EDMs in the post-Higgs discovery era: breaking beyond the 10 TeV frontier

Maxim Pospelov
Perimeter Institute/U of Victoria
CERN theory division

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Plan

1. Intro: Why EDMs?
2. SM predictions for EDMs
3. Effective Lagrangian at 1 GeV, and estimates of hardonic matrix elements.
4. *Hard realities for New Physics in 2018*. EDMs from 100 TeV SUSY.
5. *CP properties of the new Higgs-like resonance.*
6. *Theoretical wish list for EDMs. Conclusions*

Dedicated experiments to measure EDMs at CERN?

- Nuclear EDMs (apart from from neutrons) are screened inside the atoms (Schiff theorem) resulting in a huge penalty in sensitivity. Mercury EDM at 10^{-29} cm results in ~ $10^{-26 \text{ or } 25}$ cm bound on $d_{p,n}$. Not so for charged particles in the [future dedicated] storage rings.
- Opportunity for CERN to pursue the EDM projects (proton, deuteron, and in the future possibly more complicated nuclei).
- Muon EDMs are poorly constrained [we know constraints on WIMP EDMs better than muon EDMs!]. Room for improvement. *Also new ideas of probing EDMs of charm and beauty containing baryons with channeling in bent crystals.*

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.

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.

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.

Current Experimental Limits

"paramagnetic EDM", Berkeley experiment

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

"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

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

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.

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

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

CKM model

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

CP violation is closely related to flavour changing interactions.

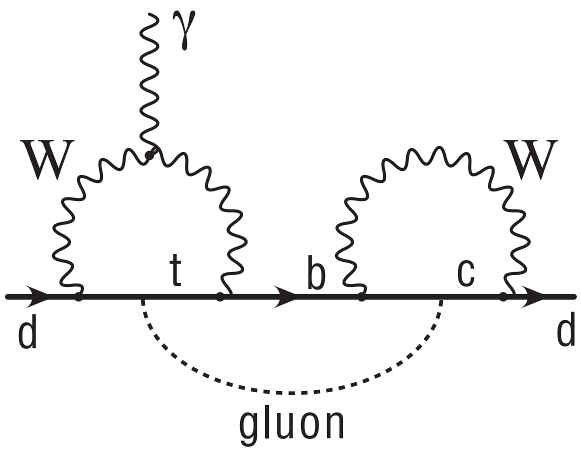
$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} .$$

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.

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

EDMs from CKM



CKM phase generates tiny EDMs:

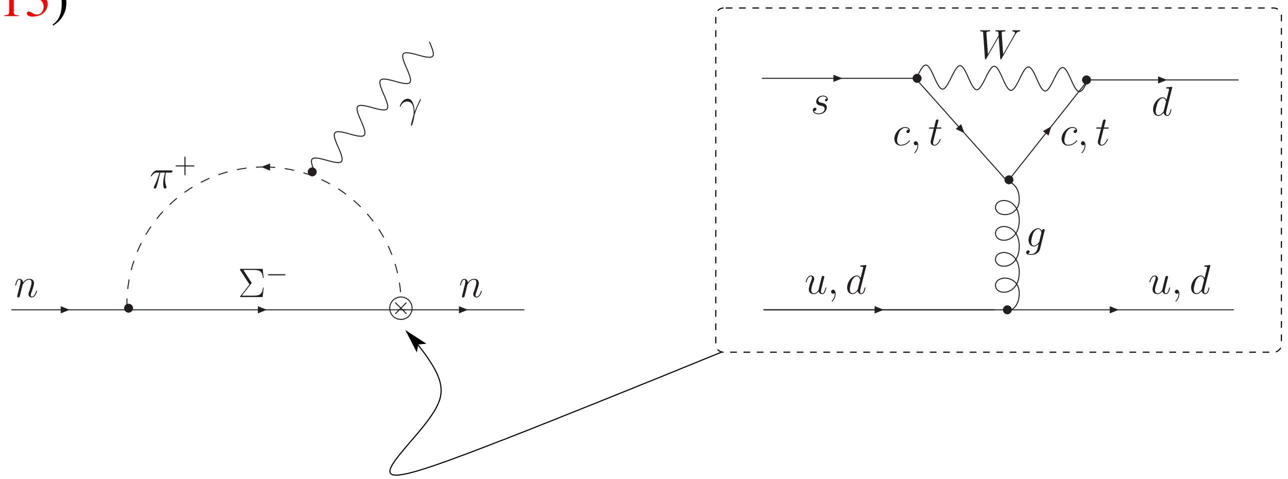
$$d_d \sim \mathrm{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*)\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$
$$< 10^{-33} e\text{cm}$$

