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$b \to s\gamma$, electron EDM and electroweak baryogenesis: a study in general 2HDM

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We study inclusive $b \to s\gamma$ decay in the context of electron EDM and baryogenesis. The *general* 2HDM (i.e. without Z_2) that possesses an extra set of Yukawa matrices can drive electroweak baryogensis via $\lambda_t \mathrm{Im}\rho_{tt}$, where ρ_{tt} is the extra diagonal top Yukawa coupling, with the eEDM constraint evaded by an exquisite flavor cancellation mechanism. We touch upon the current status of direct search for exotic H, A and H^+ scalars at the LHC, while for the plethora of flavor observables in g2HDM, we focus on $b \to s\gamma$, pointing out *chiral* enhancement of a $\rho_{tt}\rho_{bb}$ effect in g2HDM, which can bring in a CPV phase. We first explore the inclusive $\mathcal{B}(b \to s\gamma)$ rate, then showcase the progress that Belle II can make in the future, illustrating a potential 3σ effect for the inclusive $B^+ \to X_s^+\gamma$ vs $B^0 \to X_s^0\gamma$ CPV rate difference, ΔA_{CP}. Especially if eEDM emerges swiftly, perhaps one should pursue further upgrade beyond Belle II.

EPS-HEP, 21-25 August 2023, Hamburg, Germany

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PoS(EPS-HEP2023)363

1. Introduction: tension, & $t \to ch$

A three-way tension exists in present day particle physics: to have the more testable electroweak baryogenesis (EWBG), one needs very large CP violation (CPV) beyond the Standard Model (BSM), which runs into tension with No New Physics ($\mathcal{NNP}$) observed so far at the LHC.

Second, be it ACME [1] or JILA [2], electron EDM at the L.E. precision frontier provide sanity checks on large BSM-CPV, with stringent bound of $|d_e| < 0.41 \times 10^{-29} e$ cm [2]. Finally, it can be said that these "tabletop" experiments are competing head-on with the behemoth LHC.

But it is fair to say that EWBG ought to be pursued while LHC is still running!

We advocate [3] the *general* two Higgs doublet model (g2HDM); unlike the usual 2HDM with Z_2 symmetry, it has a second set of Yukawa matrices that possess flavor changing neutral couplings (FCNC). With no theorem against a second Higgs, 2HDM should be a no-brainer, but we move the well-known NFC condition of Glashow-Weinberg off its pedestal, as it is nothing but *ad hoc*.

A hallmark of g2HDM would be $t \to ch$ [4], with h the observed SM-like Higgs boson. Remarkably, besides flavor-hierarchies, *Nature* seems to throw in the emergent *alignment* phenomenon (small h-H mixing, i.e. $c_\gamma \equiv \cos\gamma$ is small, with H the exotic CP-even scalar) to protect this decay, with current limit at 0.00043 [5]. The combined coupling $\rho_{tc} c_\gamma$ now barely allows ρ_{tc} at $O(1)$.

2. General 2HDM: EWBG & eEDM

We do not show the g2HDM Higgs potential (see e.g. the brief review of Ref. [6]), but note that the convention is to take the Higgs basis where only one doublet, Φ, gives v.e.v., as without Z_2, one cannot distinguish Φ from Φ'. A minimization condition cancels the soft $\Phi^\dagger\Phi'$ term against half the $|\Phi|^2\Phi^\dagger\Phi'$ term, with the latter $\eta_6/2$ quartic coupling playing the unique role of Φ-Φ' mixing.

One advantage of g2HDM is that O(1) quartics η_i can lead to [7] 1st order phase transition (1st$O$PhT), one of the Sakharov conditions. It was then argued [8] that the exotic $H/A/H^+$ bosons would likely be sub-TeV in mass, ripe for search at the LHC. The Yukawa couplings are

$$-\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \Big[\big(-\lambda_i^f \delta_{ij} s_\gamma + \rho_{ij}^f c_\gamma \big) h + \big(\lambda_i^f \delta_{ij} c_\gamma + \rho_{ij}^f s_\gamma \big) H - i\,\mathrm{sgn}(Q_f) \rho_{ij}^f A \Big] R\, f_j$$
$$-\bar{u}_i \left[(V\rho^d)_{ij} R - (\rho^{u\dagger} V)_{ij} L \right] d_j H^+ - \bar{\nu}_i \rho_{ij}^\ell R\, \ell_j H^+ + h.c., \tag{1}$$

