Letter

Discovery prospects for electron and neutron electric dipole moments in the general two Higgs doublet model

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Baryon asymmetry of the Universe offers one of the strongest hints for physics beyond the Standard Model (BSM). Remarkably, in the *general* two Higgs doublet model (g2HDM) that possesses a second set of Yukawa matrices, one can have electroweak baryogenesis (EWBG) while the electron electric dipole moment (eEDM) is evaded by a *natural* flavor tuning that echoes the Standard Model (SM). We show that eEDM may first emerge around 10^{-30} e cm or so, followed by neutron EDM (nEDM) down to 10^{-27} e cm. We illustrate a cancellation mechanism for nEDM itself, which in turn can be probed when a facility capable of pushing down to 10^{-28} e cm becomes available.

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Introduction. With no BSM physics emerging at the Large Hadron Collider (LHC), particle physics is in a state of exasperation. It is not clear whether one can address lofty issues such as the baryon asymmetry of the Universe, arguably one of the strongest hints for BSM physics that calls for the existence of *large CP* violating (CPV) phase(s) beyond the Kobayashi-Maskawa phase [1] of SM. The current frontier is the experimental race to measure electron EDM, where the bound held by the ACME experiment [2] has recently been surpassed at JILA [3], giving $d_e < 0.41 \times 10^{-29}$ e cm at 90% C.L. This is several orders of magnitude stronger than the current nEDM bound of $d_n < 1.8 \times 10^{-26}$ e cm by the nEDM experiment at PSI [4]. However, by using ultra cold neutrons (UCN), nEDM measurement is poised to improve by two orders of magnitude within two decades [5], with many experiments joining the fray.

In fact, the EDM experiments, much smaller than the behemoth LHC and its associated experiments, pose a *general* challenge: since BAU demands extremely large BSM CPV, can one survive the EDM bounds, especially eEDM? We explore this theme and promote the *general* two Higgs doublet model (g2HDM), where dropping the usual Z_2 symmetry one can have enough CPV for BAU, but the observed *flavor* (fermion mass and mixing) *hierarchies*—a mystery in itself—allows for an exquisite *natural flavor cancellation* mechanism to work for eEDM. We project that eEDM and nEDM could well emerge in the next decade or two, and extend the parameter range beyond previous considerations.

With *one* Higgs doublet observed, the two Higgs doublet model [6] should be a no-brainer. A Z_2 symmetry is usually imposed to enforce the natural flavor conservation (NFC) condition posited by Glashow and Weinberg [7] to forbid extra Yukawa matrices of charged fermions. But as first illustrated by Cheng and Sher [8], the flavor hierarchies may help alleviate Glashow's worries about flavor changing neutral couplings (FCNCs). It was pointed [9] out, even before the top discovery, that the process to watch, then, is $t \to ch$. The bound at the LHC, however, has reached the stringent $\mathcal{B}(t \to ch) < 0.00073$ [10]. But as stressed in 2013 [11] after the observation of $h(125)$, as the ρ_{tc} coupling is associated more with the exotic H and A bosons, the tch coupling should be $\rho_{tc} c_\gamma$, where $c_\gamma \equiv \cos\gamma$ is the h–H mixing angle between the two CP-even scalars. Who would have guessed that *Nature* would throw in, circa 2015, the *alignment* (small c_γ) phenomenon from the purely Higgs sector, to protect $t \to ch$ decay.

Having introduced the ρ_{tc} element of the up-type extra Yukawa matrix, it was subsequently shown [12] that $\lambda_t \mathrm{Im}\rho_{tt}$ can robustly drive EWBG [13], with top Yukawa $\lambda_t \cong 1$ recently measured [1], and with first order phase transition arising from $O(1)$ [14] Higgs quartic couplings, where there are a total of 7 in absence of Z_2. It was further inferred with emergent alignment that the exotic scalars are likely sub-TeV [15] in mass and populate 300–600 GeV, opening up a search program at the LHC [16–20].