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)

Long(er) distance contribution dominate

- Combination of $\Delta S = +1$ and $\Delta S = -1$ (and Δ charm = $\pm$ 1) gives a larger estimate to d_n than just d_q. Can be as large as 10^{-31} e cm (Khriplovich, Zhitnitskiy; Gavela et al). Charm contribution was recently looked at by Mannel, Uraltsev.
- EDMs of diamagnetic atomic species (closed e shells, nuclear spin) are generated by the CKM contribution to the nuclear Schiff moment. (Novosibirsk group; Donoghue, Holstein, Musolf)
- Direct contribution of d_e(CKM) to d_{Atom} is negligible compared to the semi-leptonic contribution (nuclear CP-odd polarizability), $d_e^{equiv} \sim 10^{-44}$ cm. (MP, Ritz, 2013)



Bottom line: EDMs(CKM) are ~ 5 orders and more below current limits

At what values do we need to be worried about CKM-induced EDMs?

Consider an outrageous overestimate for d_n that puts loop factors like $\alpha_s/4\pi$ to 1, and chooses constituent rather current quark mass scale

$d_n \sim \mathrm{Im(VVVV)}\ G_F^2 m_c^2 \times 100\ \mathrm{MeV} < 10^{-29}$ cm.

- Nonzero neutron EDM above 10^{-29} cm is guaranteed to be NP
- Nonzero n EDM in -29 to -31 range is either NP or SM. (Once we cross 10^{-29} cm, we may need better d_n(CKM) calculations)
- Nonzero n EDM at -31 and below will be consistent with the SM, given current uncertainties.

CP violation from the Theta term

- If CKM gave too small an EDM, there is a much bigger source of CP violation in the flavor conserving channel - theta term

Energy of QCD vacuum depends on θ-angle:

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

where $\langle \bar{q}q \rangle$ 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,

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

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

Axions or clever symmetry for keeping theta=0; m_u=0…

Effective CP-odd Lagrangian at 1 GeV

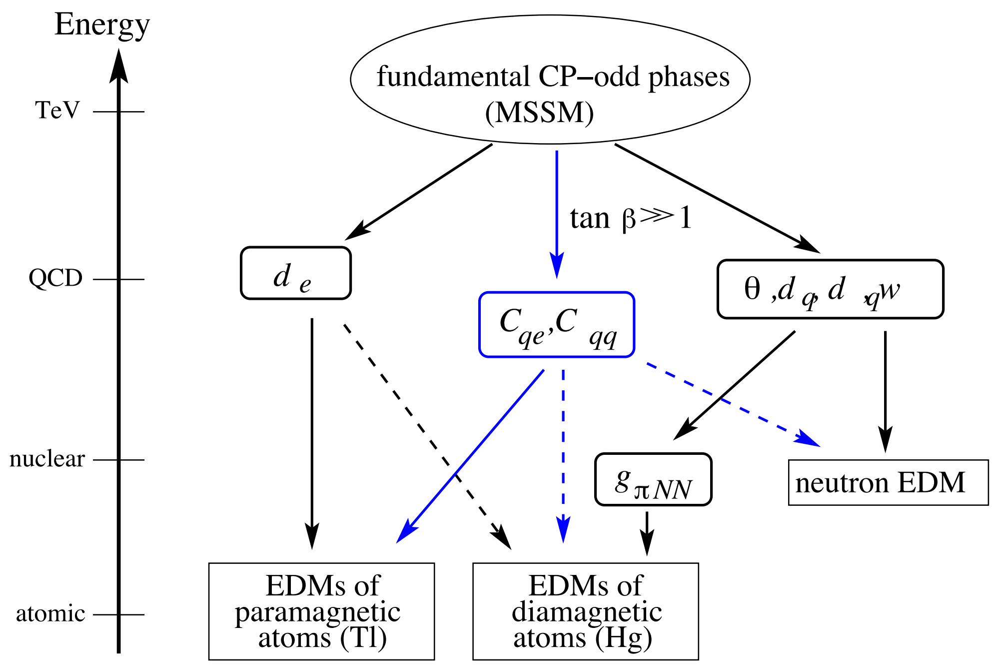
in the spirit of Wolfenstein's superweak interaction, Khriplovich et al., Weinberg,... Appying EFT, one can classify *all CP-odd operators of dimension 4,5,6,...* at $\mu = 1$ GeV.