with generation indices i, j summed over, $L, R = (1 \mp \gamma_5)/2$ are projections, V the CKM matrix, with the lepton matrix taken as unity. With c_γ small (with $s_\gamma \to -1$), the h couplings are close to diagonal, while extra ρ^f matrices are associated more with exotic scalars. An interesting aspect of H^+ couplings in Eq. (1) is that, by expanding $\rho^{u\dagger} V$, one finds $H^+ \to c\bar{b}$, $t\bar{b}$ couplings are $\rho_{tc} V_{tb}$ and $\rho_{tt} V_{tb}$, resp., so unlike in 2HDM-II, $H^+ \to c\bar{b}$ is not CKM suppressed [9].

One highlight of g2HDM is that $\lambda_t \mathrm{Im}\rho_{tt}$ can drive EWBG robustly [10], while the leading two-loop Barr-Zee diagram for eEDM can be exquisitely cancelled [11] by flavor hierarchies quite effectively: the ρ matrices *know* the SM flavor structure. In a recent paper [12, 13] we revisited this cancellation mechanism and explored the larger range of

$$\mathrm{Re}\rho_{tt} = \mathrm{Im}\rho_{tt} = -0.1, -0.2, -0.3, \tag{2}$$

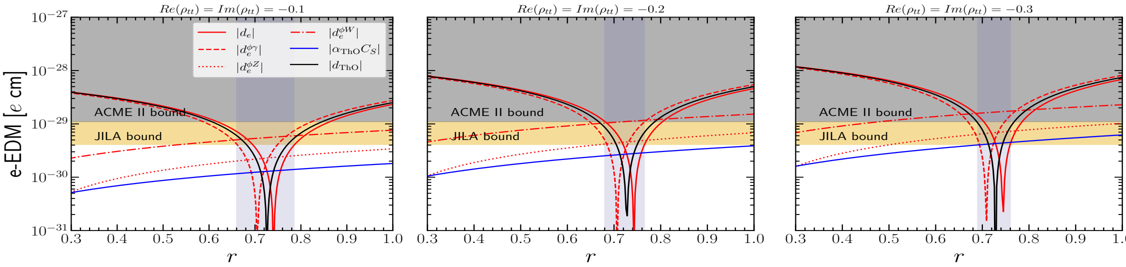

Figure 1: Cancellation of eEDM [11] for $m_H, m_A, m_{H^+} = 500$ GeV, $c_\gamma = 0.1$, and $|\rho_{tt}| \cong 0.14, 0.28, 0.42$.

as illustrated in Fig. 1. Although the allowed range in loop function r shrinks for larger $|\rho_{tt}|$, it was stressed that especially for $|\rho_{tt}| \simeq 0.42$, eEDM could emerge rather swiftly. It could then be followed by n2EDM at PSI [14] in *just* a few years. But a "new" cancellation mechanism [12] was also illustrated for nEDM itself through the unknown phase of ρ_{uu}, and the *second-whammy* from nEDM could take up to even two decades to pan out, but is still quite exciting.

3. H, A, H^+ Search & Flavor Frontiers

Sub-TeV exotic scalars should clearly be searched for at the LHC, while the *flavor* frontier is also quite promising. Here we limit ourselves to $b \to s\gamma$ for the latter, but let us first address a question: If there is a second Higgs doublet with a host of quartic and Yukawa couplings,

"Why is g2HDM hiding so well?"

Exploring this question, we *guessed* [15] a "rule of thumb" for flavor control:

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

which echoes the eEDM cancellation mechanism: the ρ^f $(f = u, d, \ell)$ matrices "*know*" the SM flavor structure, which roughly addresses the question we raised above.

