Letter

Probing baryogenesis with radiative beauty decay and electron electric dipole moment

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With the Large Hadron Collider (LHC) running, we should probe electroweak baryogenesis (EWBG) while probing CP violation (CPV) with electron electric dipole moment (eEDM). Rooted in the flavor structure of the Standard Model (SM), the general two Higgs doublet model (g2HDM) with a second set of Yukawa couplings can deliver EWBG while surviving eEDM. We point out a chiral-enhanced top-bottom interference effect that makes $b \to s\gamma$ decay an exquisite window on EWBG and eEDM, and illustrate the importance of the ΔA_{CP} observable at Belle II.

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Introduction. The rare $b \to s\gamma$ process offers the best bound [1] on the charged Higgs boson H^+ that exists in two Higgs doublet models [2], in particular 2HDM-II that is automatic with supersymmetry (SUSY). It holds true even after 15 years of LHC running, and a decade since the discovery 3]] of $h(125)$, the 125 GeV boson.

The h boson completes one Higgs doublet, so extra Higgs bosons from a second doublet *must* be searched for. 2HDM-II is one of two models that obey the natural flavor conservation (NFC) condition of Glashow and Weinberg [4]; each type of fermion charge couples to *only* one Higgs doublet; in 2HDM-II, u- and d-type quarks couple to different doublets. But since *no new physics*, SUSY included, has emerged at the LHC, one should see the NFC condition as it is *ad hoc*.

In this paper we study the general 2HDM, i.e., the *natural* case of having two Yukawa matrices. The mass matrix is diagonalized as usual, giving $\lambda_f = \sqrt{2}m_f/v$ for $f = u, d, \ell$ with v the vacuum expectation value (VEV); it has been confirmed [5] for t, b, τ and μ at the LHC. The second Yukawa matrix, ρ^f, cannot be simultaneously diagonalized in general, hence the fear of flavor-changing neutral couplings (FCNC). But as shown long ago [6], taking some fermion mass-mixing ansatz that reflects the observed hierarchical pattern, NFC may not be needed. It was stressed that mass-mixing hierarchies alone may be nature's way to control FCNC [7], with $t \to ch$ the likely harbinger, which has been pursued [5] ever since the $h(125)$ discovery. The current limit of 0.073% [8] is getting stringent.

We promote g2HDM as a likely *next* new physics. Most important is its ability to deliver [9] EWBG [10]; the disappearance of antimatter shortly after the big bang, i.e. the baryon asymmetry of the Universe (BAU). First, g2HDM with $\mathcal{O}(1)$ Higgs quartic couplings [11] can give first-order phase transition. Second, complex ρ^f couplings can give large CPV with three mechanisms; the most robust is via ρ_{tt} at $\mathcal{O}(\lambda_t)$, i.e. $\mathcal{O}(1)$ [9], and with $|\rho_{tc}| \simeq 1$ as backup if ρ_{tt} turns out accidentally small, and ρ_{bb} can also give [12,13] EWBG if its strength is large enough, but would need 10^{-3} tuning.

The emergent *alignment* phenomenon, that h resembles the SM Higgs boson [5] so well, means that the h–H mixing angle $c_\gamma \equiv \cos\gamma$ is small, where H is the exotic CP-even scalar. As the SM-Higgs boson cannot induce $t \to ch$ decay, the coupling is $\rho_{tc}c_\gamma$ [14], i.e. ρ_{tc} relates to the exotic doublet that has no VEV. With the stringent $t \to ch$ [8] bound, nature seems to throw in a nonflavor, purely Higgs-sector parameter c_γ to help suppress the $t \to ch$ FCNC process.

Alignment is not [15] in conflict with the need of $\mathcal{O}(1)$ Higgs quartics, e.g. the h–H mixing coupling $\eta_6 \sim 1$ [15] is allowed even for relatively small c_γ. Further, EWBG implies exotic H, A and H^+ bosons should be sub-TeV in mass—a boon to LHC search [16–18].

The large CPV in g2HDM for EWBG does bring on a *general challenge*: surviving eEDM constraints, which has recently leapfrogged neutron EDM (nEDM). The impressive ACME bound [19] was recently surpassed by JILA, to 0.41×10^{-29} e cm [20]. However, a "natural" *flavor-based* cancellation can evade [21] eEDM bounds elegantly. To cancel quite a few two-loop effects due to ρ_{tt} and *also* ρ_{ee}, one needs

$$|\rho_{ee}/\rho_{tt}| = r|\lambda_e/\lambda_t|, \quad \arg(\rho_{ee}\rho_{tt}) = 0, \tag{1}$$

with $r \sim 0.7$, depending on loop functions. The second "phase-lock" neutralizes the effect from pseudoscalar A [21], giving the first relation that implies the ρ^f matrices *know* about flavor hierarchies.