$$\mathcal{L}_{eff}^{1\mathrm{GeV}} = \frac{g_s^2}{32\pi^2}\,\theta_{QCD} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$$
$$-\frac{i}{2}\sum_{i=e,u,d,s} d_i\,\overline{\psi}_i(F\sigma)\gamma_5\psi_i - \frac{i}{2}\sum_{i=u,d,s}\tilde{d}_i\,\overline{\psi}_i g_s(G\sigma)\gamma_5\psi_i$$
$$+\frac{1}{3}w\; f^{abc}G^a_{\mu\nu}\widetilde{G}^{\nu\beta,b}G_{\beta}{}^{\mu,c} + \sum_{i,j=e,d,s,b} C_{ij}\,(\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j) + \cdots$$

If the model of new physics is specified, for example, a specific parameter space point in the SUSY model, Wilson coefficients $d_i, \tilde{d}_i$, etc. can be calculated.

To get beyond simple estimates, one needs $d_{n,\,atom}$ as functions of $\theta, d_i, \tilde{d}_i, w, C_{ij}$, which requires non-perturbative calculations. which I review in the next few transparencies.

From SUSY to an atomic/nuclear EDM



Hadronic scale, 1 GeV, is the normalization point where perturbative calculations stop.

Our old slide from the pre-LHC time…

Synopsis of EDM formulae

Thallium EDM:
The Schiff (EDM screening) theorem is violated by relativistic (magnetic) effects. Atomic physics to 10 – 20% accuracy gives

$$d_{\mathrm{Tl}} = -585 d_e - e\ 43\ \mathrm{GeV} C_S^{(0)}$$

where C_S is the coefficient in front of $\bar{N}N i\bar{e}\gamma_5 e$. Parametric growth of atomic EDM is $d_e \times \alpha^2 Z^3 \log Z$. Typically one need several species to limit both d_e and C_S

neutron EDM:
~50-100% level accuracy QCD sum rule evaluation of d_n is available. Ioffe-like approach gives

$$d_n = -\frac{e m_* \bar{\theta}}{2\pi^2 f_\pi^2};\ d_n = \frac{4}{3} d_d - \frac{1}{3} d_u - e\left(\frac{m_n}{2\pi f_\pi}\right)^2 \left(\frac{2}{3}\tilde{d}_d + \frac{1}{3}\tilde{d}_u\right)$$

(Reproduces naive quark model and comes close to chiral-log estimates) Also uses Vainshtein's estimate for e.m. polarizability of qcd

Mercury EDM: Screening theorem is avoided by the finite size of the nucleus

$$d_{\mathrm{Hg}} = d_{\mathrm{Hg}}\left(S(\bar{g}_{\pi NN}[\tilde{d}_i, C_{q_1 q_2}]),\ C_S[C_{qe}],\ C_P[C_{eq}],\ d_e\right).$$

For most models $\bar{g}_{\pi NN}$ is the most important source. The result is dominated by $\tilde{d}_u - \tilde{d}_d$ but the uncertainty is large:

$$d_{\mathrm{Hg}} = 7 \times 10^{-3}\, e\, (\tilde{d}_u - \tilde{d}_d) + \ldots$$

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Mercury EDM: Screening theorem is avoided by the finite size of the nucleus ?, see Ban et al, 2010

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? → $d_{\mathrm{Hg}} = 7 \times 10^{-3}\, e\, (\tilde{d}_u - \tilde{d}_d) + \ldots$

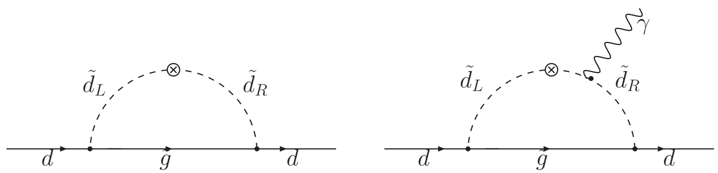
Further comments:

1. The results for d_n(W.C.) could be improved using e.g. lattice calculations. Significant efforts have been invested, not only in the tensor charge (d_q contributions), but in the $d_n(\theta)$, d_n(CEDM). Not all matrix elements are calculated yet.
2. The result for higher-dimensional operators depends on whether you have a PQ symmetry, because of the additional adjustment of axion vacuum, $\theta_{ind} \sim < O_{CP}$, G*Gdual $>$. The effect is most pronounced for CEDM of light quarks.
3. Estimates of $d_n(d_s)$, $d_n(CEDM_s)$ could use some improvement. (e.g. lattice results for $\bar{s}s$ matrix element came to be much smaller than originally thought…)
4. A better quality [indirect] limit on d_{charm} could be derived.
5. *Most important theoretical issue: Schiff moment of ^{199}Hg induced by $\bar{g}_{pnn}$ needs to be revisited by independent groups.*

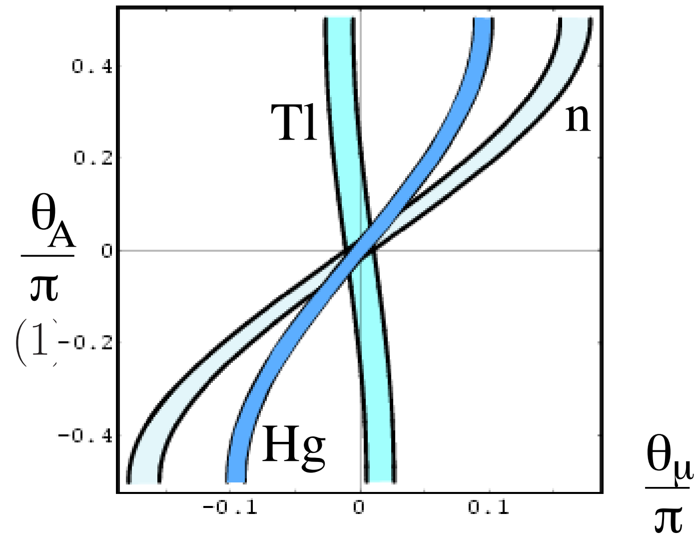
Anatomy of SUSY EDMs

Pre-LHC slide

All one-loop and most important ($\tan\beta$-enhanced) two-loop diagrams have been computed.



$M_{\rm SUSY} = 500$ GeV, and $\tan\beta = 3$.



$$\frac{d_e}{e\kappa_e} = \frac{g_1^2}{12}\sin\theta_A + \left(\frac{5g_2^2}{24} + \frac{g_1^2}{24}\right)\sin\theta_\mu \tan\beta,$$

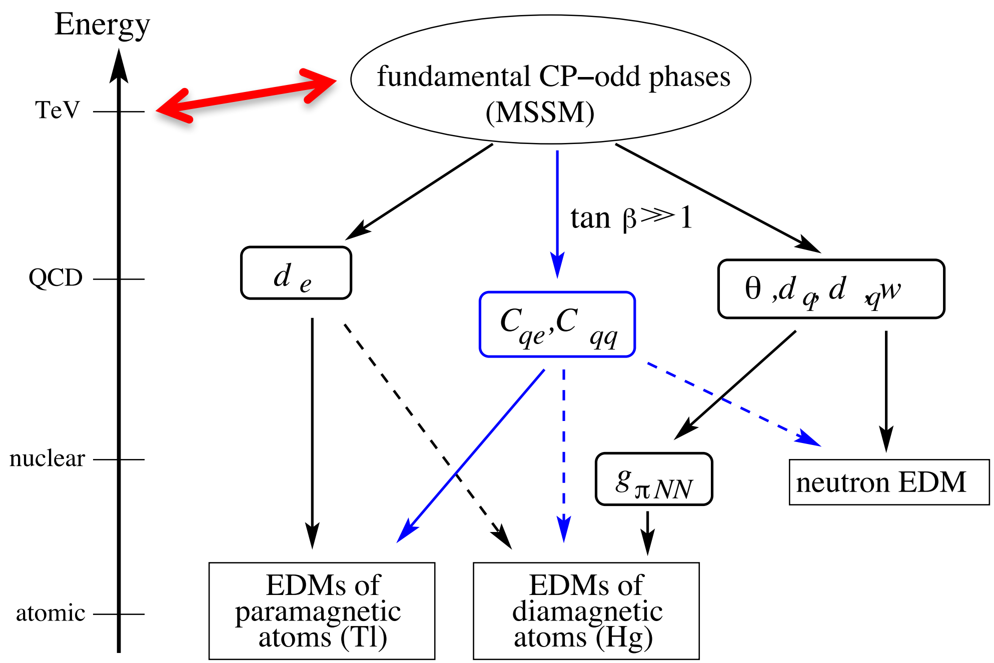
$$\frac{d_q}{e_q\kappa_q} = \frac{2g_3^2}{9}\left(\sin\theta_\mu[\tan\beta]^{\pm1} - \sin\theta_A\right) + O(g_2^2, g_1^2),$$