Leading Search Modes at the LHC.— With $t \to ch$ suppressed by c_γ, it is natural to pursue $H/A/H^+$ direct production, gaining a $s_\gamma \to -1$ factor. The leading processes are [16]

$$cg \to tH/tA \to tt\bar{c}, tt\bar{t}, \tag{4}$$

where the second step follows from $H/A \to t\bar{c}$, $t\bar{t}$ decay via ρ_{tc} and ρ_{tt} couplings. Noting that $H^+ \to c\bar{b}$, $t\bar{b}$ have the same V_{tb} factor and hence on equal footing, it was found that [9]

$$cg \to bH^+ \to bt\bar{b}, \tag{5}$$

may be more efficient, with production via ρ_{tc} and H^+ decay via ρ_{tt}, bypassing the heavy associated top in Eq. (4). Both ATLAS [17] and CMS [18] have studied process (4), where the CMS study limits to $tt\bar{c}$ final state only. No signal is found so far, which might be expected, and one awaits adding Run 3 data. Process (5) apparently has not been studied yet, which we look forward to.

4. Chiral-enhanced $b \to s\gamma$ Observables

The $b \to s\gamma$ process as a probe of H^+ effects in 2HDM-I and II [19] still provides the best respective bounds on m_{H^+}. Here we are interested in the effects in g2HDM [20], finding

$$\delta C^{(0)}_{7,8}(\mu) = \frac{|\rho_{tt}|^2}{3|\lambda_t|^2} F^{(1)}_{7,8}(x_t) - \frac{\rho_{tt}\rho_{bb}}{\lambda_t \lambda_b} F^{(2)}_{7,8}(x_t), \tag{6}$$

where $x_t = m_t(\mu)^2/m^2_{H^+}$ is at heavy scale μ. The $\lambda_{t,b}$ couplings in the denominators are actually *masses*, hence the second term is m_t/m_b-enhanced, as it is rooted in *chiral* H^+ couplings. Since $|\rho_{bb}| \sim 0.1$ can also drive EWBG, it can be probed by $b \to s\gamma$ via chiral enhancement as well.

Defining $\phi \equiv \arg \rho_{tt}\rho_{bb} = \phi_{tt} + \phi_{bb}$, we use Flavio v2.4.0 [21] to estimate $b \to s\gamma$ observables, with WCs at heavy scale $\mu \sim m_{H^+}$ evolved down to the physical scale. We consider the well-measured inclusive $\mathcal{B}(B \to X_s\gamma)$, and the inclusive CPV difference [22],

$$\Delta A_{\rm CP}(b \to s\gamma) \equiv A_{\rm CP}(B^+ \to X^+_s\gamma) - A_{\rm CP}(B^0 \to X^0_s\gamma), \tag{7}$$

for the future, where the projection of Belle II physics book is used. We use HFLAV'21 for current data. Note that the error in $\mathcal{B}(B \to X_s\gamma)$ improves by less than a factor of two with full Belle II data. What's notable then is the projected order of magnitude improvement in $\Delta A_{\rm CP}$. Although the current sign from HFLAV'21 is insignificant, the numerics of Fig. 2 corresponds to the HFLAV'21 value in the Table below.

Observable	HFLAV'21	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
$\mathcal{B}(B \to X_s\gamma)$	$(3.49 \pm 0.19) \times 10^{-4}$	$(3.49 \pm 0.14) \times 10^{-4}$	$(3.49 \pm 0.11) \times 10^{-4}$
$\Delta A_{\rm CP}$	$(3.70 \pm 2.80) \times 10^{-2}$	$(0 \pm 0.98) \times 10^{-2}$	$(0 \pm 0.30) \times 10^{-2}$

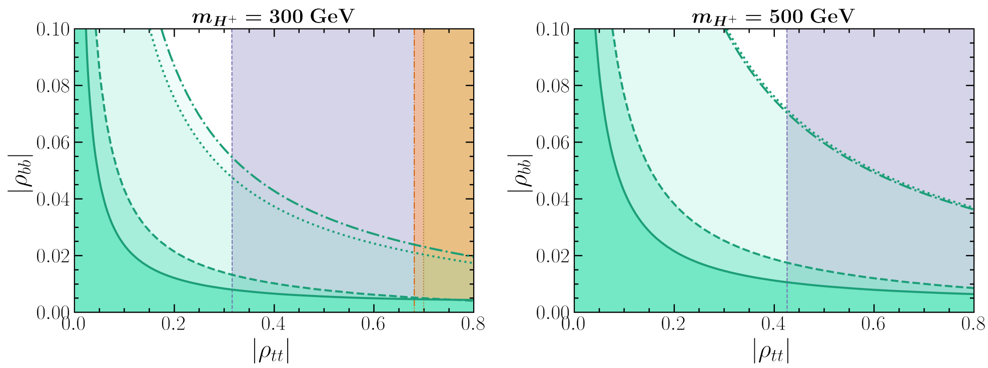

Figure 2: Results for phase $\phi = 0$ (solid), $\pm\pi/2$ (dot-dash/dots), π (dash), *allowed region* (green) from combined $b \to s\gamma$ observables, and *ruled out regions* from B_s mixing (purple) and $B_s \to \mu\mu$ (orange).

