta}) + 2 \Gamma_{ss} \delta_{ss}, \\
\partial_\mu H^\mu &= \Gamma_{\text{t}}(\xi_T - \xi_H - \xi_{Q_\beta}) + \Gamma_{\text{t}}(\xi_{L_3} - \xi_{\bar{r}} - \xi_H) - 2 \Gamma_H \xi_H, \\
\partial_\mu L_{\beta}^\mu &= -\Gamma_{\text{mt}}(\xi_{L_3} - \xi_{\bar{r}}) - \Gamma_{\text{t}}(\xi_{L_3} - \xi_{\bar{r}} - \xi_H) + S^{CPV}_{\mu \tau}, \\
\partial_\mu H_{\beta}^\mu &= -\Gamma_{\text{t}}(\xi_{H} + \xi_{\bar{r}}) + \Gamma_{\text{t}}(\xi_{L_3} - \xi_{\bar{r}} - \xi_H), \\
\partial_\mu L_{\beta}^\mu &= -\Gamma_{\text{mt}}(\xi_T - \xi_{Q_\beta}) - \Gamma_{\text{t}}(\xi_H - \xi_{Q_\beta}) - \Gamma_{\text{ss}} \delta_{ss}, \\
\partial_\mu H_{\beta}^\mu &= S^{CPV}_{\mu \tau},
\end{align*}
$$

(14)

where $\delta_{ss} = \xi_T + 9 \xi_B - 2 \xi_{Q_\beta}$, $\xi_a = n_a/k_a$, with $k_a$ being the statistical weight [11] associated with the number density $n_a$ of species “a”; and $\partial_{\mu} \approx v_w \frac{d}{dz} - D_a \frac{\partial}{\partial \bar{z}}$ with $D_a$ being the diffusion constant [32] from the diffusion approximation. The CPV source terms are

$$
S^{CPV}_{\mu \tau} = -S^{CPV}_{\mu \tau} = \frac{-v_w^2 d\beta/d\bar{z} \text{Im}(J_{A\tau})}{2\pi^2} I, 
$$

(15)

where $I$ is a momentum-space integral that depends on the leptonic thermal masses (see Ref. [33]) and $d\beta/d\bar{z}$ characterizes the local variation of $\tan(\beta(z))$ as one moves across the bubble wall. Furthermore $\Gamma_{\text{mt}} \approx 160 T$ is the strong sphaleron rate [34]; $\Gamma_{\text{mt}}$ is the two body top relaxation rate [11]; and $\Gamma_{\text{t}}$ is the $t/\tau$ Yukawa induced three body rate [35]. After solving for the densities in Eqs. (14), we obtain $n_L = \sum_i (Q_i + L_i)$ [36] and $n_B$, which is a constant in the broken phase:

$$
n_B = \frac{3 \Gamma_{\text{ew}}}{D_q} \int_0^{\infty} n_L(z) e^{-\lambda-\bar{z} d\bar{z}},
$$

(16)

where $\Gamma_{\text{ew}} \approx 1200 \text{[cm/s]} T$ [37] and $\lambda = (v_w \pm \sqrt{v_w^2 + 15 \Gamma_{\text{ew}} D_q})/(2 D_q)$.

Assuming a fast $\tau_R$ diffusion [38], we solve the transport equations perturbatively at the leading order of $\Gamma_{\text{mt}}^{-1}$, $\Gamma_{\text{t}}^{-1}$ and $\Gamma_{\text{ss}}^{-1}$. We have further neglected $\Gamma_{\text{mt}}$ in the final result as it is generally small compared with $\Gamma_{\text{mt}}$; then $n_B$ is proportional to $\text{Im}(y_\tau)$ with no dependence on $\text{Re}(y_\tau)$. One important remaining parametric uncertainty is the difference of $\beta(z)$ in the broken and symmetric phases ($= \Delta \beta$) since the CPV source term and thus $\Delta \beta$ are both directly proportional to it. Here we take its maximum magnitude to be 0.4 and vary it to obtain the bands in Fig. 1 where the upper and lower bands give opposite signs of BAU resulting from the unknown sign of $\Delta \beta$. Imposing the condition $|M_{\mu \tau}| < m_\tau$ as discussed above then restricts $\text{Re}(y_\tau)$ to the region of overlap between the pink bands and the two circular regions.

**Results and collider probes.** Combining the analyses above, we find that there exist parameter regions in Fig. 1 where the observed BAU can be explained without violating current experimental bounds. These regions are characterized by $|\text{Im}(y_\tau)| \gtrsim O(0.1)$, corresponding to $|\text{Im}(J_A)| \gtrsim O(10^{-5})$, or $|\phi_\pi| > O(10^9)$. As indicated above, the present EDM upper bounds on these CPV parameters are roughly an order of magnitude larger than the BAU requirements. The next generation searches for neutron, atomic, and molecular EDMs that plan for order magnitude or better improvements in sensitivities may, thus, begin to probe the BAU-viable parameter space.