The large $\mathrm{Im}\rho_{tt}$ at $O(\lambda_t) \sim 1$ that drives EWBG brings up our theme of how to survive eEDM. A typical two-loop Barr-Zee diagram [21] for eEDM is given in Fig. 1. To cancel the leading effect due to ρ_{tt} *and* ρ_{ee}, specifically the $\phi\gamma\gamma^*$ insertion, one finds [22]

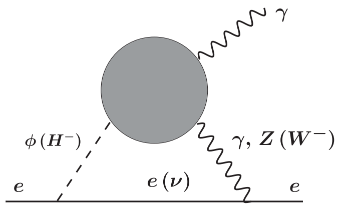

FIG. 1. A two-loop Barr-Zee diagram for electron EDM with extra Yukawa coupling ρ_{ee} on electron line, and top (hence ρ_{tt}) and W run in the gray blob for neutral scalar $\phi = h$, H, A. Neutron EDM has many more contributions, including u- and d-quark chromo-moments and the Weinberg operator.

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

with $r \simeq 0.7$, where the first relation follows from a phase-lock between ρ_{ee} and ρ_{tt} for $\phi = A$. Equation (1) is remarkable in that the ρ matrices seem to "know" the quark mass and mixing hierarchies in SM.

The purpose of this paper is to show that the combined eEDM and nEDM effort provides the cutting edge probe of ρ_{tt}-driven EWBG in g2HDM: as the experimental competition heats up, we may first observe eEDM in the $10^{-30} - 10^{-31}$ e cm range, followed by confirmation at n2EDM at PSI for $d_n \sim 10^{-26} - 10^{-27}$ e cm in about a decade. But as we will illustrate a general cancellation mechanism for nEDM itself, a more advanced nEDM experiment may confirm down to 10^{-28} e cm in two decades. To unravel the underlying dynamics, the "decadal mission" [23] with direct exotic scalar search at the LHC, flavor physics explorations with LHCb and Belle II, plus μ and τ studies, would be needed.

g2HDM and EDMs. For simplicity, we assume CP-conserving [15,24] Higgs potential of g2HDM, removing it as a CPV source without discussing it any further here, so CPV is relegated to extra Yukawa couplings. As already stated, $O(1)$ Higgs quartics supply [12,14] the prerequisite first order EW phase transition for BAU, which is a bonus in g2HDM.

To clarify the flavor and EWBG discussion in the Introduction, without any Z_2 symmetry, there are extra Yukawa matrices ρ^f for charged fermions $f = u, d, \ell$ [18,24], which are complex and nondiagonal,

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

with generation indices i, j summed over, $L, R = 1 \mp \gamma_5$, and $s_\gamma \equiv \sin\gamma$. The A, H^+ couplings are c_γ-independent, while in the alignment limit ($c_\gamma \to 0$, $s_\gamma \to -1$), h couples diagonally and H couples via extra Yukawa couplings $-\rho_{ij}^f$, which can drive BAU. Thus, besides mass-mixing hierarchy protection [9] of FCNCs, alignment provides [15] further safeguard, such as for $t \to ch$, without the need of NFC. Furthermore, the $\mu_{12}^2\Phi^\dagger\Phi'$ term in the Higgs potential is eliminated after symmetry breaking by minimization, leaving a unique $h - H$ mixing parameter, η_6, which can be $O(1)$ [15] for small c_γ, with H, A, H^+ likely in the 300–600 GeV mass range.

Considering how effective g2HDM *evades* stringent flavor constraints, and to address the question "What makes g2HDM so well hidden so far?", we guessed a "rule of thumb" [25] for flavor control:

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

with $j \neq 1$. This allows $\rho_{tt} = \mathcal{O}(1)$ but $\rho_{bb} \simeq 0.02$. However, ρ_{ij}^d seems to be an order of magnitude weaker by flavor constraints.

With complications of transport equations for EWBG [12], the simplified case with H, A, H^+ degenerate at 500 GeV was studied. The ACME experiment [2] taught us the lesson to keep the weakest ρ_{ee} coupling in the Barr-Zee diagrams of Fig. 1, where the exquisite cancellation mechanism of Eq. (1) was uncovered [22]. The prowess of ACME, however, led one to illustrate with the timid $|\rho_{tt}| \simeq 0.1$, which we seek to extend here.