Considering how well g2HDM *evades* flavor constraints, we conceived [22] a rule of thumb:

$$\rho_{ii} \lesssim \mathcal{O}(\lambda_i), \quad \rho_{1i} \lesssim \mathcal{O}(\lambda_1), \quad \rho_{3j} \lesssim \mathcal{O}(\lambda_3), \tag{2}$$

for $j \neq 1$, giving $\rho_{tt} = \mathcal{O}(1)$ but $\rho_{bb} \simeq 0.02$. Indeed, $|\rho_{tt}| \lesssim 0.6$ is allowed [17] by LHC data, and can further soften by finite ρ_{tc}. But we do not really know the parameter values. Since ρ_{tt}, ρ_{bb} can each induce EWBG, in view of the prowess of eEDM—discovery may come around $10^{-30}\,e\,$cm!—we point out an m_t/m_b chiral-enhanced H^+ effect of ρ_{tt}–ρ_{bb} interference that compensates the smallness of ρ_{bb} to make $b \to s\gamma$ an exquisite probe of EWBG. We explore next-to-leading order (NLO) effects for future development.

Formalism. We assume CP-conserving [15,23] Higgs potential of g2HDM, removing it as a CPV source to simplify, without discussing it further. To clarify the flavor discussion given in the Introduction, the Yukawa couplings to charged fermions [18,23] are

$$\begin{aligned}\mathcal{L} = &-\frac{1}{\sqrt{2}}\sum_{f=u,d,\ell}\bar{f}_i\Big[(-\lambda_i^f\delta_{ij}s_\gamma + \rho_{ij}^f c_\gamma)h \\ &+ (\lambda_i^f\delta_{ij}c_\gamma + \rho_{ij}^f s_\gamma)H - i\,\mathrm{sgn}(Q_f)\rho_{ij}^f A\Big]Rf_j \\ &- \bar{u}_i[(V\rho^d)_{ij}R - (\rho^{u\dagger}V)_{ij}L]d_jH^+ \\ &- \bar{\nu}_i\rho_{ij}^L R\ell_j H^+ + \text{H.c.},\end{aligned} \tag{3}$$

with family indices i, j summed over, $L, R = 1 \mp \gamma_5$, and $s_\gamma \equiv \sin\gamma$. The A, H^+ couplings do not depend on c_γ; in the alignment limit ($c_\gamma \to 0$, $s_\gamma \to -1$), h couples diagonally and H couples via $-\rho_{ij}^f$. Thus, besides mass-mixing hierarchy protection [7] of FCNC, alignment gives [15] further safeguard, without the need of NFC.

We follow the $b \to s\gamma$ formalism of Ref. [24] (see also Ref. [25]). By replacing $A_u \to \rho_{tt}/\lambda_t$, $A_d \to \rho_{bb}/\lambda_b$, one-loop corrections to the Wilson coefficients (WCs) C_7 and C_8 induced by H^+ in g2HDM are

$$\delta C_{7,8}^{(0)}(\mu) = \frac{|\rho_{tt}|^2}{3|\lambda_t|^2}F_{7,8}^{(1)}(x_t) - \frac{\rho_{tt}\rho_{bb}}{\lambda_t\lambda_b}F_{7,8}^{(2)}(x_t), \tag{4}$$

with $x_t = m_t(\mu)^2/m_{H^+}^2$ at heavy scale μ, and loop functions $F_{7,8}^{(i)}(x)$ ($i = 1, 2$) given in Ref. [24]. From B_d and B_s mixing constraints [26], we set $\rho_{ct} = 0$.

While the form of Eq. (4) is correct, the denominators, i.e. the $|\lambda_t|^2$ and $|\lambda_t\lambda_b|$ factors actually arise from balancing explicit *masses* for H^+ couplings in 2HDM-I and II, rather than from dynamical couplings as the numerators. Thus, the second $\rho_{tt} - \rho_{bb}$ interference term receives m_t/m_b chiral enhancement. Unlike chiral enhancement in left-right symmetric models [27,28], in Eq. (4) it is rooted in the chiral H^+ couplings of Eq. (3), where its origins will be elucidated further later.

