KM model, semileptonic CP violation and EDMs

Maxim Pospelov
University of Minnesota/FTPI

Flambaum, MP, Ritz, Stadnik, 1912.13129 (PRD2020)
Y. Ema, T. Gao, MP 2108.05398 (PRL2021)
Y. Ema, T. Gao, MP 2202.10524 (PRL2022)
Y. Ema, T. Gao, MP 2205.11532 (JHEP2022)

Plan

1. Intro: why EDMs
2. Paramagnetic EDMs from Hadronic CP violation
3. Independent constraints on Theta$_{QCD}$, color EDM from semi-leptonic EDM-like operators (C_S).
4. CKM CP-violation → C_S via the "double-penguin" diagram.
5. New indirect constraints on EDMs of muons, c- b- quarks.
6. *Conclusions*

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

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

$d \neq 0$ 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

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

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.

Current limits translate to multi-TeV sensitivity to M.

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

$|d_n| < 3 \times 10^{-26} e\,{\rm cm}$ $1.8 \times 10^{-26}\, e$ cm

Notice that Thallium EDM is usually quoted as $d_e < 1.6\ 10^{-27}$ e cm bound. It was modestly improved by YbF results.

$|d_e| < 4.1 \times 10^{-30}$

$|d_e| < 1.1 \times 10^{-29}$

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

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

If dark matter particles have EDM...

it also must be small. They will contribute to the elastic scattering on normal nuclei (Pospelov, ter Veldhuis, 2000),

$$\sigma = 8\pi Z^2 \left(\frac{d}{e}\right)^2 \left(\frac{\alpha}{v}\right)^2 \frac{S+1}{3S} \ln \frac{q_{min}}{q_{max}}.$$

Recent constraints from Xenon 100 experiments would limit an EDM of a hypothetical 100 GeV WIMP to better than 10^{-23} e cm.

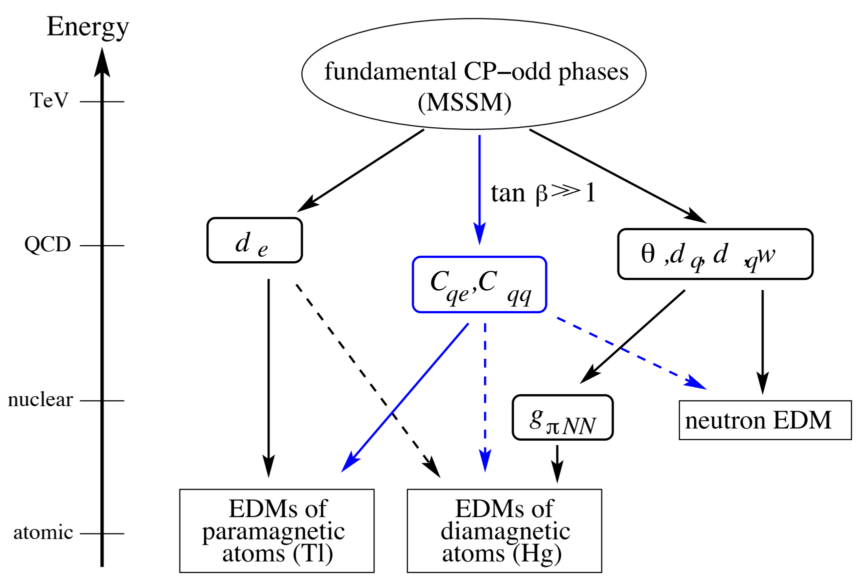
LZ experimental results [2022] limit e.g. EDM of a 30 GeV dark matter particle as $1*10^{-25}$ e cm.

BSM physics and EDMs

$$\mathcal{L}_{eff}^{1\mathrm{GeV}} = \frac{g_s^2}{32\pi^2}\,\theta_{QCD} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$$

$$-\frac{i}{2}\sum_{i=e,u,d,s} d_i\,\overline{\psi}_i(F\sigma)\gamma_5\psi_i - \frac{i}{2}\sum_{i=u,d,s}\widetilde{d}_i\,\overline{\psi}_i g_s(G\sigma)\gamma_5\psi_i$$

$$+\frac{1}{3}w\; f^{abc}G^a_{\mu\nu}\widetilde{G}^{\nu\beta,b}G_{\beta}{}^{\mu,c} + \sum_{i,j=e,d,s,b} C_{ij}\,(\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j) + \cdots$$



- One needs hadronic, nuclear, atomic matrix elements to connect Wilson coefficients to observables

- Extremely high scales [10-100 TeV] can be probed if new physics generating EDMs violates CP maximally.