Alternatively, collider measurements of the CP properties of the $h/\tau$ coupling may also test this scenario. For example, recent studies show that use of the $p$-meson decay plane method or impact parameter method...
at the LHC may allow a determination of $\phi_r$ with an uncertainty of $15^\circ(9^\circ)$ with an integrated luminosity of 150fb$^{-1}(500fb^{-1})$, or $\sim 4^\circ$ with 3ab$^{-1}$ [17]. At Higgs factories, $\phi_r$ could be measured with an accuracy $\sim 4.4^\circ(2.9^\circ)$, with a 250 GeV run and 1 ab$^{-1}(5$ ab$^{-1}$) luminosity [39, 40]. Therefore, the collider measurements of the CP-properties of the $h\tau\tau$ coupling complement the measurements of $h \to \tau\mu$ or $\tau \to \mu\gamma$, which constrain more the parameter regions with relatively small $|\text{Im} y_{\tau\mu}|$ or $|\phi_r|$.

**Conclusion.** In this letter, we explored EWBG in a simplified $\tau - \mu$ Yukawa texture in type III 2HDM. We show that three phenomena in particle physics and cosmology

- flavor-violating Higgs decay at colliders
- cosmic baryon asymmetry (CBA)
- non-trivial CP-properties of Higgs coupling with $\tau\tau$ leptons at colliders.

are strongly coherent in this context. That is, a non-trivial Higgs coupling with $\tau\mu$, if deciphered in type III 2HDM [41–46], generically implies the existence of a new Jarlskog invariant in the Yukawa sector which can be orders larger than the CKM one, thus explaining the CBA, and meanwhile yields a CP-violating Higgs coupling with $\tau\tau$ as “smoking guns” at colliders. Compared to the existent studies on EWBG and leptogenesis in 2HDM in literatures, the new study quantitatively correlates the generation of CBA with flavor-conserving and flavor-violating Higgs measurements both of which are being actively taken at the LHC. Interestingly, the phenomenology study in this setup can be extended to neutrino and quark sectors. For example, this setup does yield a CP-violating coupling between neutrinos and charged Higgs boson which is proportional to $\text{Im}(N_{\tau\tau})$. This effect could be probed in the decay of charged Higgs boson to $\tau$ and neutrinos at LHC. Extending a similar flavor structure to the quark sector, the anomalies in the measurements of $B \to D\tau\nu$ and $B \to D^*\tau\nu$ can be well-explained [47]. Here the misaligned Yukawa textures can lead to CLFV interactions via the mediator $H^\pm$. We hope that our study can trigger more interests on the potential roles of Higgs bosons in flavor physics and cosmology, as well as their intrinsic correlation.

**Acknowledgments.** We would like to thank E. Barberio, W. Chao, C. Y. Seng and D. Zanzi for helpful discussions. MJRM and HKG are supported in part under U.S. Department of Energy contract DE-SC0011095. HKG is also supported by the China Scholarship Council. JS is supported by the National Natural Science Foundation of China (NSFC) under grant No.11647601, No.11690022 and No.11675243 and also supported by the Strategic Priority Research Program of the Chinese Academy of Sciences under grant No.XDB21010200 and No.XDB23030100. YYL is supported by the the Hong Kong PhD Fellowship Scheme (HKPFS). TL is supported by the Collaborative Research Fund (CRF) under Grant No. HKUST4/CRF/13G and the General Research Fund (GRF) under Grant No. 16312716. Both the HKPFS and the CRF, GRF grants are issued by the Research Grants Council of Hong Kong S.A.R.. MJRM, TL and JS would like to thank the hospitality of MIAPP (TL would extend the thanks to MITP and Aspen Center for Physics) during the finalization of this article.

---

[1] P. A. R. Ade et al. [Planck Collaboration], arXiv:1502.01589 [astro-ph.CO].
[2] A. Sakharov *Pisma Zh. Eksp. Teor. Fiz.* 5 (1967) 32–35.
[3] V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 155, 36 (1985); M. E. Shaposhnikov, JETP Lett. 44, 465 (1986) [Pisma Zh. Eksp. Teor. Fiz. 44, 364 (1986)]; M. E. Shaposhnikov, Nucl. Phys. B 287, 757 (1987).
[4] D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. 14, 125003 (2012)
[5] CMS Collaboration, V. Khachatryan et al. *Phys. Lett.* B749 (2015) 337–362.
[6] CMS Collaboration [CMS Collaboration], CMS-PAS-HIG-17-001.
[7] G. Aad et al. [ATLAS Collaboration], arXiv:1604.07730 [hep-ex].
[8] G. Branco, P. Ferreira, L. Lavoura, M. Rebelo, M. Sher, et al. *Phys.Rept.* 516 (2012) 1–102.
[9] F. J. Botella, G. C. Branco, A. Carmona, M. Nebot, L. Pedro and M. N. Rebelo, JHEP 1407, 078 (2014).
[10] A. Riotto *Phys.Rev.* D58 (1998) 095009.
[11] C. Lee, V. Cirigliano, and M. J. Ramsey-Musolf *Phys.Rev.* D71 (2005) 075010.
[12] A. Hayreter, X. G. He and G. Valencia, arXiv:1606.00951 [hep-ph]; A. Hayreter, X. G. He and G. Valencia, arXiv:1603.06326 [hep-ph].
[23] A. J. Buras, hep-ph/9806471.