Results: Interplay of eEDM and nEDM. In our numerical illustration, we shall keep the degeneracy at 500 GeV, but explore a broader range of

$$\mathrm{Re}\rho_{tt} = \mathrm{Im}\rho_{tt} = -0.1, \ -0.2, \ -0.3, \tag{4}$$

and follow the numeric ansatz [22] for $f = u, c; d, s, b$,

$$\mathrm{Re}\rho_{ff} = -r\frac{\lambda_f}{\lambda_t}\mathrm{Re}\rho_{tt}, \ \ \mathrm{Im}\rho_{ff} = +r\frac{\lambda_f}{\lambda_t}\mathrm{Im}\rho_{tt}, \tag{5}$$

where $r \simeq 0.71$ is a combination of loop functions that is insensitive [22] to exotic Higgs spectrum.

In Fig. 2 we illustrate the *natural* "flavor tuning" [22] of Eq. (1), for ρ_{tt} values in Eq. (4) and numeric ansatz of Eq. (5), where both bounds of ACME [2] and JILA [3] are shown. We take some liberty in the visual effect of the light purple band, with left side taken from the red-dashed $d_e^{\phi\gamma}$ curve [22], and right side from the red-solid d_e curve. This is in part because, though the cancellation point (black-solid curve sitting in the middle, with final shift from C_S effect [22]) is insensitive to the spectrum [22], there should be some spread in exotic scalar masses, which we refrain from exploring.

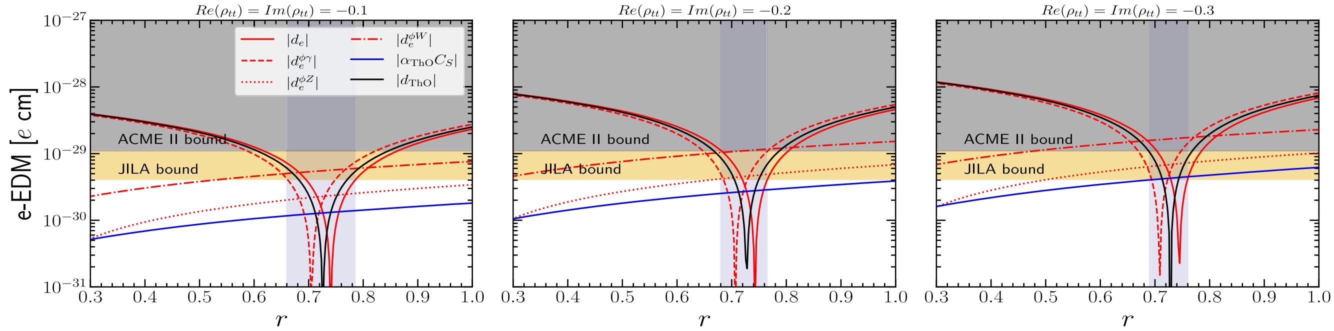

FIG. 2. Cancellation mechanism [22] for eEDM for ρ_{tt} values in Eq. (4), $c_\gamma = 0.1$, and $m_H, m_A, m_{H^+} = 500$ GeV.

From left to right in Fig. 2, as ρ_{tt} strength rises, the "funnel" is raised, but at 10^{-30} e cm, the opening of the funnel is still decent, suggesting a still robust discovery likelihood, although by 10^{-31} e cm, it approaches a pinpoint and may no longer seem plausible. In any case, these plots are for numeric illustration.

Turning to nEDM, besides effects of ρ_{uu} and ρ_{dd} through Barr-Zee type diagrams, there are also chromo-moments and the Weinberg operator, with progressively larger theory uncertainties. While the classic review of Pospelov and Ritz [26] continue to be widely cited, it is a bit dated. We use the more recent formula [27],

$$d_n = -0.20 d_u + 0.78 d_d + e(0.29\tilde{d}_u + 0.59\tilde{d}_d) + e23\ \text{MeV} C_W, \tag{6}$$

where we evaluate chromo-moments $\tilde{d}_{u,d}$ and the Weinberg operator C_W term [28] by following Refs. [29,30], respectively. A recent discussion on uncertainties can be found in Ref. [28].

