Electron EDM and dark sectors

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Plan

1. Intro: Why EDMs?
2. Recent progress with electron EDMs
3. **Can "dark" sectors** (for this talk = *renormalizable extension of SM, consisting only of neutral particles*) **induce observable levels of electron EDMs?**
4. Models with heavy Dirac neutrinos and Higgs-portal singlets.
5. Sensitivity of electron-EDM-like observables to the hadronic CP-violation.
6. *Conclusions*

Purcell and Ramsey (1949) ("How do we know that strong interactions conserve parity?" $\longrightarrow |d_n| < 3 \times 10^{-18} e\mathrm{cm}.$)

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$d \neq 0$ means that both P and T are broken. If CPT holds then CP is broken as well.

CPT is based on locality, Lorentz invariance and spin-statistics = very safe assumption.

search for EDM = search for CP violation, if CPT holds

Relativistic generalization

$$H_{\mathrm{T,P-odd}} = -d\mathbf{E} \cdot \frac{\mathbf{S}}{S} \rightarrow \mathcal{L}_{\mathrm{CP-odd}} = -d\frac{i}{2}\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu},$$

corresponds to dimension five effective operator and naively suggests $1/M_{\text{new physics}}$ scaling. Due to $SU(2) \times U(1)$ invariance, however, it scales as m_f/M^2.

Why bother with EDMs?

Is the accuracy sufficient to probe TeV scale and beyond?

Typical energy resoultion in modern EDM experiments

$$\Delta\text{Energy} \sim 10^{-6}\text{Hz} \sim 10^{-21}\text{eV}$$

translates to limits on EDMs

$$|d| < \frac{\Delta\text{Energy}}{\text{Electric field}} \sim 10^{-25}\text{e} \times \text{cm}$$

Comparing with theoretically inferred scaling,

$$d \sim 10^{-2} \times \frac{1\ \text{MeV}}{\Lambda_{CP}^2},$$

we get **sensitivity to**

$$\Lambda_{CP} \sim 1\ \text{TeV}$$

Comparable with the LHC reach! EDMs are one of the very few low-energy measurements sensitive to the fundamental particle physics.

Current Experimental Limits

"paramagnetic EDM", Berkeley experiment

$$|d_{\rm Tl}| < 9 \times 10^{-25} e\, {\rm cm}$$ Interpreted $|d_e| < 1.6 \times 10^{-27}$

"diamagnetic EDM", U of Washington experiment

$$|d_{\rm Hg}| < 2 \times 10^{-28} e\, {\rm cm}$$

factor of 7 improvement in 2009! And another factor of 4 in 2016

$$|d_{\rm Hg}| < 3 \times 10^{-29} e\, {\rm cm}$$ $7.4 \times 10^{-30}\, e$ cm

neutron EDM, ILL experiment

$$|d_n| < 3 \times 10^{-26} e\, {\rm cm}$$

Notice that Thallium EDM is usually quoted as $d_e < 1.6\ 10^{-27}$ cm

bound. It was modestly improved by YbF results. $|d_e| < 1.1 \times 10^{-29}$

2013 ThO result by Harvard-Yale collaboration: $|d_e| < 8.7 \times 10^{-29}$

"Confirmed" using different techniques at JILA, $|d_e| < 1.3 \times 10^{-28}$

“Paramagnetic” EDMs:

- Paramagnetic EDM (EDM carried by electron spin) can be induced not only by a purely leptonic operator

$$d_e \times \frac{-i}{2}\,\overline{\psi}\sigma_{\mu\nu}\gamma_5 F_{\mu\nu}\psi$$

but by semileptonic operators as well:

$$C_S \times \frac{G_F}{\sqrt{2}}\,\overline{N}N\,\overline{\psi}i\gamma_5\psi$$

- Only a linear combination is limited in any single experiment. ThO 2018 ACME result is:

  $|d_e| < 1.1\times10^{-29}$ e cm at $C_S = 0$

  $|C_S^{singlet}| < 7.3\times10^{-10}$ at $d_e = 0$

- In the SM the answer is very small, and C_S is more important, both for Θ_{QCD} and δ_{CKM}.

Recent progress is very significant

- From 10^{-27} cm to 10^{-29} cm is a factor of 1/100, and sensitivity to Λ is increased by an order of magnitude.

