Electric Dipole Moments in a General Two-Higgs Doublet Model

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Abstract

Something something motivation, baryogenesis, cp violation. Something something general two-Higgs doublet model (g2HDM). Something something precision experiments, electric dipole moment (EDM), leptons, quarks.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

One of the biggest unanswered questions of particle physics is that of baryogenesis. Specifically, if electroweak baryogenesis (EWBG) [**?**] were to occur, one would require very large CP violation (CPV) beyond the Standard Model (BSM), since the SM currently houses all its CPV in the CKM matrix [**?**]. However, such large BSM-CPV should have led to new discoveries at the LHC, which evidently is *not* what has been observed. Moreover, in the low-energy precision frontier, electric diploe moments (EDMs) provide a *litmus test* for CPV effects, and experiments have achieved higher and higher precision without discoveries, setting ever more stringent bounds. In a sense, these “tabletop experiments” are directly competing with the LHC!

Chapter 2

The General Two-Higgs Doublet Model

Following Gell-Mann's *Totalitaian principle*, as a natural extension to the SM, we can introduce a second Higgs doublet. This second doublet couples to all flavors and families of fermions, and has no symmetry requirement imposed upon it. Hence, it is referred to as the "General Two Higgs Doublet Model", or g2HDM for short.

The g2HDM Lagrangian can be written as [**?**, **?**]

$$\mathcal{L} = -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i \Big[\Big(-\lambda_i^f \delta_{ij} s_\gamma + \rho_{ij}^f c_\gamma \Big) h + \Big(\lambda_i^f \delta_{ij} c_\gamma + \rho_{ij}^f s_\gamma \Big) H - i\,\mathrm{sgn}(Q_f) \rho_{ij}^f A \Big] R\, f_j$$
$$-\bar{u}_i \left[(V\rho^d)_{ij} R - (\rho^{u\dagger} V)_{ij} L \right] d_j H^+ - \bar{\nu}_i \rho_{ij}^L R\, \ell_j H^+ + \text{h.c.}, \tag{2.1}$$

where the generation indices i, j are summed over, L, $R = (1 \pm \gamma_5)/2$ are projections, V is the CKM matrix for quarks and unity for leptons. λ^f are the SM Yukawa matrices, and ρ^f are the extra-Yukawa matrices. A key takeaway is that each family of fermions (u-type, d-type, lepton) is associated with its own extra-Yukawa ρ matrix. In this scenario, flavor-changing neutral Higgs (FCNH) processes are controlled by *flavor hierarchies* and *alignment*. Flavor hierarchies means that the ρ matrices somehow "know" the current flavor structure of the SM, represented by the "rule of thumb" [**?**]

$$\rho_{ii} \lesssim \mathcal{O}(\lambda_i), \quad \rho_{1i} \lesssim \mathcal{O}(\lambda_1), \quad \rho_{3j} \lesssim \mathcal{O}(\lambda_3), \tag{2.2}$$

with $j \neq 1$. Alignment means that $c_\gamma \equiv \cos\gamma = \cos(\beta - \alpha)$ is small. Consequently, the SM-like Higgs h is mostly controlled by the SM Yukawas, while the newly introduced ρ matrices control the exotic Higgses $H, A, H^\pm$. A remarkable feature of g2HDM is that $\mathcal{O}(1)\,\rho_{tt}$ can drive EWBG through [**?**] $\lambda_t \mathrm{Im}\rho_{tt}$. This feature, however, is immediately put the test in the realm of EDMs.

Chapter 3

Electric Dipole Moment

The effective interaction term that produces EDM d_f for a fermion f is the dimension-5 operator

$$-\frac{i}{2}d_f\left(\bar{f}\sigma^{\mu\nu}\gamma_5 f\right)F_{\mu\nu}. \tag{3.1}$$

In g2HDM, the first finite contribution to EDM appears at one-loop. The dipole operator is chirality violating, so an additional mass insertion is required on the fermion line to obtain the correct chiral structure. This means that those one-loop diagrams with lighter leptons in the loop are chirally suppressed. The next contribution to this operator is the two-loop Barr-Zee diagram. Naively, one would directly assume these to be loop-suppressed. However, the two-loop diagram having only one chirality flip, compared to three chirality flips for the one-loop diagram, effectively compensates for the loop suppression.

It is straightforward yet tedious to calculate the two-loop Barr-Zee diagrams analytically, but it can be done nonetheless, as seen in the original paper by Barr and Zee [**?**] for neutral scalar contributions with a top quark or gauge boson in the loop, as well as later extensions [**?**] to other loop diagrams. The final formulae for tha various Barr-Zee diagrams are as follows, following the notations of [**?**],

List the formulae here or in an appendix?