We give in Fig. 3 the scan plot for $r \in [0.6, 0.8]$ for same range of ρ_{tt} and exotic Higgs masses as in Fig. 2, showing both the JILA bound [3] on eEDM, and PSI bound [4] on nEDM. One survives the PSI bound even for $|\rho_{tt}| \simeq 0.3\sqrt{2}$, while $r \simeq 0.7$ nicely illustrates the *natural* flavor cancellation of eEDM. The follow-up experiment to nEDM at PSI, i.e. n2EDM [31], plans to reach down to 10^{-27} e cm sensitivity within a decade, and should be able to cover the range illustrated in Fig. 3.

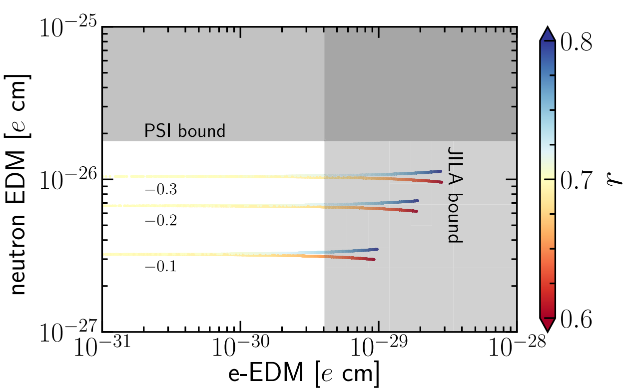

FIG. 3. Combined scan result for $r \in [0.6, 0.8]$ for electron and neutron EDM for same range of ρ_{tt} and exotic Higgs masses as in Fig. 2, with ρ_{ff} fixed according to Eq. (5).

But we should admit that Eq. (5) is nothing but an ansatz [22] for sake of numeric illustration. The fact is, we have little knowledge of the actual strength of extra Yukawa couplings such as ρ_{uu}. Our "rule of thumb" of Eq. (3) is our guess of the "flavor protection" in g2HDM, which echoes the remarkable cancellation mechanism of Eq. (1) for eEDM. Taking Eq. (3) literally, it states that $|\rho_{uu}| = O(\lambda_u)$, with phase unknown. Thus, taking the usual sense of "an order of magnitude," we vary

$$|\rho_{uu}| \in [0.3\lambda_u, 3\lambda_u], \quad \arg\rho_{uu} \in [-\pi, \pi], \tag{7}$$

while keeping other ρ_{ff}s according to Eq. (5). This explores the impact of ρ_{uu} strength and phase on nEDM. Since ρ_{tt} is in the 3rd quadrant in Eq. (4), in the convention of Eq. (7), $\arg\rho_{tt} = -3\pi/4$.

A scan plot of the variation of Eq. (7) is given in Fig. 4 for illustration. For negative $\arg\rho_{uu}$, nEDM is closer to the PSI bound (red and yellow scan points), and for the largest $|\rho_{tt}| = 0.3\sqrt{2}$ (right plot), the bound cuts a little bit into the scan space. But interestingly, for positive $\arg\rho_{uu}$, i.e. *opposite* the sign of $\arg\rho_{tt}$, the blue scan points extend below 10^{-27} e cm, which can evade n2EDM of PSI. Therefore, the scan in Fig. 4 illustrates a *general* cancellation mechanism that may well be operative in *Nature* for neutron EDM. It can be probed, however, at more advanced nEDM facilities, such as the nEDM experiment under construction at the Spallation Neutron Source [32] at Oak Ridge National Lab (ORNL), which utilizes UCN and can probe down to 10^{-28} e cm. Although this may go beyond the next decade, the possibility appears to be covered fully, as the blue scan points tend to run out by 10^{-28} e cm.

Thus, if g2HDM is the source of EWBG, the combined effort of eEDM and nEDM experiments seem poised for major discoveries in the coming decade or two.