- In terms of probing Λ, progress in electron EDM is similar to the transition from Tevatron to the LHC [but of course requires flavour-diagonal CP-violation]

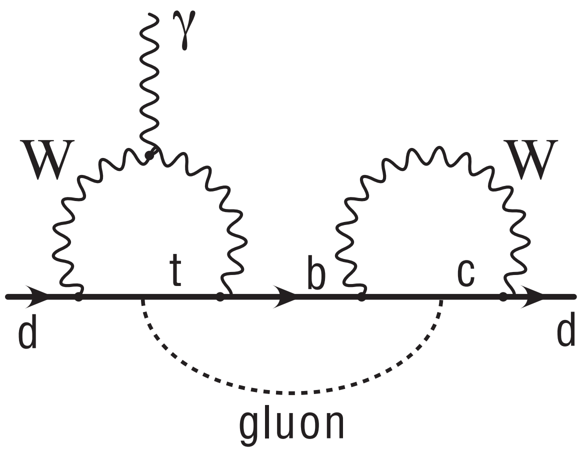
- E.g. EDMs indirectly probe contact CP-odd Higgs-gamma-gamma coupling with accuracy far greater than usual h-γ–γ.

- With some luck extends sensitivity to super-partners to a multi-10-TeV/100 TeV regime.

- More progress with d_e could be anticipated.

  (1806.06774 suggests a possibility of going down to 10^{-34} e cm)

EDMs from CKM



CKM phase generates tiny EDMs:

$$d_d \sim \mathrm{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*)\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$

$$< 10^{-33} e\text{cm}$$

Direct quark EDMs identically vanish at 1 and 2 loop levels (Shabalin, 1981). 3-loop EDMs are calculated by Khriplovich.

d_e first appears at 4 loops (Khriplovich, MP, 1991) $< 10^{-38}$ e cm

Two questions for today

- Q1: If in the next round of improvements we see a non-zero electron EDM, does it imply new physics above the EW scale with new charged particles (SUSY, ED, LR models, multi-Higgs models etc)? Or electron EDM can emerge as a consequence of new low-energy UV complete sectors?

- Q2: given rapid progress in ThO measurements, what is the current sensitivity to purely hadronic CP violation?

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(S. Okawa, MP, A. Ritz, *to appear*)

- Q2: given rapid progress in ThO measurements, what is the current sensitivity to purely hadronic CP violation?

(V. Flambaum, MP, A. Ritz, Y. Stadnik, *to appear*)

Neutral "portals" to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda\, S^2 + A\, S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$L H N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

I'll stick to renormalizable UV complete extensions for this talk (i.e. will not touch axions or multi-Higgs theories…)

A systematic search for light particles coupled through vector, Higgs, neutrino and axion portal has intensified in recent years.

(See recent "Physics Beyond Colliders" working group summary, arxiv 1901.09966, for the up-to-date limits)

Precision frontier: UV physics or IR?

Typical approach: we measure an observable (e.g. $\mu \rightarrow e\, \gamma$, EDM, rare meson decays etc), we perform calculation of the same quantity in the SM, take a difference, and whatever is left is interpreted in terms of physics at a TeV, 10 TeV, XXX TeV scales – *all of them being UV scales*.

More correct approach: Assume that New Physics consist of UV pieces, Assume IR pieces or both,

$$\mathcal{L}_{\rm NP} = \mathcal{L}_{\rm UV} + \mathcal{L}_{\rm IR}.$$

$$\mathcal{L}_{\rm UV} = \sum_{d\geq 5} \frac{1}{\Lambda_{\rm UV}^{d-4}} \mathcal{O}_d. \;\; \mathcal{L}_{\rm IR} = \kappa B^{\mu\nu} V_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N LHN + \mathcal{L}_{\rm hid}$$

If result for NP is consistent with 0, we can set constraints on both. If it is non-zero: then *more work is required in deciding IR or UV*

UV physics or IR: examples of NP that we know

Neutrino oscillations: We know that new phenomenon exists, and if interpreted as neutrino masses and mixing, is it coming from deep UV, via e. .g Weinberg's operator

$$\mathcal{L}_{\rm NP} \propto (HL)(HL)/\Lambda_{\rm UV} \ \text{with} \ \Lambda_{\rm UV} \gg \langle H \rangle$$

or it is generated by *new IR field*, such as RH component of Dirac neutrinos? *New dedicated experimental efforts are directed in trying to decide between these possibilities.*

Dark matter: 25% of Universe's energy balance is in dark matter: we can set constraints on both. If it is embedded in particle physics, then e.g. neutralinos or axions imply new UV scales.