Combined $b \to s\gamma$ Observables.— The impact of current $\mathcal{B}(B \to X_s\gamma)$ is plotted in Fig. 2 at LO.[1] We see that the curves for $\phi = 0, \pi$ (and also for $\pm\pi/2$) are not so different. Of some interest is that, if $|\rho_{tt}|$ turns out rather small, it could be $\rho_{bb} \sim 0.1$ that drives EWBG, which is *also* probed by the chiral enhancement effect through Eq. (6), as one can see from Fig. 2 for $|\rho_{tt}| < 0.05$.

[1]Things appear quite different at NLO, implying potential future work; difference for $\phi = \pm\pi/2$ is also larger at NLO.

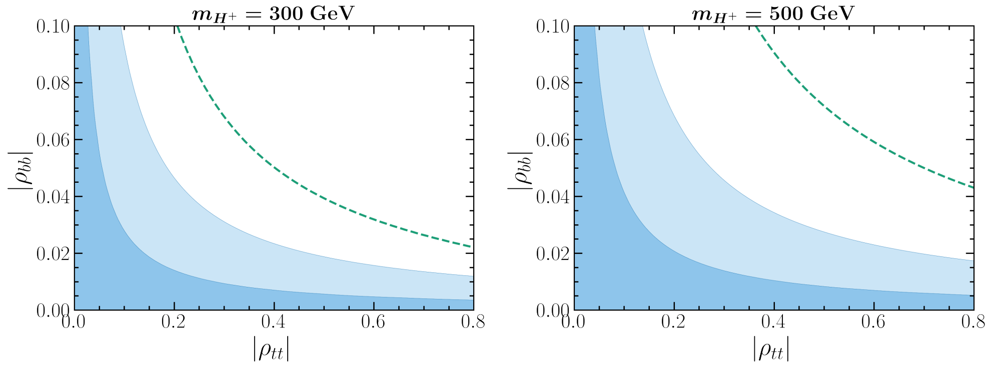

Figure 3: For $\phi = \pm\pi/2$, (light) blue shaded region *allowed* by null $\Delta A_{\rm CP}$ with (5) 50 ab^{-1} Belle II data, with green dash-dot line the individual $\mathcal{B}(B \to X_s\gamma)$ lower bound. All are 1σ constraints.

$\Delta A_{\rm CP}$ *Present and Future.*— More promising may be the CPV observable $\Delta A_{\rm CP}$, Eq. (7), the CPV difference of inclusive B^+ vs B^0 radiative decays, which we plot in Fig. 3. Only the *null* sensitivity is shown for maximal phase $\phi = \pm\pi/2$, hence we look forward to the actual measurement!

Not knowing what $\Delta A_{\rm CP}$ values might turn up, we explore Eq. (2), the allowed $|\rho_{tt}|$ values for eEDM cancellation, but set maximal phase $\phi = \pm\pi/2$ and show in Table 1. Comparing with the Table above Fig. 2, we see that for $|\rho_{tt}| \simeq 0.42$ with maximal phase $\phi = \pm\pi/2$, there could be an almost 3σ effect! Especially for the case where eEDM emerges real soon, whether one has an echo from nEDM or not, if a 3σ effect emerges with full Belle II data, one may face the question of "To B-III or Not to B-III?", i.e. whether to probe CPV further in $b \to s\gamma$.

m_{H^+}	$|\rho_{tt}|$=x, $|\rho_{bb}|$=0.02			$|\rho_{tt}|$=0.05, $|\rho_{bb}|$=0.1
	$x = 0.1\sqrt{2}$	$x = 0.2\sqrt{2}$	$x = 0.3\sqrt{2}$	
300 GeV	$\mp(3.041 \pm 0.046)$	$\mp(6.026 \pm 0.091)$	$\mp(8.902 \pm 0.134)$	$\mp(5.352 \pm 0.080)$
500 GeV	$\mp(2.055 \pm 0.031)$	$\mp(4.097 \pm 0.063)$	$\mp(6.111 \pm 0.093)$	$\mp(3.628 \pm 0.055)$

Table 1: In units of 10^{-3}, for maximal phse $\phi = \phi_{tt} + \phi_{bb} = \pm\pi/2$.