As ρ_{tt} and ρ_{bb} can each lead to EWBG, we define

$$\phi \equiv \arg(\rho_{tt}\rho_{bb}) = \phi_{tt} + \phi_{bb}, \tag{5}$$

and illustrate with $\phi = 0, \pi, \pm\pi/2$, as explained later.

At NLO in QCD, $\delta C_{7,8}$ at scale μ are defined as

$$\delta C_{7,8}(\mu) = C_{7,8}^{(0)}(\mu) + \frac{\alpha_s(\mu)}{4\pi}C_{7,8}^{(1)}(\mu), \tag{6}$$

where $\delta C_{7,8}^{(0)}$ are given in Eq. (4), and $\delta C_{7,8}^{(1)}$ are

$$\delta C_7^{(1)}(\mu) = G_7(x_t) + \Delta_7(x_t)\log\frac{\mu^2}{m_{H^+}^2} - \frac{4}{9}E(x_t), \tag{7}$$

$$\delta C_8^{(1)}(\mu) = G_8(x_t) + \Delta_8(x_t)\log\frac{\mu^2}{m_{H^+}^2} - \frac{1}{6}E(x_t), \tag{8}$$

with $G_{7,8}(x)$, $\Delta_{7,8}(x)$ and $E(x)$ given in Ref. [24]. For 2HDM-I and II results at NNLO, see Ref. [29].

Numerical results. We consider the following $b \to s\gamma$ [30] observables; inclusive $B \to X_s\gamma$; exclusive $B^{+,0} \to K^*\gamma$ and $B_s \to \phi\gamma$, and CP asymmetries $A_{\rm CP}(B^{+,0} \to K^*\gamma)$, and the inclusive CPV difference [31] $\Delta A_{\rm CP}(b \to s\gamma) \equiv A_{\rm CP}(B^+ \to X_s^+\gamma) - A_{\rm CP}(B^0 \to X_s^0\gamma)$. More observables can be included, but do not improve the bounds.

We illustrate with $m_{H^+} = 300$, 500 GeV. For exclusive modes, $B \to V$ ($V = K^*, \phi$) form factors are needed. We follow Ref. [30] and use the package FLAVIO [32] for our estimation. The WCs in Eq. (4) at heavy scale $\mu \sim m_{H^+}$ should be evolved down to the physical scale [32] of 2 (4.8) GeV for inclusive (exclusive) processes, which is done using the package Wilson [33].

FLAVIO v2.4.0 and experimental values for inclusive $\mathcal{B}(B \to X_s\gamma)|_{E_\gamma > 1.6\ \rm GeV}$ branching ratios are [32,34]

$$(3.29 \pm 0.22) \times 10^{-4}, \quad (\texttt{Flavio}\ [32]) \tag{9}$$

$$(3.49 \pm 0.19) \times 10^{-4}, \quad (\text{HFLAV}\ [34]) \tag{10}$$

compared with the detailed theory value of $\mathcal{B}(B \to X_s\gamma)|_{E_\gamma > 1.6\ \rm GeV} = (3.40 \pm 0.17) \times 10^{-4}$ [35], where error

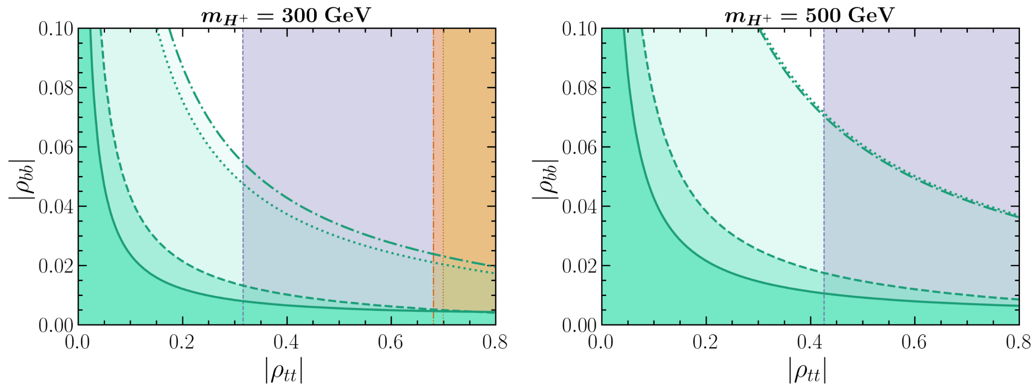

FIG. 1. *Allowed regions* from $b \to s\gamma$ observables, given for $\phi = \phi_{tt} + \phi_{bb} = 0$ (green solid), π (green dashed), $+\pi/2$ (green dot-dash), and $-\pi/2$ (green dots) for $m_{H^+} = 300$ (left), 500 (right) GeV. Constraints from Δm_{B_s} (light-blue short dash), $B_s \to \mu\mu$ (red dot dash) and ε_K (brown dots) on ρ_{tt} are also shown, with shaded region ruled out to the right.

is closer to experiment. We use FLAVIO to cover more observables to compare with data [34] and show that, with ρ_{tt} and ρ_{bb} both present, $b \to s\gamma$ is the best probe of EWBG parameter space in g2HDM.