However, *there are models of DM where NP is completely localized in the UV, and no new scales are necessary*.

New efforts underway both in the UV and IR category.

[Some people at this meeting believe that] ***flavour anomalies*** *may already be pointing to NP. It necessarily has states in the UV. Discrepancy in (g-2)$_\mu$, on the other hand, if real, does not unambiguously point to either IR or UV.*

Classification of all precision observables

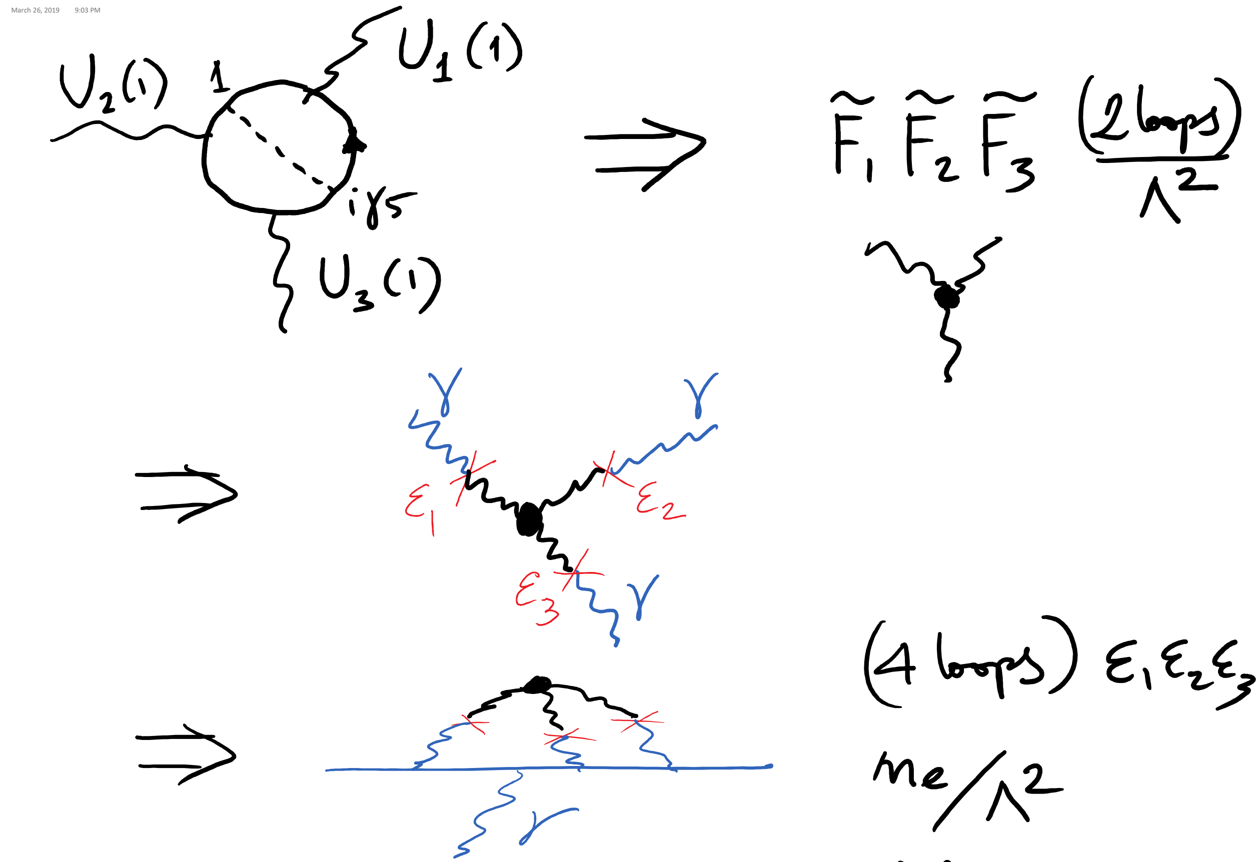
In 2015, LeDall, MP, Ritz classified all precision observables from that point of view, IR or UV or both. [*Among EDMs, for example, neutron EDM can be a consequence of UV physics, or IR physics, theta term in QCD*]

Electron EDM close to current sensitivity – no EW or below EW models were found.