$$\frac{\tilde{d}_q}{\kappa_q} = \frac{5g_3^2}{18}\left(\sin\theta_\mu[\tan\beta]^{\pm1} - \sin\theta_A\right) + O(g_2^2, g_1^2).$$

$$\kappa_i = \frac{m_i}{16\pi^2 M_{\rm SUSY}^2} = 1.3\times 10^{-25}{\rm cm}\times\frac{m_i}{1{\rm MeV}}\left(\frac{1{\rm TeV}}{M_{\rm SUSY}}\right)^2.$$

From SUSY to an atomic/nuclear EDM

Is this connection still here?



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EDMs and New Physics

- EDM observable ~

  ~ [some QCD/atomic/nuclear matrix elements] ×

  SM mass scale (m_e, m_q) × (CP phase)$_{NP}$/Λ_{NP}^2

With some amount of work all matrix elements can be fixed. For the flavor blind NP, $d_i \sim m_i$. Unfortunately, we have no idea where actually Λ_{NP} is !!!

100 GeV, 1 TeV, 10 TeV, 100 TeV, 1000 TeV … GUT scale … M_P

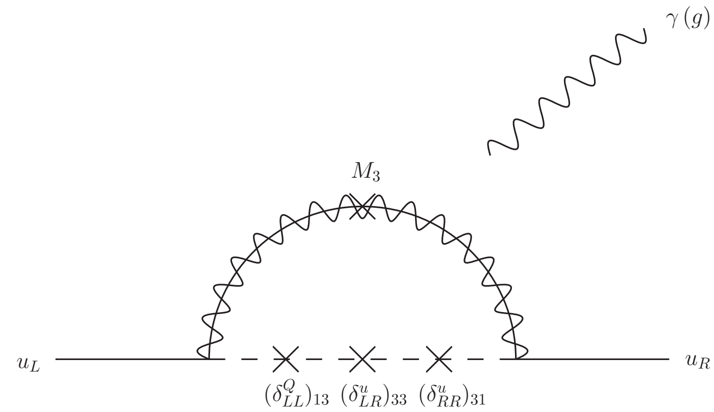
After the LHC did not find the abundance of new states immediately above EW scale, "guessing EDMs" became even more difficult. *What shall we put in the denominator*? E.g. $(\text{TeV})^2$ or $(\text{PeV})^2$?

EDMs from 100 TeV SUSY

- Measured Higgs mass value, ~126 GeV, may be pointing toward very heavy squark mass scale. The Higgs potential must be "tuned" to a considerable level.
- Such mass scale, 50 TeV-PeV allows [almost] not to worry about SUSY flavor issues [and about producing sfermions at the LHC]. Wells, 2003; …. In the post-Higgs era by Arvanitaki et al., Arkani-Hamed et al, other groups, 2012-2013. "Mini-split" scenario.
- Gaugino could be around EW scale, giving dark matter and allowing many models of SUSY breaking to easily explain such a scenario.
- Such a huge mass scale suppresses all EDMs, of course, but the absence of flavor-diagonal squark mass matrix can lead to a considerable enhancement via $d_i \sim m_{top}$, McKeen, MP, Ritz, *2013*. See also Altmannshofer et al., 2013.