Example: CP-odd channel for Higgs-γ–γ coupling

Consider two effective operators from some physics that is integrated out: $\frac{c_h v}{\Lambda^2} h F_{\mu\nu} F^{\mu\nu} + \frac{\tilde{c}_h v}{\tilde{\Lambda}^2} h F_{\mu\nu} \tilde{F}^{\mu\nu}$

Then, $R_{\gamma\gamma} = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\rm SM}} \simeq \left| 1 - c_h \frac{v^2}{\Lambda^2} \frac{8\pi}{\alpha A_{\rm SM}} \right|^2 + \left| \tilde{c}_h \frac{v^2}{\tilde{\Lambda}^2} \frac{8\pi}{\alpha A_{\rm SM}} \right|^2$

and deviations are O(1) if c/Λ ~ 1/5 TeV.

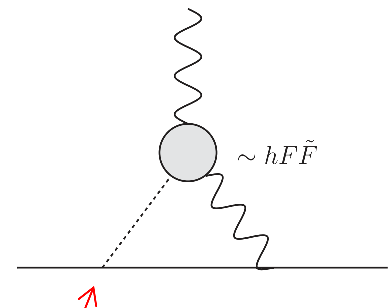
Given that coefficients c and c^tilde are most likely perturbative, ~ α, then O(1) deviations are only if Lambda is relatively low.

Higgs-gamma loop induces electron EDM

Integrating *h-gamma*, we end up with log-sensitivity to UV scale,

$$d_i = \tilde{c}_h \frac{|e| m_f}{4\pi^2 \tilde{\Lambda}^2} \ln\left(\frac{\Lambda_{\rm UV}^2}{m_h^2}\right)$$

$$= d_f^{(2l)} \times \frac{\tilde{c}_h}{\alpha/(4\pi)} \times \frac{v^2}{\tilde{\Lambda}^2} \ln\left(\frac{\Lambda_{\rm UV}^2}{m_h^2}\right)$$



Assuming h couples to e

Cutting the log at the same scale, one ends up with

$$\tilde{\Lambda} \gtrsim 50\sqrt{\tilde{c}_h}\ \mathrm{TeV}.$$

which is a lot *larger* than h→2 gamma rates "wants".
Consequently, once the EDM bound is imposed,

$$\Delta R_{\gamma\gamma}(\tilde{c}_h) \lesssim 1.6 \times 10^{-4}.$$

New number: $\Delta R_{\gamma\gamma} < 1.1\times 10^{-6}$

This is very restrictive.

Conclusion: unless one fine-tunes EDMs to 0, Higgs→ $\gamma\gamma$ cannot have a large CP-odd admixture.

Two sources of CP-violation in SM

- Theta term of QCD: too large EDMs if theta is arbitrary → new naturalness problem because of EDMs. ($d_n \sim \theta\, m_q/m_n^2$, $\theta < 10^{-10}$)

- Cabibbo-Kobayashi-Maskawa matrix and nearly maximal CP phase → still EDMs are too small to be observable in the next round of EDM experiments.

Strong CP problem

Energy of QCD vacuum depends on θ-angle:

$$E(\bar{\theta}) = -\frac{1}{2}\bar{\theta}^2 m_* \langle \overline{q}q \rangle + \mathcal{O}(\bar{\theta}^4, m_*^2)$$

where $\langle \overline{q}q \rangle$ is the quark vacuum condensate and m_* is the reduced quark mass, $m_* = \frac{m_u m_d}{m_u + m_d}$. In CP-odd channel,

$$d_n \sim e\frac{\bar{\theta} m_*}{\Lambda_{\rm had}^2} \sim \bar{\theta} \cdot (6 \times 10^{-17})\, e\,\mathrm{cm}$$

Strong CP problem = naturalness problem = Why $|\bar{\theta}| < 10^{-9}$ when it could have been $\bar{\theta} \sim O(1)$? $\bar{\theta}$ can keep "memory" of CP violation at Planck scale and beyond. Suggested solutions

- Minimal solution $m_u = 0 \leftarrow$ apparently can be ruled out by the chiral theory analysis of other hadronic (CP-even) observables.
- $\bar{\theta} = 0$ by construction, requiring either exact P or CP at high energies + their spontaneous breaking. Tightly constrained scenario.
- Axion, $\bar{\theta} \equiv a(x)/f_a$, relaxes to $E = 0$, eliminating theta term. $a(x)$ is a very light field. Not found so far.

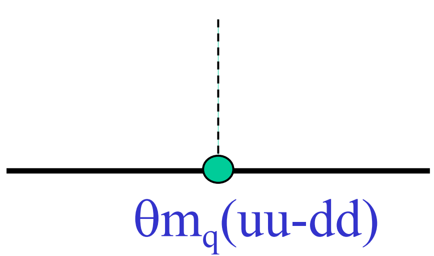
Matrix elements of GGdual

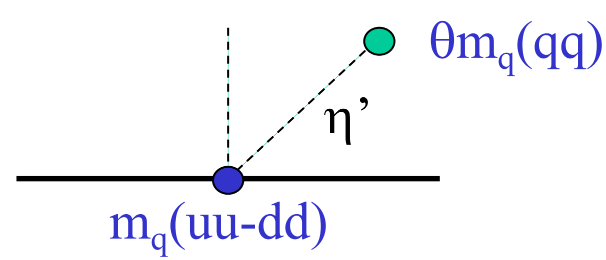
- Consider a matrix element of $<H_1\ \pi\ |\ GGdual\ |H_2>$ operator, for the states of a soft pion, where H are arbitrary in- and out- states.