- *This question could be important if one sees a nonzero d_e. Would it then imply new physics at high scale and "justify" new collider, or IR models can be found?*

$m_e << \Lambda$; $m_W \rightarrow$ infinity

In this limit, only kinetic mixing [and some new gauge symmetries] remain as viable option. You need 3 new U(1) gauge groups and CP violation in the dark sector.

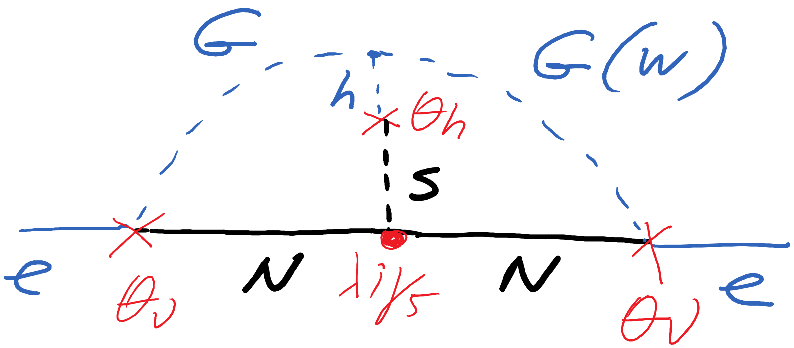


Minimum is 4 loops and 3 kinetic mixings. For Λ below 10 GeV, the result is too small

assuming $m_2, m_1, m_3 \sim \Lambda$.
$m_1 \neq m_2 \neq m_3$

If it is only 1 extra U(1), then interm. operator is FFFFdual, and de ~ $\varepsilon^4 \times 5$ loops

Model with heavy Dirac Neutrinos and Higgs portal singlets



Edm of electron is generated at 2 loops and 3 mixing angles

$$HLN; \quad (H^\dagger H)S; \quad S\overline{N}i\gamma_5 N \quad \text{portals}$$

CP violation in the dark sector

Mixing angles θ_h and θ_ν do not have to be small if S, N are EW scale

Two-loop calculation

We have performed calculation in $\alpha_W \rightarrow 0$ limit, where only Goldstone loops matter (and for $m_N > m_W$).

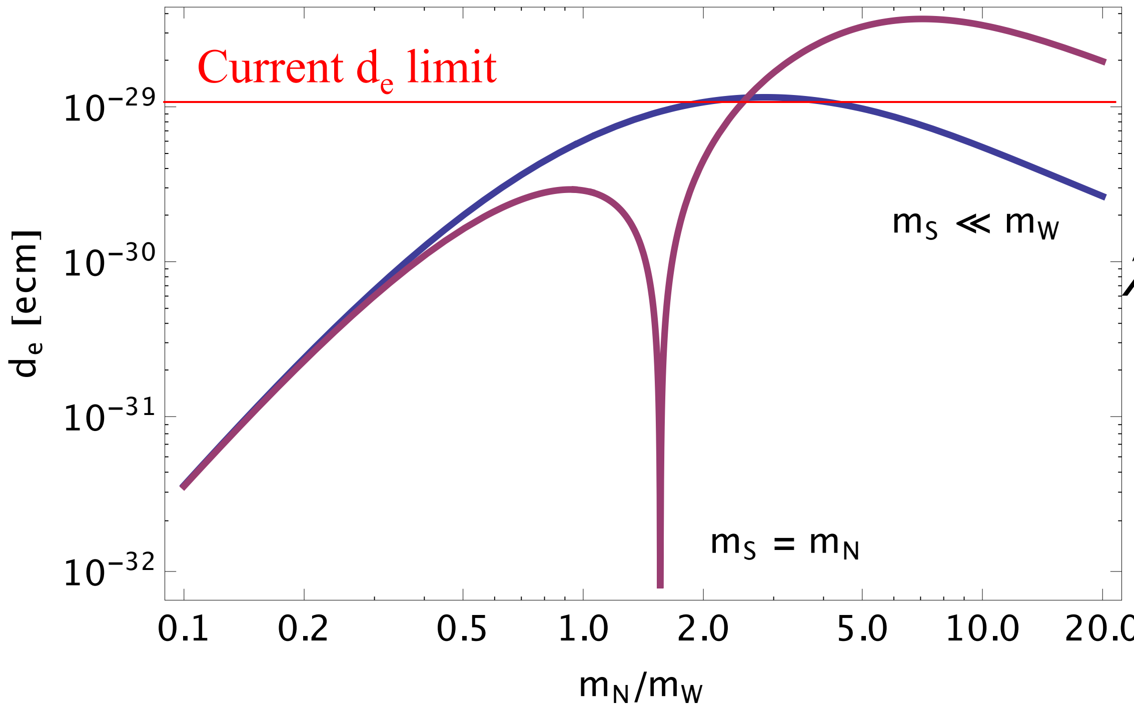
Answer = $d_e^{scale} \times$ 2loop function