Naturalness of masses and EDMs

$$\tilde{d}_u \simeq \frac{\alpha_s}{4\pi} M_3 \, (\delta^u_{LL})_{13} \, (\delta^u_{LR})_{33} \, (\delta^u_{RR})_{31} \times \frac{3}{M^2_{\rm sc}} \log\left(\frac{M^2_{\rm sc}}{M^2_3}\right) \sin\phi_{\tilde{u}\mu}$$
$$\sim 3 \frac{\delta m_u}{\Lambda^2_{\rm SUSY}} \log\left(\frac{\Lambda^2_{\rm SUSY}}{M^2_3}\right) \sin\phi_{\tilde{u}\mu}$$
$$\sim 1 \times 10^{-26}\ {\rm cm} \left(\frac{3}{\tan\beta}\right) \left(\frac{\theta^2_u}{1/3}\right) \left(\frac{M_3}{1\ {\rm TeV}}\right) \left(\frac{100\ {\rm TeV}}{\Lambda_{\rm SUSY}}\right)^3$$
$$\times \left[\log\left(\frac{\Lambda^2_{\rm SUSY}}{M^2_3}\right) \Big/ 10\right] \left(\frac{\sin\phi_{\tilde{u}\mu}}{0.1}\right)$$



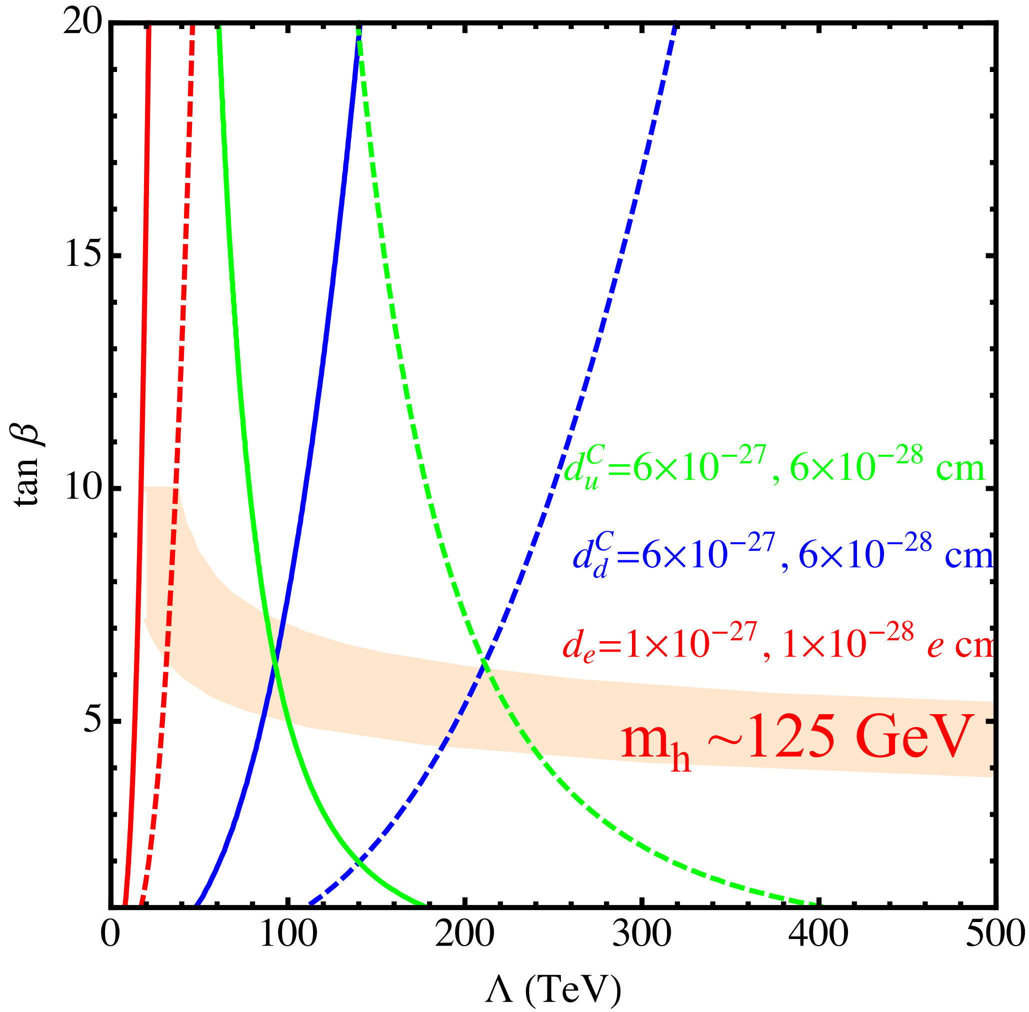
Common squark, Higgsino mass scale is assumed. Quark mass itself is also corrected and we require the tuning in m_u not be very large,

