Lepton and Neutron EDM as Probe of General Two Higgs Doublet Model

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Motivation

- Baryogenesis: CP violation (CPV) beyond Kobayashi-Masakawa
- Electric dipole moments (EDMs): Precision measurements that put constraints on CPV

g2HDM

The *general* two Higgs doublet model (g2HDM)

- Add a second Higgs doublet, natural extension of SM
- No imposed $\mathbb{Z}_2$ symmetry constraint (hence *general*)
- Flavor-changing neutral Higgs couplings controlled by flavor hierarchies and alignment ($c_\gamma \equiv \cos\gamma = \cos(\beta - \alpha)$ is small)

Lagrangian:

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

g2HDM

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

Takeaway

c_γ small (alignment)

- One ρ matrix per fermion family (u, d, ℓ)
- SM Yukawas control SM-like Higgs, ρ controls exotic Higgses

Important parameters

- $\mathcal{O}(1)$ ρ_{tt} can drive baryogenesis through[1] $\lambda_t \, \mathrm{Im}\, \rho_{tt}$
- ρ_{tt} along with ρ_{ff} drive EDM for fermion f

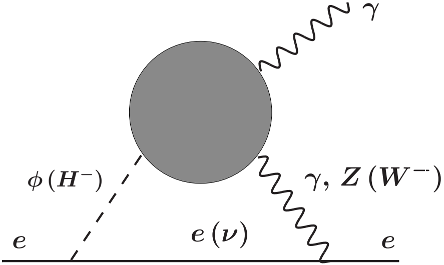
[1] K. Fuyuto, W.-S. Hou, E. Senaha, PLB**776**(2018)402, [1705.05034]

g2HDM and EDMs

Interaction term for EDMs:

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

Main drive for EDMs in g2HDM is two-loop Barr-Zee diagram[2].



[2] S.M. Barr and A. Zee, PRL**65**(1990)21

Electron EDM

Current bound for electron EDM (eEDM)

- ACME (2018)[3]: $|d_e| < 1.1 \times 10^{-29}\ e\,\mathrm{cm}$
- JILA (2023)[4]: $|d_e| < 4.1 \times 10^{-30}\ e\,\mathrm{cm}$

Very high precision from "tabletop experiments"!

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

[4] T.S. Roussy et al., Science **381** (2023) 46

Electron EDM

Large ρ_{tt} needed for baryogenesis, but would also drive large EDMs.

A previous study by Fuyuto, Senaha, and Hou[5] proposed a "cancellation ansatz" between ρ_{ee} and ρ_{tt} to evade eEDM bounds.

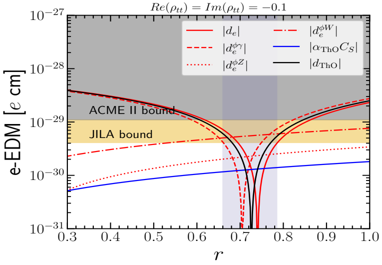
$$\mathrm{Re}\,\rho_{ee} = -r\frac{\lambda_e}{\lambda_t}\,\mathrm{Re}\,\rho_{tt}, \qquad \mathrm{Im}\,\rho_{ee} = +r\frac{\lambda_e}{\lambda_t}\,\mathrm{Im}\,\rho_{tt} \tag{1}$$

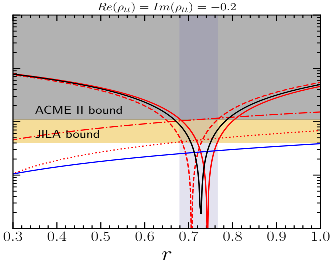
which gives both a flavor hierarchy $|\rho_{ee}|/|\rho_{tt}| \sim \lambda_e/\lambda_t$ that reflects SM, as well as a phase lock. r depends on loop functions.
For sake of numerical illustration of the flavor hierarchy, we extend this ansatz to all ρ_{ff} except top.

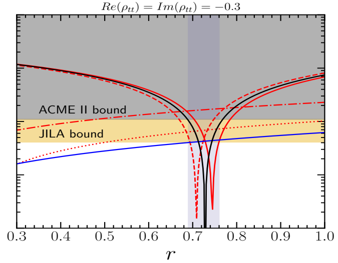
[5] K. Fuyuto, W.-S. Hou, E. Senaha, PRD**101**(2020)011901(R), [1910.12404]

Electron EDM

We explore larger range of $|\rho_{tt}|$. ($c_\gamma = 0.1,\ m_{H,A,H^\pm} = 500\,\mathrm{GeV}$)







Allowed window shrinks.