$$d_e^{\rm scale} = e\lambda_N\theta_\nu^2 \times \frac{2}{(16\pi^2)^2}\frac{Am_em_N}{v^2m_h^2} = e\lambda_N\theta_\nu^2\theta_h \times \frac{2}{(16\pi^2)^2}\frac{m_em_N}{v^3}$$

$$d_e^{\rm scale} = 4.4 \times 10^{-29} e\,{\rm cm} \times \frac{\lambda_N\theta_\nu^2\theta_h}{10^{-2}} \times \frac{m_N}{m_W}.$$

2-loop function is calculated numerically, and analytic expressions are obtained in various hierarchical limits (e.g. $m_W << m_S << m_N$)

Two-loop calculation results



$$\lambda_N \theta_h \theta_\nu^2 = 10^{-2}.$$

$m_N >> m_W$ has a chance of creating electron EDM above 10^{-29} cm.

- Answer to Q1: two-loop d_e via Higgs and ν portals. Example of model inducing d_e using only neutral BSM particles around EW scale. For the *first example of this type*, see A. Abada, T. Toma, 2015, in a model with two heavy RH neutrinos.
- Best chance at probing EW scale N's – high-luminosity LHC
- A good chance for EW baryogenesis – N carry lepton number

Two-photon exchange induced C_S

- Th used by ACME collaboration is a spin-less nucleus.
- ThO is mostly sensitive to CP violation in the lepton sector. If CP is broken in the strong interaction sector, *two photon exchange* can communicate it to the electron shells.
- Cutting across the two photons, the intermediate result can be phrased via CP-odd nuclear polarizability, $\mathbf{E}\mathbf{B}\,\delta(\mathbf{r})$, where E and B are created by an electron.
- Good scale separation is possible, $m_p >> p_F,\ m_\pi >> m_e \sim Z\alpha\, m_e$
- Nuclear uncertainties could be under control if the result is driven by "bulk" [as opposed to valence] nucleons.