For quarks, they participate in the strong interaction, so there will be QCD-related effects. This can be found in two additional terms in the Lagrangian: the chromo-EDM $\tilde{d}_f$ for fermion f, and the Weinberg term C_W for gluon interactions [**?**], written as

$$-\frac{ig_s}{2}\tilde{d}_f\left(\bar{f}\sigma^{\mu\nu}T^a\gamma_5 f\right)G^a_{\mu\nu} \qquad\qquad -\frac{1}{3}C_W f^{abc}G^a_{\mu\sigma}G^{b,\sigma}_{\nu}\tilde{G}^{c,\mu\nu} \tag{3.2}$$

The formulae for calculating the cEDM are

The contribution of the Weinberg diagram can be evaluated using QCD running.

Chapter 4

Electric Dipole Moment of Leptons

Naturally, following the framework laid out previously, we want to perform calculations on the various leptons. A brief review of past experimental results shows that the experimental development of electron EDM (eEDM) over the past few years has been remarkably rapid. Just earlier last year, JILA [**?**] has surpassed the previous bound from ACME [**?**] and pushed the precision of eEDM down to $|d_e| < 4.1 \times 10^{-30}\, e\,\mathrm{cm}$. It is noteworthy to point out that these eEDM experiments are relatively small in scale, "tabletop experiments" even when compared to behemoths like the LHC, which makes the extreme precision achieved all the more impressive. For the electron, an extensive study in eEDM in g2HDM can be found in the 2018 and 2020 papers of Fuyuto, Senaha, and Hou (Refs. [**?**]). Our investigation on eEDM is essentially an extension of the 2020 paper to a larger parameter space. Motivation due to tension between baryogenesis v.s. precision measurements. Cancellation mechanism, re-empasize "rule of thumb". Present results. Comment on prospect of future experiments, as well as interplay with neutron EDM, which will be discussed later.

After the electron, we move on to its slightly heavier cousin, the muon.

Lastly, we analyze the heaviest lepton, the tau. On the experiment front, the precision of tauEDM measurements are still pretty low. As seen in Figure **??**, when performing the same analysis as the muon, our predicted values are still several orders of magnitude below current experimental results. Further precision or methodology improvements are required for a more fruitful analysis of tauEDM, so we just present our results here without much further comment.

Chapter 5

Electric and Chromo-electric Dipole Moment of Quarks

After the analysis for leptons, we turn our gaze towards EDMs involving quarks. The prime candidate in this case would be the neutron EDM (nEDM). As mentioned in the theory section, there are additional chromo-EDM and Weinberg term contributions to take into account. We use the recent formula [**?**]

$$d_n = -0.20\, d_u + 0.78\, d_d + e\,(0.29\, \tilde{d}_u + 0.59 \tilde{d}_d) + e\, 23\ \text{MeV}\, C_W \tag{5.1}$$

to estimate the nEDM. We evaluate the contributions to $\tilde{d}_{u,d}$ and C_W in g2HDM by following Refs. [**?**] and [**?**], with discussion on theoretical uncertainties found in Ref. [**?**]. We present the results for nEDM in Fig. **??**, as well as combined results for eEDM and nEDM in the range $r \in [0.6, 0.8]$ in Fig. **??**, with the ansatz applied. Interestingly, our predictions for nEDM are not too far below the current experimental bound. We relax the ansatz for ρ_{uu}, and explore the range of $\mathcal{O}(\lambda_u)$. We present our results. We comment on the *natural* cancellation present between ρ_{uu} and ρ_{tt}. When viewed together with eEDM, the experimental prospects for discovery are promising.

Chapter 6

Conclusion

Some comments, perhaps regarding the masses and degeneracy of the heavy Higgses.

We present an analysis of various EDMs of fundamental particles in the framework of a g2HDM. We note that to evade precision bounds while satisfying the conditions for baryogenesis, a cancellation is possible, which is also an indicator of an underlying *flavor hierarchy*. This is most prevalent in eEDM, where bounds are the strongest, and experimental precision improving rapidly. We analyze muEDM, with our predictions still being a couple orders of magnitude below current experimental bounds. Comment on interplay with muon g-2. We present results for tauEDM, but provide no further analysis since the bounds are still too imprecise. We analyze quark EDM through nEDM, and optain promising prospective results, especially when viewed together with eEDM. We stress that this is a notewothy area to pay attention to in the upcoming decade or two.

Reference