Echo in Neutron EDM?

Current bound for Neutron EDM (nEDM)

- PSI (2020)[6]: $|d_n| < 1.8 \times 10^{-26}\ e\,\mathrm{cm}$

Precision poorer than eEDM.

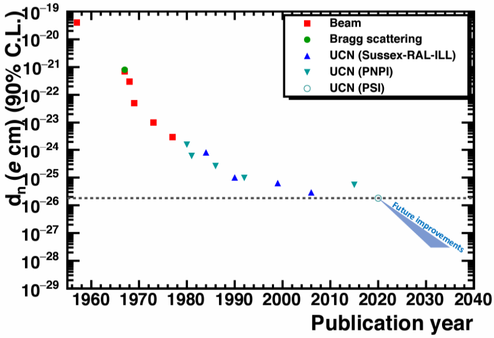


Figure from Snowmass report[7]

[6] C. Abel et al. [nEDM], PRL**124**(2020)081803, [2001.11966]

[7] R. Alarcon et al. [2203.08103]

Neutron EDM

Two additional contributions:

Chromo-EDM of fermions and Weinberg term for gluons

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

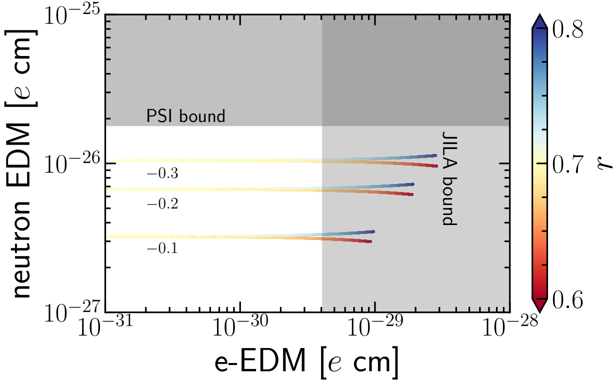
We use the following formula[8]

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

[8] Hisano, Kobayashi, Kuramoto, Kuwahara, JHEP **11** (2015) 085, [1507.05836]

Neutron EDM, even $|\rho_{tt}| \sim 0.42$ not ruled out!

We show combined results for eEDM and nEDM.



Note: $r \approx 0.7$ is a good loop function value.

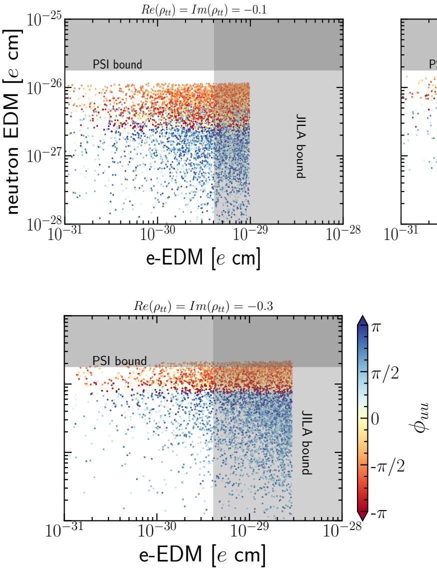
Neutron EDM

Since the ansatz is just numerical illustration of flavor hierarchy, we further explore[9] $\rho_{uu} \sim \mathcal{O}(\lambda_u)$ by varying

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

[9] W.-S. Hou, G. Kumar, PRD **102**(2020)115017, [2008.08469]

Neutron EDM, with $|\rho_{uu}| \in [0.3\lambda_u, 3\lambda_u]$, $\arg \rho_{uu} \in [-\pi, \pi]$



Blue dots have lower nEDM

$\Rightarrow$ *natural* "cancellation mechanism"
nEDM could be much below
PSI bound.

Discussion and Summary

- Future sensitivity:
  - n2EDM at PSI ($\sim 10^{-27}$)
  - Spallation Neutron Source at ORNL ($\sim 10^{-28}$)

  can probe most of our projected nEDM range.
- Prospect of Discovery:
  If g2HDM is indeed behind electroweak baryogenesis, then combined eEDM-nEDM are poised for **Discovery**.
- Note on Heavy Higgs masses: we have taken $H, A, H^{\pm}$ degenerate at $500\,\mathrm{GeV}$; if nondegenerate, need to face electroweak precision constraints.