As only the combined phase $\phi = \phi_{tt} + \phi_{bb}$ of Eq. (5) enters, we plot in Fig. 1 the global $b \to s\gamma$ constraint at leading order (LO) in the $|\rho_{tt}|$–$|\rho_{bb}|$ plane, for $m_{H^+} =$ (left) 300 GeV and (right) 500 GeV, illustrating for $\phi = 0, \pi, \pm\pi/2$, where shaded region is *allowed*, i.e. ruled out to the right. We also show three flavor constraints as vertical lines: B_s mixing [36], $\mathcal{B}(B_s \to \mu\mu)$ [37], and ε_K [36], where shaded regions to the right are ruled out. Only 1σ bounds are shown to illustrate the prowess of $b \to s\gamma$ as probe, otherwise the two weaker flavor bounds would fly out of the plot. We comment on this later.

We see that, while Δm_{B_s} limits ρ_{tt} strength, thanks to chiral enhancement, the $b \to s\gamma$ constraint is more exquisite, probing even small $|\rho_{bb}| \lesssim 0.02$ values when ρ_{tt} is sizable. The $\delta C_{7,8}$ corrections [see Eq. (4)] are small compared to the SM effect, which is enhanced by QCD [38,39] and is close to real, which is why the $\phi = \pm\pi/2$ cases are more accommodating, as the H^+ effect sums only in quadrature.

We also give the result for NLO by taking $\delta C^{(1)}_{7,8}$ of Eqs. (7) and (8) into Eq. (6), run down from μ scale to low scale, and plot in Fig. 2, which is visibly different from Fig. 1. We leave to the experts for proper refinement. Not shown are $m_{H^+} = 1$ TeV results, where the parameter space is more generous, as expected.

From Eq. (2), if we take $|\rho_{bb}| \sim 0.02$ to mean the range of $0.01 \lesssim |\rho_{bb}| \lesssim 0.03$, for $m_{H^+} = 300\,(500)$ GeV in Fig. 1. For the most stringent $\phi = 0$ case, the bounds are $|\rho_{tt}| \lesssim 0.08$ (0.14) for $\rho_{bb} = 0.03$, and $|\rho_{tt}| \lesssim 0.24$ (0.43) for $\rho_{bb} = 0.01$. These ρ_{tt} strengths are still more or less robust for EWBG [9], while ρ_{bb} seems a bit small to be the driver. However, if ρ_{tt} turns out much less than 0.1 and ineffective for EWBG, we see from Fig. 1 that $|\rho_{bb}| \sim 0.1$ becomes allowed by $b \to s\gamma$ and could [12,13] drive EWBG. For the ρ_{tc} mechanism that evades eEDM, the $t \to ch$ bound [8] puts some stress on $|\rho_{tc}| \sim 1$, despite alignment assistance. Note that Refs. [9,12,13] has the known issue of overestimating BAU compared to the semiclassical approach [40], which is especially severe for the ρ_{bb}-EWBG mechanism. But due to large uncertainties in several parameters [41], it may still be open as one awaits a more precise estimation.

The $\phi = 0$ case may be special. In the ρ_{ee}–ρ_{tt} eEDM cancellation mechanism, the second relation of Eq. (1) imposes a phase-lock, that ϕ_{ee} is opposite in sign to ϕ_{tt}. In estimating the CPV $e - N$ scattering correction, Ref. [21]