- Chiral PT / current algebra / soft pion theorem allow to "reduce" the pion so that

$< H_1\ \pi\ |\ GGdual\ |\ H_2 > \rightarrow i\,(F_\pi)^{-1} < H_1\ \ |\ m_q(uu\text{-}dd)\ |\ H_2 >$. If $H_1,\ H_2$ are nucleons, we get a scalar-isovector matrix element, part of the n-p mass splitting.

- This is however not the whole story. In *our world* with light quarks $m_\pi^2 = B\ m_q$ while $m_{\eta'}^{\ 2} = B\ m_q + m_0^2$, and heavy mass of η' requires m_0^2 to be large and m_q independent in the limit of large m_q. In an *imaginary world*, where eta-prime is light and $m_0^2 = 0$, there is a second diagram that cancel the first one (SVZ 1980, MP, Ritz 1999)





CP violation via in CKM matrix

There are two possible sources of CP violation at a renormalizable level: δ_{KM} and θ_{QCD}.

δ_{KM} is the form of CP violation that appears only in the charged current interactions of quarks.

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{U}_L \not{W}^+ V D_L + (\text{H.c.}) \right) .$$

CP violation is closely related to flavour changing interactions.

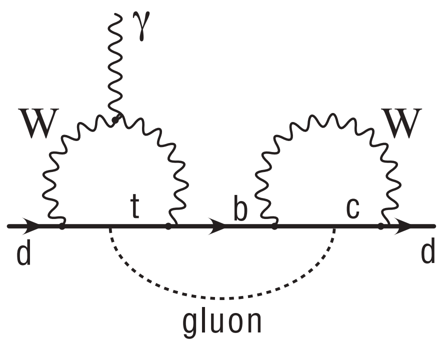
$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} .$$

CKM model of CP violation is independenly checked using nutral K and B systems. *No other sources of CP are needed to describe observables!*

CP violation disappear if any pair of the same charge quarks is degenerate or some mxing angles vanish.

$$J_{CP} = \text{Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \times$$
$$(y_t^2 - y_c^2)(y_t^2 - y_u^2)(y_c^2 - y_u^2)(y_b^2 - y_s^2)(y_b^2 - y_d^2)(y_s^2 - y_d^2)$$
$$< 10^{-15}$$

EDMs from SM sources: CKM



CKM phase generates tiny EDMs:

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

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

- Quark EDMs identically vanish at 1 and 2 loop levels, $EW^2=0$

(Shabalin, 1981).

- 3-loop EDMs, EW^2QCD^1 are calculated by Khriplovich; Czarnecki, Krause.

- d_e vanishes at EW^3 level (Khriplovich, MP, 1991) < 10^{-38} e cm. It was calculated recently by Yamaguchi, Yamanka to be 6 10^{-40} e cm

- Long distance effects give neutron EDM ~ 10^{-32} e cm; uncertain.

My first work on Kobayahsi-Maskawa CP-violation and EDMs with Khtiplovich

Electric dipole moment of the W boson and the electron in the Kobayashi-Maskawa model

M.E. Pospelov (Novosibirsk, IYF), I.B. Khriplovich (Novosibirsk, IYF)
1991

4 pages
Published in: *Sov.J.Nucl.Phys.* 53 (1991) 638-640, *Yad.Fiz.* 53 (1991) 1030-1033

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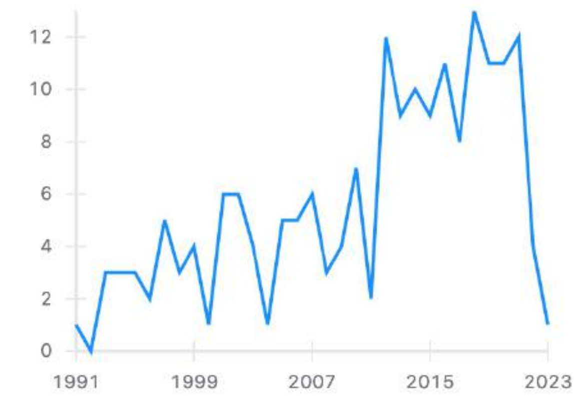
Citations per year



“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 $d_e = 0$

$d_e^{\mathrm{equiv}} = d_e + C_S \times 1.5 \times 10^{-20}\, e\,\mathrm{cm}$ ← Specific for ThO

$d_e^{equiv} = d_e + C_S*0.9*10^{-20}$ e cm ← Specific for Hf F+

Recent exp progress is very significant

- From 1.6 10^{-27} cm to 4.1 10^{-30} cm is a factor of 1/500, and sensitivity to Λ is increased by a factor of ~ 20.
- 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)

What is sensitivity of paramagnetic EDMs (aka d_e) to hadronic CP violation? Theta term, EDMs of quarks, color EDMs etc?