$$\delta m_u \sim \frac{\alpha_s}{4\pi} \theta^2_u \frac{m_t M_3}{\Lambda_{\rm SUSY} \tan\beta}$$
$$\sim 2\ {\rm MeV} \left(\frac{3}{\tan\beta}\right) \left(\frac{\theta^2_u}{1/3}\right) \left(\frac{M_3}{1\ {\rm TeV}}\right) \left(\frac{100\ {\rm TeV}}{\Lambda_{\rm SUSY}}\right)$$

Saturating naturalness in m_u allows fixing many free parameter in d_u.

Current bounds on d_{Hg} limit CEDM of up quark at ~ 5×10^{-27} cm

Naturalness estimates for EDMs



d_e, d_{Hg} probe ~ 100 TeV scale in this scenario. So, sub-PeV SUSY is not hopeless for EDMs. But we may never learn that it is SUSY…

Dimension 5 operators in superpotential

Pospelov, Ritz, Santoso, 2005,2006.

MSSM is an effective theory. Even if the soft-breaking sector tuned/constructed to have no CP-violation, higher-dimensional effective operators can generate EDMs. Some of these operators, $QQQL$, $DDUE$, LH_uLH_u, have been studied extensively in connection with proton decay, $0\nu 2\beta$ decays, and neutrino masses.

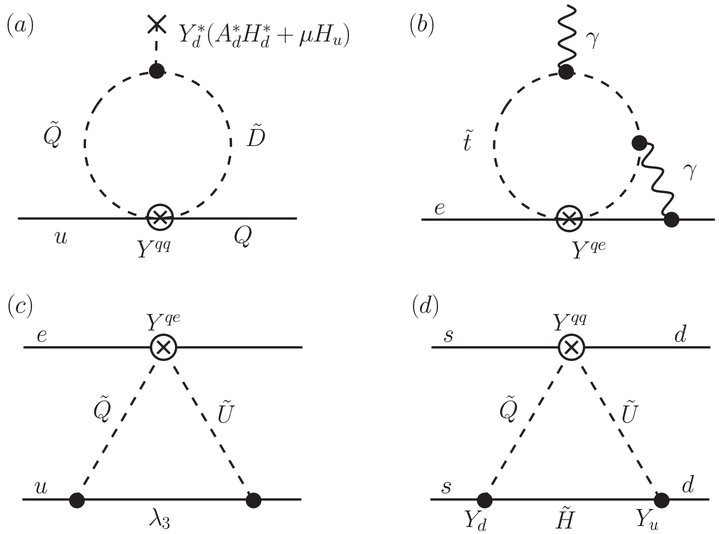
Extra dim=5 operators capable of inducing EDMs:

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + \frac{y_h}{\Lambda_h} H_d H_u H_d H_u + \frac{Y^{qe}}{\Lambda_{qe}} (UQ)EL$$

$$\frac{Y^{qq}}{\Lambda_{qq}} (UQ)(DQ) + \frac{\tilde{Y}^{qq}}{\Lambda_{qq}} (Ut^A Q)(Dt^A Q)$$

Decoupling properties of the observables: $\sim v_{EW}/(m_{soft}\Lambda_{(5)})$.

Dim 5 of MSSM → Dim 6 of SM



$$\mathcal{L}_{CP} = -\frac{\alpha_s \mathrm{Im} Y^{qe}_{1111}}{6\pi\Lambda_{qe} m_{\mathrm{susy}}}\left[(\bar{u}u)\bar{e}i\gamma_5 e + (\bar{u}i\gamma_5 u)\bar{e}e\right]$$

Assumption of $\mathrm{Im}Y \sim O(1)$ gives (m$_{\mathrm{SUSY}}$= 300 GeV is used)