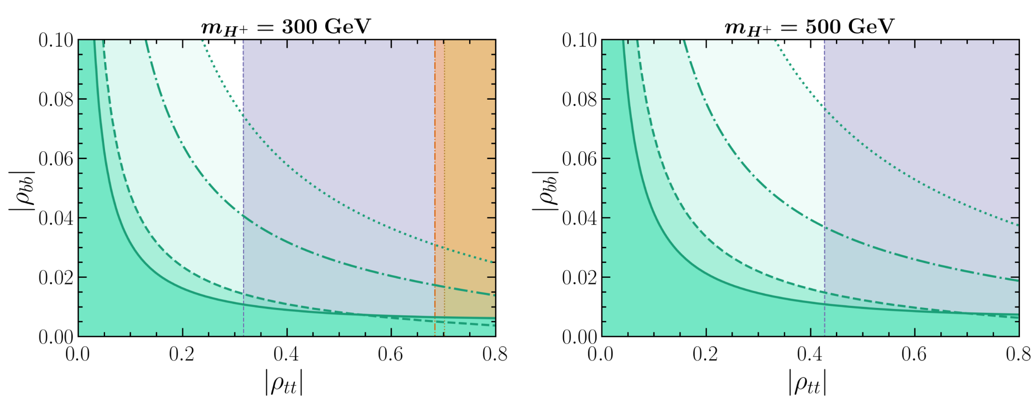

FIG. 2. Same as Fig. 1, but for $b \to s\gamma$ constraint at NLO.

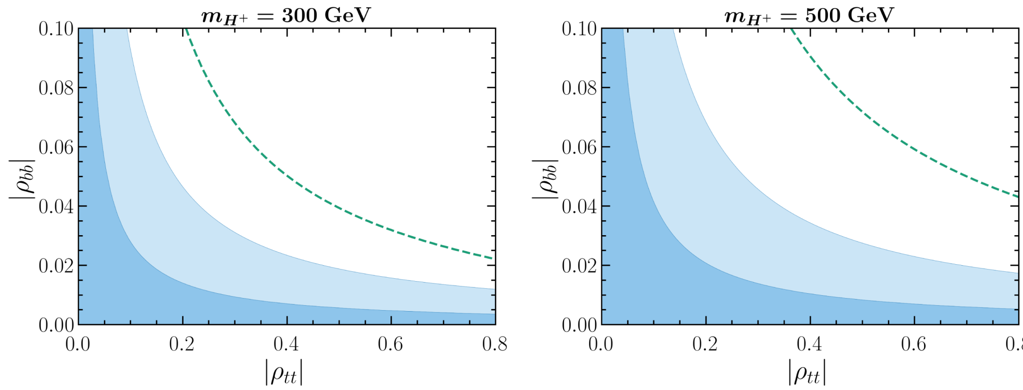

FIG. 3. (Light) blue shaded region *allowed* by $\Delta A_{\rm CP}$($\simeq$0 assumed) with (5 ab^{-1}) 50 ab^{-1} Belle II data, and $\mathcal{B}(B \to X_s\gamma)$ constraint (green dashed line) for $\phi = \pm\pi/2$. All are 1σ constraints.

took the "Ansatz" of $\phi_{qq} = -\phi_{tt}$. While not written in stone, we would like to bring in a "bias" from charge unification, that in context of grand unified theories (GUT), charged leptons and d-type quarks seem grouped together. Thus, while u-type quarks may not have this "phase-lock" with ϕ_{tt}, $\phi_{bb} + \phi_{tt} = 0$ may be plausible, hence favor $\phi = 0$. If no CPV is observed in $b \to s\gamma$ with all Belle II [42] data, $\phi = 0$ (or π) may be suggested. Even so, the ϕ_{tt} and ϕ_{bb} phases can still contribute separately to EWBG.

Future Belle II measurement of inclusive CPV difference $\Delta A_{\rm CP}$ [31] can probe the phase ϕ. We show the 1σ constraint on $\Delta A_{\rm CP}$ in Fig. 3 for 5 and 50 ab^{-1} data, for $\phi = \pm\pi/2$ and $m_{H^+} =$ (left) 300 GeV, (right) 500 GeV. The $\mathcal{B}(B \to X_s\gamma)$ bound is also shown, which does not improve by much: $\Delta A_{\rm CP}$ *indeed* probes ϕ.

The eEDM cancellation mechanism was recently extended to broader parameter range [43], and an nEDM cancellation mechanism was illustrated by variation of ρ_{uu} strength and phase. We show in Table I that, interestingly, for the largest ρ_{tt} strength and phase, $\Delta A_{\rm CP}$ could approach 3σ with full Belle II data. If eEDM emerges soon, and with good prospects for nEDM [43], one may face the decision on extending Belle II data taking, or even upgrade to Belle III.