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*, **EB** $\delta(\mathbf{r})$, 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.

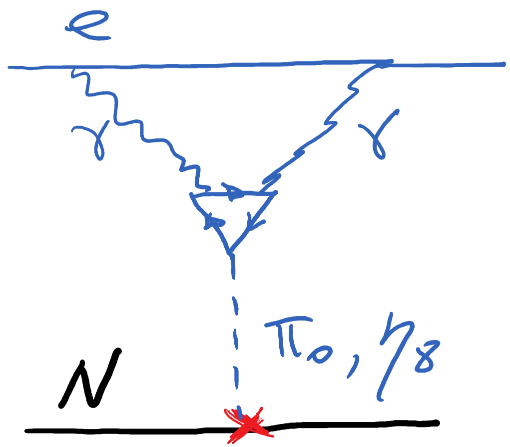
Hadronic CP violation contributing to C_S

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

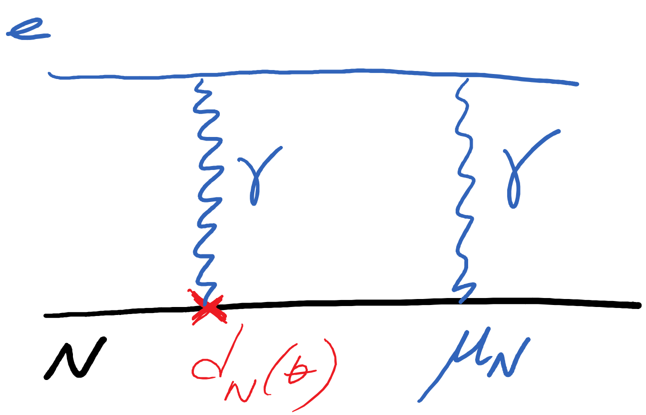
m_q counting:

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

$\sim O(m_q^0)$



Almost complete cancellation of π_0 and η_8 contributions



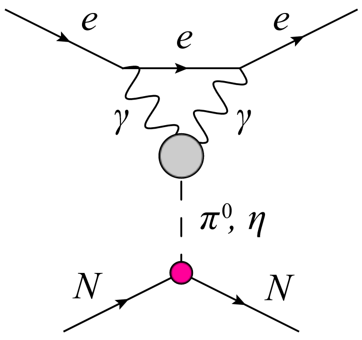
+ cross diagrams

m_q counting:

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

LO chiral contribution:

- T-channel pion exchange gives



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

$$= (\bar{e} i \gamma_5 e)(\bar{n}n - \bar{p}p) \times \frac{3.2 \times 10^{-13}\theta}{\text{MeV}^2}.$$

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, $d_p \simeq -d_n \simeq 1.6 \times 10^{-3} e\mathrm{fm}\theta$

Full answer including chiral NLO. (accidental cancellation of π^0 and η)

$$C_{SP}(\bar{\theta}) \approx \left[0.1_{\mathrm{LO}} + 1.0_{\mathrm{NLO}} + 1.7_{(\mu d)}\right] \times 10^{-2}\bar{\theta} \approx 0.03\,\bar{\theta}$$

Limit on theta term from ThO (electron EDM) experiment:

$$|\bar{\theta}|_{\mathrm{ThO}} \lesssim 3 \times 10^{-8}$$

Constraints on other hadronic Wilson coeff.

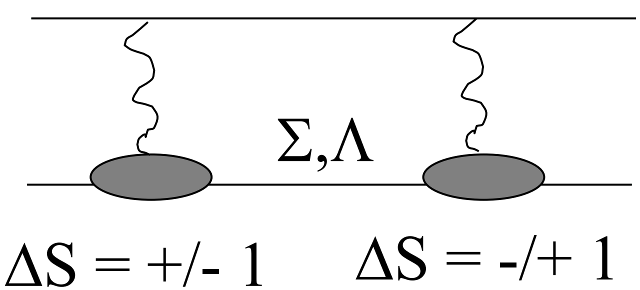
- Proton EDM, other CP-violating inputs can be limited:

System	$\lvert d_p \rvert$ $(e \cdot \mathrm{cm})$	$\lvert \bar{g}^{(1)}_{\pi NN} \rvert$	$\lvert \tilde{d}_u - \tilde{d}_d \rvert$ (cm)	$\lvert \bar{\theta} \rvert$
ThO	$\mathbf{2 \times 10^{-23}}$	$\mathbf{4 \times 10^{-10}}$	$\mathbf{2 \times 10^{-24}}$	$\mathbf{3 \times 10^{-8}}$
n	—	1.1×10^{-10}	5×10^{-25}	2.0×10^{-10}
Hg	2.0×10^{-25}	1×10^{-12} [a]	5×10^{-27} [a]	1.5×10^{-10}
Xe	3.2×10^{-22}	6.7×10^{-8}	3×10^{-22}	3.2×10^{-6}

- Current constraints on Theta$_{\mathrm{QCD}}$ trail d_n sensitivity by two orders of magnitude
- Given fast progress of recent years with ``paramagnetic'' EDMs, a further increase by ~ 100 will provide comparable sensitivity.
- New Colorado result: factor of ~ 2 improvement.