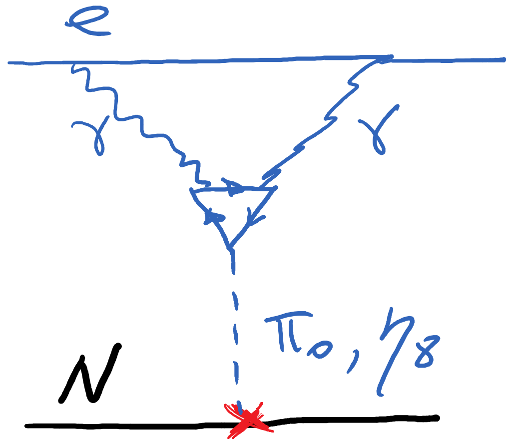
Two questions for today

$(\bar{e}\, i\gamma_5\, e)\,\bar{N}N$ operators

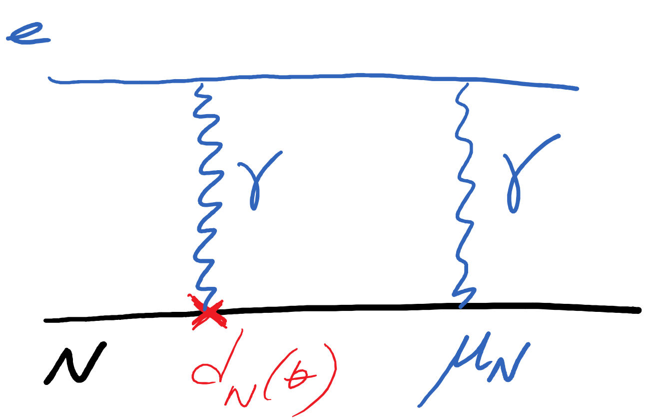
m_q counting:

$\theta\, m_q / m_\pi^2$

$\sim O(m_q^0)$



Almost complete cancellation of π_0 and η_8 contributions



+ cross diagrams

m_q counting:

$\sim O(m_q \log(m_q))$

Unexpected complication:

- T-channel pion exchange gives

$$\mathcal{L} = \theta \times \frac{1}{m_\pi^2} \times 0.017 \times 3.5 \times 10^{-7} (\bar{e} i \gamma_5 e)(\bar{n} n - \bar{p} p)$$
$$= (\bar{e} i \gamma_5 e)(\bar{n} n - \bar{p} p) \times \frac{3.2 \times 10^{-13} \theta}{\mathrm{MeV}^2}.$$

implying $|\theta| < 8.4 \times 10^{-8}$ sensitivity. However, adding exchange of η_8,

$$1 \to 1 - \frac{1}{3} \frac{f_\pi^2 m_\pi^2}{f_\eta^2 m_\eta^2} \times \frac{m_d - m_u}{m_d + m_u} \times \frac{A \times \sigma_N}{\frac{m_d - m_u}{2} \langle p | \bar{u} u - \bar{d} d | p \rangle \times (N - Z)}$$

$$1 \to 1 - 0.88 \simeq 0.12.$$

The effect can completely cancel within error bars on nucleon sigma term σ_N.

Photon box diagrams:

- Diagrams are IR divergent but regularized by Fermi momentum in the Fermi gas picture of a nucleus (intermediate N is above Fermi surface).

$$\mathcal{L} = \bar{e} i \gamma_5 e \bar{N} N \times \frac{2m_e \times 4\alpha \times \overline{d\mu} \times 6.2}{\pi p_F} = \bar{e} i \gamma_5 e \bar{N} N \times 2.4 \times 10^{-4} \times \overline{d\mu}$$

$$\overline{d\mu} = \frac{Z}{A}\mu_p d_p + \frac{A-Z}{A}\mu_n d_n = \frac{e}{2m_p} \times (1.08 d_p - 1.16 d_n)$$

- Nucleon EDM (theta) is very much a triplet, $d_p \simeq -d_n \simeq 1.6 \times 10^{-3} e\mathrm{fm}\theta$

Constructive interference. [Preliminary] answer:

$$C_S^s \sim 0.025 \times \theta \quad \text{or} \quad |\theta| < 3 \times 10^{-8}.$$

Bonus: limit on protons EDM

$$C_S^s \sim \frac{\sqrt{2}}{G_F} \times 2.4 \times 10^{-4} \times \frac{4\pi\alpha}{2m_p} \times 1.08 \times \frac{d_p}{e} < 7.3 \times 10^{-10} \implies d_p < 10^{-23} e\mathrm{cm}$$

Conclusions

- Electron EDM/ semileptonic C_S operator are limited rather strongly by the recent results of ACME collaboration.
- New levels of sensitivity, 10^{-29} e cm, is probing not only UV models of new physics with new SM-charged states, but can also probe “dark sectors” where new physics is neutral [and UV complete].
- Models with heavy [singlet] Dirac Neutrinos and [singlet] scalar mixed with the Higgs can induce d_e at two loops and three portal insertions. The answer was demonstrated to be as big as 10^{-29} e cm.
- Electron EDM experiments are sensitive to the hadronic CP violation via a two-photon exchange diagrams.
- Simple evaluations of sensitivity results in $|\theta| < 3\times10^{-8}$. Further progress by O(100) for d_e type of experiments will bring the sensitivity to hadronic CP violation on par with current d_n limits.