On the other hand, if $\Delta A_{\rm CP}$ stays consistent with zero with full Belle II data, it could be pointing at $\Delta A_{\rm CP} \sim 0$, which may support the GUT scenario, that the phase of ρ_{bb} cancels against ρ_{tt}, as suggested by eEDM cancellation mechanism, and the usual view that ℓ and d-type quarks are grouped together under GUTs.

5. Summary

Rather than accepting the "$\mathcal{NNP}$" fate, we advocate g2HDM where the exotic H, A and H^+ scalars could well be $O(500)$ GeV in mass, responsible for EWBG while accommodating eEDM — and could be verified at the LHC, which would be *fantastic*! Thrown in as bonus would be a bunch of FPCP processes [15] .

In this talk we covered only the $b \to s\gamma$ process, the well known probe of H^+ in SUSY-type 2HDM-II. We illustrate the power of $b \to s\gamma$ to probe both ρ_{tt}- and ρ_{bb}-EWBG through *chiral* *enhancement*. Currently, the inclusive rate is the best measured, but we advocate that Belle II can measure $\Delta A_{\rm CP}$ in the future to possibly provide a crosscheck on eEDM and EWBG!

Acknowledgements. We thank Marzia Bordone, Fionn Bishop, Chen Chen and Kam-Biu Luk for comments and fruitful discussions. We also thank Girish Kumar for carefully reading the manuscript.

References

[1] V. Andreev *et al.* [ACME], Nature **562**, 355 (2018).

[2] T. S. Roussy *et al.*, Science **381**, adg4084 (2023).

[3] W.-S. Hou, Chin. J. Phys. **77**, 432 (2022).

[4] W.-S. Hou, Phys. Lett. B **296**, 179 (1992).

[5] G. Aad *et al.* [ATLAS], JHEP **12**, 195 (2023).

[6] W.-S. Hou and T. Modak, Mod. Phys. Lett. A **36**, 2130006 (2021).

[7] S. Kanemura, Y. Okada and E. Senaha, Phys. Lett. B **606**, 361 (2005).

[8] W.-S. Hou and M. Kikuchi, EPL **123**, 11001 (2018).

[9] D.K. Ghosh, W.-S. Hou and T. Modak, Phys. Rev. Lett. **125**, 221801 (2020).

[10] K. Fuyuto, W.-S. Hou and E. Senaha, Phys. Lett. B **776**, 402 (2018).

[11] K. Fuyuto, W.-S. Hou and E. Senaha, Phys. Rev. D **101**, 011901(R) (2020).

[12] W.-S. Hou, G. Kumar and S. Teunissen, Phys. Rev. D **109**, L011703 (2024).

[13] Talk by Sven Teunissen, 21 August, EPS-HEP 2023.

[14] N.J. Ayres *et al.* [n2EDM], Eur. Phys. J. C **81**, 512 (2021).

[15] W.-S. Hou and G. Kumar, Phys. Rev. D **102**, 115017 (2020).

[16] M. Kohda, T. Modak and W.-S. Hou, Phys. Lett. B **776**, 379 (2018).

[17] G. Aad *et al.* [ATLAS], JHEP **12**, 081 (2023).

[18] A. Hayrapetyan *et al.* [CMS], [arXiv:2311.03261 [hep-ex]], to appear in Phys. Lett. B.

[19] W.-S. Hou and R.S. Willey, Phys. Lett. B **202**, 591 (1988).

[20] W.-S. Hou, G. Kumar and T. Modak, Phys. Rev. D **109**, L011701 (2024).

[21] D.M. Straub, [arXiv:1810.08132 [hep-ph]].

[22] M. Benzke, S.J. Lee, M. Neubert and G. Paz, Phys. Rev. Lett. **106**, 141801 (2011).