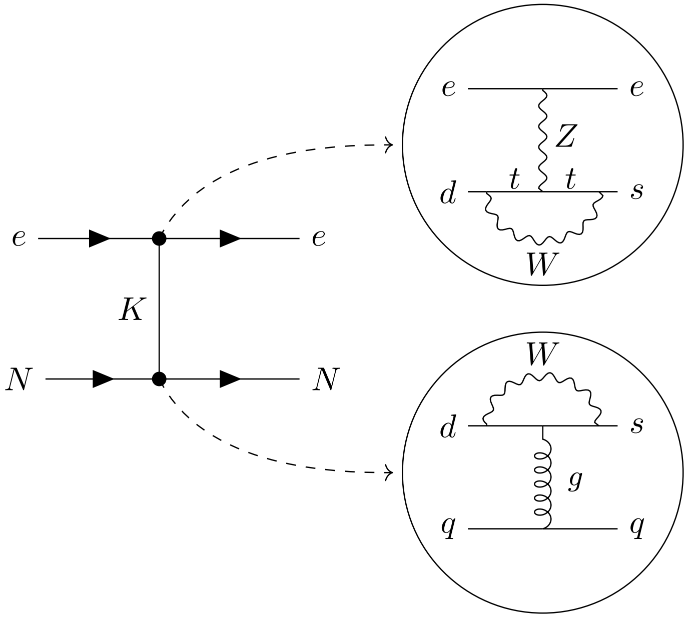
CKM CP-violation and paramagnetic EDMs

- Several groups attempted to calculate d_e (MP, Khriplovich; …)
- The result is small ~ few 10^{-40} e cm. (Yamaguchi, Yamanaka)
- Semileptonic (C_S) operator is more important. MP and Ritz (2012) estimated two-photon mediated EW^2EM^2 effects and found that CS is induced at the level equivalent to ~ 10^{-38} e cm



It turns out that there are much larger contributions at EW^3 order

Semileptonic CP operator at EW^3 order



- The induced semileptonic operator is calculable in chiral perturbation theory (in m_s expansion)
- The result is large, d_e(equiv) = + 1.0 10^{-35} e cm
- Same EW penguin that is responsible for $B_s \rightarrow \mu\mu$, Re $K_L \rightarrow \mu\mu$

Semileptonic Electroweak Penguin

- The upper part: EW penguin $\mathcal{L}_{\rm EWP} = \mathcal{P}_{\rm EW} \times \bar{e}\gamma_\mu\gamma_5 e \times \bar{s}\gamma^\mu(1-\gamma_5)d + (h.c.)$

$$\mathcal{L}_{Uee} = -\frac{i f_0^2}{2}\mathcal{P}_{\rm EW} \times \bar{e}\gamma_\mu\gamma_5 e \times {\rm Tr}\left[h^\dagger\left(\partial^\mu U\right)U^\dagger\right] + (h.c.),$$

In the leading order, the dominant diagram is K_S exchange.

$$\mathcal{L}_{Kee} = -2\sqrt{2} f_0 m_e \bar{e} i\gamma_5 e\left(K_S \times {\rm Im}\mathcal{P}_{\rm EW} + K_L \times {\rm Re}\mathcal{P}_{\rm EW}\right)$$

- Lower part: EW[1] B-B-M coupling is related by flavor SU(3) to the s-wave amplitudes of the non-leptonic hyperon decays. Theory fit to decay amplitudes is [surprisingly] good (~5-10%):

$$\mathcal{L}_{\rm SP} = -a{\rm Tr}(\bar{B}\{\xi^\dagger h\xi, B\}) - b{\rm Tr}(\bar{B}[\xi^\dagger h\xi, B]) + (h.c.).$$

contains $2^{1/2} f_0^{-1}((b-a)\bar{p}p + 2b\bar{n}n)K_S$

LO kaon exchange result

- Using EW penguin and strong penguin below,

$$\mathcal{L}_{KNN} \simeq -\frac{\sqrt{2}\,G_F \times [m_{\pi^+}]^2 f_\pi}{|V_{ud}V_{us}|f_0} \times 2.84(0.7\bar{p}p + \bar{n}n)$$
$$\times \left(\mathrm{Re}(V_{ud}^* V_{us})K_S + \mathrm{Im}(V_{ud}^* V_{us})K_L\right).$$