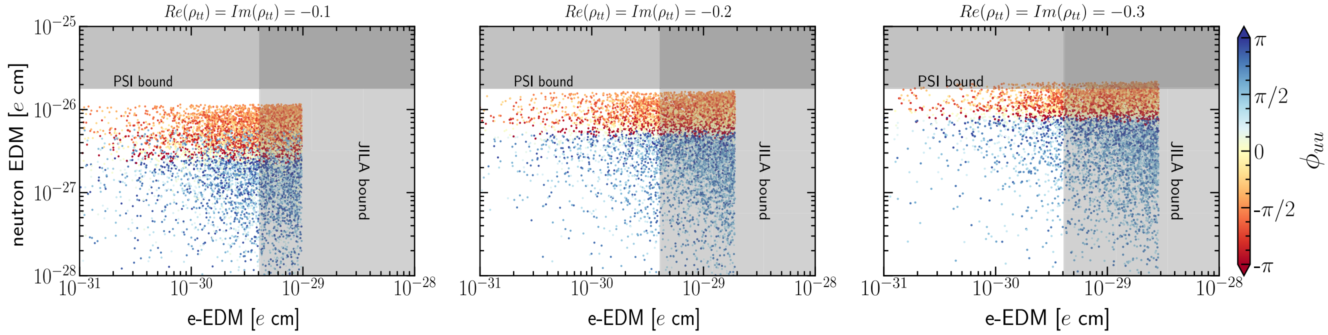

FIG. 4. Scan for eEDM and nEDM using Eq. (1) as in Fig. 3, except varying $|\rho_{uu}| \in [0.3\lambda_u, 3\lambda_u]$, $\phi_{uu} \in [-\pi, \pi]$.

Discussion and summary. This work was actually stimulated by the ability at the LHC to probe top CPV,[1] i.e. top chromo-moments [38]. As this is a new beginning, top chromo-moment bounds are still rather weak. We realized instead that prospects for electron and neutron EDMs are rather good in g2HDM.

We have kept H, A, and H^+ degenerate at 500 GeV and have not revisited EWBG, but we have checked that features at 300 GeV are quite similar, where baryogenesis should be more efficient. The actual parameter space should therefore be considerably larger. For example, breaking the degeneracy, one would need to face precision electroweak constraints [1], where either one keeps $m_A = m_{H^+}$ (custodial symmetry), or take the twisted-custodial [39] case of $m_H = m_{H^+}$.

We have emphasized as our theme that it is nontrivial that g2HDM can provide electroweak baryogenesis while surviving the eEDM constraint, a remarkable feat rooted in the *flavor* structure as revealed by the SM sector. With exotic H, A, and H^+ bosons sub-TeV in mass, search programs at the LHC [19,20] have started.

For sake of discussion, a study [40] of $pp \to A/H \to \tau\tau, \tau\mu$ with ρ_{tt}, $\rho_{\tau\tau}$, and $\rho_{\tau\mu}$ comforming with Eq. (3), found consistency with current searches [1], but could be promising at the High-Luminosity LHC. Reference [17] studied $pp \to bH^+ \to bt\bar{b}$ and considered $H^+ \to t\bar{b}$ constraints, but there are no experimental results so far on the specific processes. For a discussion of good flavor probes, see Ref. [25]. More recently, a global analysis of $b \to s\gamma$ observables (including inclusive and exclusive $b \to s\gamma$ decays and CP asymmetries) in g2HDM was carried out [41]. But since ρ_{bb} is rather small in our setup [Eq. (5)], the $b \to s\gamma$ constraint can be safely ignored.

Ultimately, any BSM theory of EWBG would need to face the litmus test of surviving the eEDM bound [3]. We may sound optimistic in the discovery prospect for eEDM at 10^{-30} e cm. Note that both the JILA and ACME bounds are still consistent even with $O(10^{-29})$ e cm. Considering possible fluctuations in data, discovery not far below the existing bound is quite plausible, especially if *Nature* has already marked g2HDM up for baryogenesis. A known example is the ARGUS discovery [42] of B^0–$\bar{B}^0$ mixing, which practically sits right on top the previous CLEO [43] bound.

In summary, g2HDM without Z_2 symmetry achieves baryogenesis but can evade the eEDM bound by *natural* flavor tuning. Electron EDM may harbinger a new era, echoed not long after by neutron EDM; while this does not prove g2HDM is behind EWBG, it would likely become a frontrunner. With exotic Higgs search at the LHC, ongoing efforts at Belle II and other flavor fronts, and with excellent prospects for electron and neutron EDM measurements, the future looks bright for unveiling what may actually lie behind baryogenesis.

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[1]For collider analysis of CPV $t\bar{t}h$ interaction and its interplay with EDMs, see Refs. [33–36]. See also Ref. [37].

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