Discussion and conclusion. Chiral enhancement was noted in Ref. [26], but the $\rho^{u,d}$ matrices were taken as real. Here, with large *CPV* from complex ρ_{tt} and ρ_{bb} contributing to EWBG and eEDM, we study specifically the effect of $\phi = \phi_{tt} + \phi_{bb}$ on $b \to s\gamma$.

So what is the origin of this chiral enhancement? Analogous to the elucidation given in one [44] of the earliest works on $b \to s\gamma$ in 2HDM-I and II, one needs a $\bar{s}\sigma_{\mu\nu}m_bRb$ dipole structure, which could arise in two ways; from H^+ coupling to the internal top at both ends of the loop, thereby $\propto |\rho_{tt}|^2$, but would need an m_b insertion in the external b line; or $H^\pm$ couplings to ρ_{bb} at b quark end while ρ_{tt} at s quark end. To achieve the chirality flip in $\bar{s}\sigma_{\mu\nu}Rb$, an m_t insertion is needed, resulting in the m_t/m_b chiral enhancement.

Our figures show 1σ bounds to contrast with other flavor constraints. We could show 2σ constraints, but note that FLAVIO errors [32] are 50% larger than experiment [34]. As experimental errors improve at Belle II [42], theory needs to improve as well, which we expect [42] will happen.

With JILA surpassing the ACME to reach $0.41 \times 10^{-29}\,e\,$cm, the eminence of eEDM goes without saying. They are, however, still consistent with $10^{-29}\,e\,$cm. Given that g2HDM can achieve EWBG, with an exquisite cancellation mechanism for ρ_{tt}-EWBG while the less elegant ρ_{bb}-EWBG is also possible, a few $\times 10^{-30}\,e\,$cm would be quite contentious, as the *likelihood* within g2HDM is large. If eEDM emerges soon, it would provide support for EWBG *à la* g2HDM. Any other EWBG proposal with large new physics *CPV* would have to pass the eEDM test. As the cancellation mechanism for ρ_{tt}-EWBG invokes flavor hierarchies, Eq. (1), while nature seems to provide flavor protection against a plethora of

TABLE I. Expected $\Delta A_{\rm CP}$ ($\times 10^{-3}$) for $\phi = \pm\pi/2$. In ρ_{tt} (ρ_{bb}) benchmark, $|\rho_{bb}| = 0.02$ ($|\rho_{tt}| = 0.05$) is used for illustration.

	ρ_{tt} benchmark			ρ_{bb} benchmark
m_{H^+} (GeV)	$|\rho_{tt}| = 0.1\sqrt{2}$	$|\rho_{tt}| = 0.2\sqrt{2}$	$|\rho_{tt}| = 0.3\sqrt{2}$	$|\rho_{bb}| = 0.1$
300	$\mp$ (3.041 $\pm$ 0.046)	$\mp$ (6.026 $\pm$ 0.091)	$\mp$ (8.902 $\pm$ 0.134)	$\mp$ (5.352 $\pm$ 0.080)
500	$\mp$ (2.055 $\pm$ 0.031)	$\mp$ (4.097 $\pm$ 0.063)	$\mp$ (6.111 $\pm$ 0.093)	$\mp$ (3.628 $\pm$ 0.055)

probes [22], both seem to point to g2HDM: having a second Higgs doublets but without NFC condition.

Flavor physics does provide [22] a set of probes, such as $\mathcal{B}(B \to \mu\nu)/\mathcal{B}(B \to \tau\nu)$ [45] and $\tau \to \mu\gamma$ at Belle II, $B_s \to \mu\mu$ at CMS and LHCb, $K^+ \to \pi^+\nu\nu$ at NA62 for heavier H^+ [36], and the possible revival of muon physics in $\mu \to e\gamma$, $\mu \to 3e$ and $\mu N \to eN$ [22]. Direct search for the sub-TeV exotic H, A, H^+ Higgs bosons at the LHC [16–18] should also be earnestly pursued, where ATLAS has made the first step [46].

In conclusion, g2HDM can provide electroweak baryogenesis while surviving electron EDM constraint, a remarkable feat that is rooted in the flavor structure as revealed in the SM sector. With exotic H, A and H^+ bosons sub-TeV in mass, search programs at the LHC have started, while there are also some good flavor probes. In this work we show that $b \to s\gamma$ offers an exquisite window on baryogenesis and eEDM via a chiral enhancement of a special $t-b$ interference effect. With ongoing efforts at Belle II and other flavor fronts, and exotic Higgs search at the LHC, together with the supercharged eEDM front, the future looks bright for unveiling what may actually lie behind baryogenesis.

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