We calculate C_S

$$C_S \simeq \mathcal{J} \times \frac{N + 0.7Z}{A} \times \frac{13[m_{\pi^+}]^2 f_\pi m_e G_F}{m_K^2} \times \frac{\alpha_{\mathrm{EM}} I(x_t)}{\pi \sin\theta_W^2}$$

$$\mathcal{J} = \mathrm{Im}(V_{ts}^* V_{td} V_{ud}^* V_{us}) \simeq 3.1 \times 10^{-5}$$

That has the following LO scaling

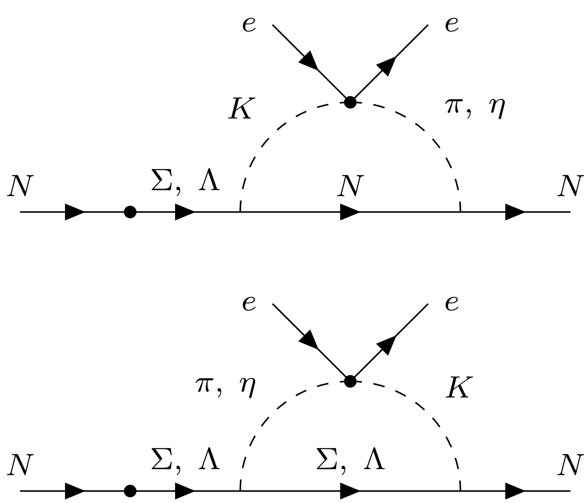
$$G_F C_S \propto \mathcal{J} G_F^3 m_t^2 m_e m_s^{-1} \Lambda_{\mathrm{hadr}}^2$$

Numerically, it is

$$C_S(\mathrm{LO}) \simeq 5 \times 10^{-16}.$$

NLO kaon-pion loop

- We calculate leading order corrections that have $(m_s)^{-1/2}$ scaling



- The loop itself is proportional to ~ m_K, but there is a baryonic pole that brings $1/m_s$.

The NLO brings positive contribution of ~ 30%.

$$\frac{C_{S,NLO}(p)}{C_{S,LO}(p)} = \frac{m_K^3(0.77D^2 + 2.7DF - 2.3F^2)}{24\pi f_0^2(m_{\Sigma^+} - m_p)}$$

$$\frac{C_{S,NLO}(n)}{C_{S,LO}(n)} = \frac{m_K^3}{24\pi f_0^2}\left(\frac{(a/b+3)}{2\sqrt{6}(m_\Lambda - m_n)}\times(-0.44D^2 + 3.2DF + 1.3F^2) + \frac{a/b-1}{2\sqrt{2}(m_{\Sigma^0} - m_n)}\left(-0.53D^2 - 1.9DF + 1.6F^2\right)\right).$$

Final result

- Combining $(m_s)^{-1}$ and $(m_s)^{-1/2}$ effects, we get

$$C_S(\mathrm{LO}+\mathrm{NLO}) \simeq 6.9 \times 10^{-16}$$
$$\Longrightarrow \; d_e^{\mathrm{equiv}} \simeq 1.0 \times 10^{-35}\, e\,\mathrm{cm}.$$

- The result EW^3 much larger than the EW^2EM^2 estimate by ~1000.

- Note that actually establishing the correct sign is tricky.

- The result is under "best possible" theoretical control, and can be improved on the lattice

$$\langle N|i(\bar{s}\gamma_\mu(1-\gamma_5)d - \bar{d}\gamma_\mu(1-\gamma_5)s)|N\rangle_{\mathrm{EW}^1} = \frac{f_S}{m_N} iq_\mu \bar{N}N + \frac{f_T}{m_N} q_\nu \bar{N}\sigma_{\mu\nu}\gamma_5 N.$$

EDMs of heavy flavors

- Among Wilson coefficients of different kind, EDMs of heavy flavours d_i are interesting. i = muon, tau, charm, bottom, top.

- Muon EDM is limited as a biproduct of BNL g-2 experiment. Can be significantly improved in dedicated beam experiments (PSI, Fermilab, J-Parc)