[24] BaBar Collaboration, B. Aubert et al. Phys. Rev. Lett. 104 (2010) 021802.

[25] J. Baron et al. [ACME Collaboration], Science 343, 269 (2014).

[26] J. Shu and Y. Zhang, Phys. Rev. Lett. 111, no. 9, 091801 (2013) doi:10.1103/PhysRevLett.111.091801 [arXiv:1304.0773 [hep-ph]].

[27] S. Inoue, M. J. Ramsey-Musolf, and Y. Zhang Phys. Rev. D89 no. 11, (2014) 115023.

[28] L. Bian, T. Liu and J. Shu, Phys. Rev. Lett. 115, 021801 (2015) doi:10.1103/PhysRevLett.115.021801 [arXiv:1411.6695 [hep-ph]].

[29] J. M. Cline, M. Joyce, and K. Kainulainen JHEP 0007 (2000) 018.

[30] G. D. Moore, JHEP 0003, 006 (2000) doi:10.1088/1126-6708/2000/03/006 [hep-ph/0001274].

[31] P. John and M. G. Schmidt, Nucl. Phys. B 598, 291 (2001) Erratum: [Nucl. Phys. B 648, 449 (2003)] doi:10.1016/S0550-3213(00)00768-9, 10.1016/S0550-3213(02)01014-3 [hep-ph/0002050].

[32] M. Joyce, T. Prokopec, and N. Turok Phys. Rev. D53 (1996) 2930–2957.

[33] T. Liu, M. J. Ramsey-Musolf, and J. Shu Phys.Rev.Lett. 108 (2012) 221301.

[34] G. F. Giudice and M. E. Shaposhnikov Phys. Lett. B326 (1994) 118–124; G. D. Moore Phys.Lett. B412 (1997) 359–370.

[35] V. Cirigliano, M. J. Ramsey-Musolf, S. Tulin, and C. Lee Phys. Rev. D73 (2006) 115009.

[36] M. S. Carena, M. Quiros, M. Seco, and C. Wagner Nucl.Phys. B650 (2003) 24–42.

[37] N. S. Manton Phys. Rev. D28 (1983) 2019; F. R. Klinkhamer and N. S. Manton Phys. Rev. D30 (1984) 2212; D. Bodeker, G. D. Moore, and K. Rummukainen Phys. Rev. D61 (2000) 056003; G. D. Moore Phys. Rev. D62 (2000) 085011; M. D’Onofrio, K. Rummukainen and A. Tranberg, Phys. Rev. Lett. 113, no. 14, 141602 (2014).

[38] D. J. H. Chung, B. Garbrecht, M. J. Ramsey-Musolf and S. Tulin, Phys. Rev. Lett. 102, 061301 (2009). D. J. H. Chung, B. Garbrecht, M. J. Ramsey-Musolf and S. Tulin, Phys. Rev. D 81, 063506 (2010).

[39] R. Harnik, A. Martin, T. Okui, R. Primulando, and F. Yu Phys. Rev. D88 no. 7, (2013) 076009.

[40] X. Chen and Y. Wu, arXiv:1703.04855 [hep-ph].

[41] Talk by Simone Bifani for the LHCb collaboration, CERN, 18/4/2016 https://indico.cern.ch/event/580620/

[42] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 113, 151601 (2014) doi:10.1103/PhysRevLett.113.151601 [arXiv:1406.6482 [hep-ex]].

[43] R. Aaij et al. [LHCb Collaboration], JHEP 1406, 133 (2014) doi:10.1007/JHEP06(2014)133 [arXiv:1403.8044 [hep-ex]].

[44] R. Aaij et al. [LHCb Collaboration], JHEP 1509, 179 (2015) doi:10.1007/JHEP09(2015)179 [arXiv:1506.08777 [hep-ex]].

[45] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 111, 191801 (2013) doi:10.1103/PhysRevLett.111.191801 [arXiv:1308.1707 [hep-ex]].

[46] R. Aaij et al. [LHCb Collaboration], JHEP 1602, 104 (2016) doi:10.1007/JHEP02(2016)104 [arXiv:1512.04442 [hep-ex]].

[47] A. Crivellin, C. Greub and A. Kokulu, Phys. Rev. D 86, 054014 (2012) doi:10.1103/PhysRevD.86.054014 [arXiv:1206.2634 [hep-ph]].