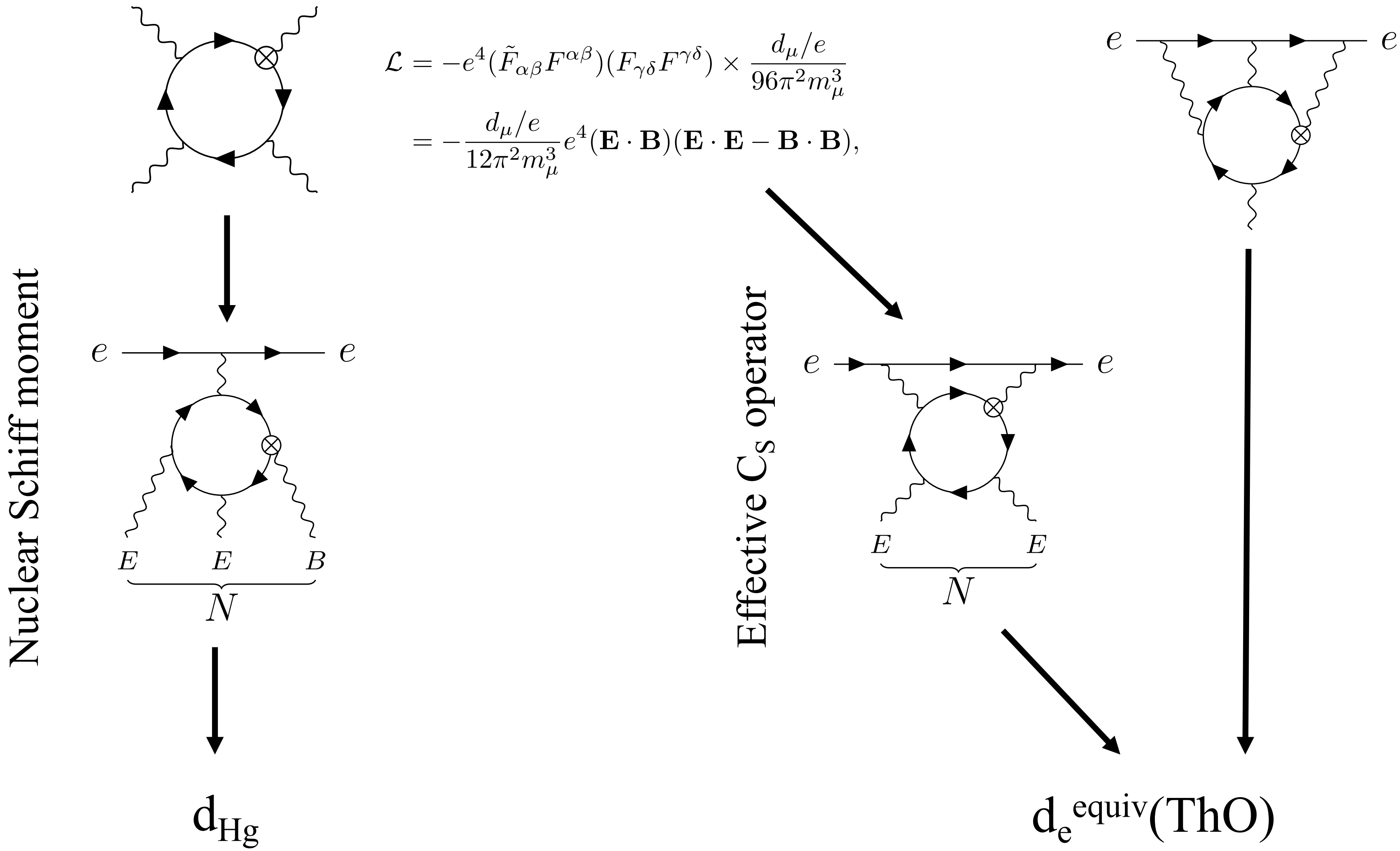
- There is a creative proposal to measure MDMs and limit EDMs of charmed baryons using thin fixed target and bent crystal technology just before the LHCb experiment (E. Bagli et al, 2017).

- Heavy flavors contribute to observable EDMs via loops. Top quark EDM is limited indirectly by electron EDM via a two-loop (top-Higgs-gamma) Barr-Zee diagrams. The result is stronger than the direct measurements at LHC.

Muon EDM inside a loop

- Muon loop induces E^3B effects, and electron EDM at 3-loops.

$$\mathcal{L} = -e^4(\tilde{F}_{\alpha\beta}F^{\alpha\beta})(F_{\gamma\delta}F^{\gamma\delta}) \times \frac{d_\mu/e}{96\pi^2 m_\mu^3}$$
$$= -\frac{d_\mu/e}{12\pi^2 m_\mu^3} e^4 (\mathbf{E}\cdot\mathbf{B})(\mathbf{E}\cdot\mathbf{E} - \mathbf{B}\cdot\mathbf{B}),$$



New indirect constraints on muon EDM

- Owing to the fact that the electric field inside a large nucleus is not that small $eE \sim Z\alpha R_N^{-1} \sim 30$ MeV compared to m_μ, effects formally suppressed by higher power of m_μ win over three-loop electron EDM.

- New results:

Hg EDM experiment: $S_{^{199}\mathrm{Hg}}/e \simeq (d_\mu/e) \times 4.9 \times 10^{-7}\,\mathrm{fm}^2, \quad |d_\mu| < 6.4 \times 10^{-20}\,e\,\mathrm{cm}$

ThO EDM experiment: $d_e^{\mathrm{equiv}} \simeq 5.8 \times 10^{-10}\,d_\mu \implies \boxed{|d_\mu| < 1.9 \times 10^{-20}\,e\,\mathrm{cm}.}$

New limit from Boulder HfF: ~9*10^{-21}

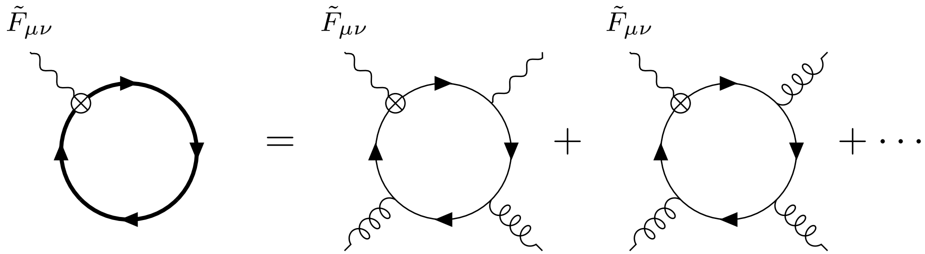
- Factor of 20 improvement over the BNL constraint, $|d_\mu| < 1.8 \times 10^{-19}$
- New benchmark for the muon beam EDM experiments.

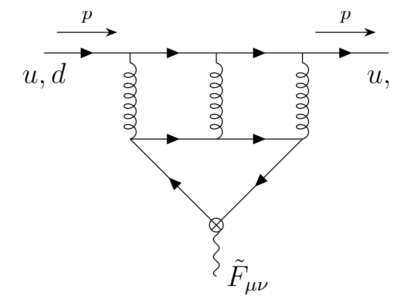
NB: 3-loop contributions calculated by Grozin et al. will be revised

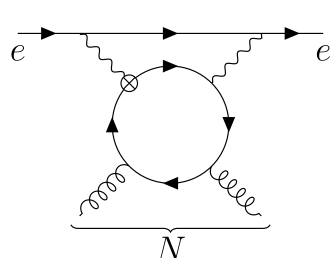
- Tau EDM is constrained by three-loop induced d_e.

Charm and bottom EDMs

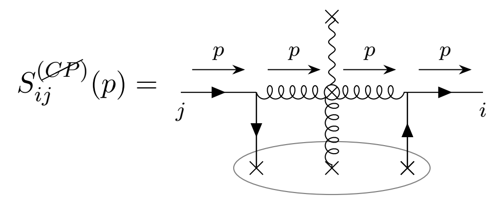
Charm loop gives $(\gamma)^2(\text{gluon})^2$ and $(\gamma)^1(\text{gluon})^3$ effective operators







$$\langle N|\frac{g_s^2}{32\pi^2}G^a_{\mu\nu}G^{a\mu\nu}|N\rangle = -\frac{m_N}{9}\bar{N}N,$$



Nonperturbative 3-gluon induced tensor charge

$d_e^{\text{equiv}}(\text{ThO})$

d_n , d_{Hg}

- All EDMs are induced by charm and bottom EDMs.

New indirect constraints on c-, b- quarks EDMs

- New results:

Neutron EDM experiment: $|d_c| < 6 \times 10^{-22}\, e\,\text{cm}, \quad |d_b| < 2 \times 10^{-20}\, e\,\text{cm},$

ThO EDM experiment: $|d_c| < 1.3 \times 10^{-20}\, e\,\text{cm}, \quad |d_b| < 7.6 \times 10^{-19}\, e\,\text{cm},$

- Neutron EDM estimates have uncertainty ~ up to a factor of O(few) due to limitation of QCD sum rule method in this channel. CS derived limits have *minimal* uncertainty, O(10%).
- Independent of (similar order of magnitude) bounds based on RG running of operators, and contribution to the GGGdual Weinberg operator.
- The strength of these limits on charm EDMpoints to the conclusion that future charmed baryon EM moment proposal should focus on MDM.

Conclusions

- EDMs are an important tool for searching for flavor-diagonal CP violation. Multi-TeV scales are probed, and can be further improved.
- In *lots of models*, including the SM, the paramagnetic EDMs (*experiments looking for d_e*) are induced by the semi-leptonic operators of (electron pseudoscalar)*(nucleon scalar) type.
- C_S is induced by theta term via a two-photon exchange resulting in sensitivity $|\theta| < 1.5\times10^{-8}$. 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.
- CKM induces C_S. The result is large and calculable and is dominated by the EW^3 order. The *equivalent* d_e (ThO) is found to be $+1.0 \times 10^{-35}$ e cm. This is 1000 times larger than previously believed.
- New indirect limits on muon, charm and bottom provide new target for the EDM beam experiments:

$$|d_c| < 6 \times 10^{-22}\, e\,\mathrm{cm}, \quad |d_b| < 2 \times 10^{-20}\, e\,\mathrm{cm}, \quad |d_\mu| < 1.9 \times 10^{-20}\, e\,\mathrm{cm}.$$

Strengthened by ~ 2 due to recent Boulder group result