$\Lambda^{qe} > 3 \times 10^8$ GeV from Tl EDM

$\Lambda^{qe} > 7 \times 1.5 \times 10^8$ GeV from Hg EDM

$\Lambda^{qq} > 7 \times 3 \times 10^7$ GeV from Hg EDM

Sensitivity to scales of New Physics

Standard Model + New Physics at Λ

Phenomenon	Limit/Reach in GeV	Source
p decay	$\Lambda_{\not B} \gtrsim few \times 10^{15}$	p lifetime
ν oscillations	$\Lambda_R \sim 10^{15} - 10^{16}$	Δm_ν^2
$\Delta F = 2$ meson mixing	$\Lambda_{QF} \gtrsim 10^7 - 10^8$	$\Delta m_{K(B)}$; ϵ_K
EDMs	$\Lambda_{CP} \gtrsim 10^6$	EDMs of n, Tl, Hg
lepton flavour	$\Lambda_{LF} \gtrsim 10^6$	$\mu \to e$ conversion
PNC	$\Lambda_{Z'} \gtrsim 10^2 - 10^3$	Cs; Moller sc.

Weak scale **Supersymmetric SM + New Physics at Λ**

Phenomenon	Limit/Reach in GeV	Source
p decay	$\Lambda_{\not B} \gtrsim 10^{24}$	SuperK
ν oscillations	$\Lambda_R \sim 10^{15} - 10^{16}$	Δm_ν^2
$\Delta F = 2$ meson mixing	$\Lambda_{QF} \gtrsim 10^7 - 10^8$	$\Delta m_{K(B)}$; ϵ_K
EDMs	$\Lambda_{CP} \gtrsim 10^8 - 10^9$	EDMs of n, Tl, Hg
lepton flavour	$\Lambda_{LF} \gtrsim 10^8$	$\mu \to e$ conversion
PNC	$\Lambda_{Z'} \gtrsim 10^2 - 10^3$	Cs; Moller sc.

Constraining properties of 125 GeV Higgs-like particle with EDMs

- New resonance discovered last year at the LHC may be exactly the SM Higgs or it may be a SM-Higgs-like with some deviations of its couplings from what's expected in the SM

-

  EDMs are *less direct* but most sensitive way or testing CP violation for H(125)..

- If so, does it have any implications for the EDMs, and vice verse, do EDMs put certain constraints on the couplings and decay channels of this new resonance?

Example of $\Gamma_{\gamma\gamma}$

$$\Gamma_{\gamma\gamma}^{\rm SM} = \frac{m_h^3}{4\pi}\left(\frac{\alpha}{4\pi}\right)^2 \left|\frac{A_{\rm SM}}{2v}\right|^2 \simeq 9.1 \text{ keV},$$

which corresponds to branching of 0.0023. Top contribution to amplitude is positive, and W is negative and large,

$$A_{\rm SM}(m_h = 125 \text{ GeV}) \simeq A_W + A_t \simeq -6.5$$

Before the Higgs discovery, one could guess that if anything

$$R_{\gamma\gamma} = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\rm SM}}$$

will go down because more heavy matter fields like tops is possibly out there.

More on the CP-odd channel for Higgs
(McKeen, MP, Ritz, 2012)

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

and deviations are O(1) if $c/\Lambda \sim 1/5$ TeV.

Given that coefficients c and c_tilde are most likely perturbative, $\sim \alpha$, then O(1) deviations are only if Lambda is relatively low.

The CP is probed rather well in many channels – is it reasonable to expect large contribution from the CP-odd channel?

Current sensitivity of electron EDM

2012 limit on electron electric dipole moment,

$$|d_e| < 8.7 \times 10^{-29}$$

This is beyond the 2-loop benchmark from EW scale particles:

In comparison, 2-loop EW-induced typical value is

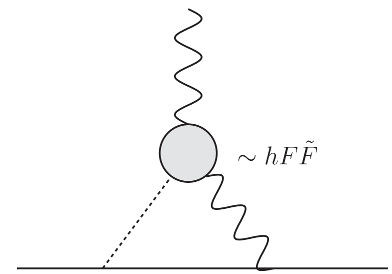
$$d_f^{(2l)} \equiv \frac{|e|\alpha m_f}{16\pi^3 v^2} \quad \Longrightarrow \quad d_e^{(2l)} \simeq 2.5 \times 10^{-27}\ e \cdot \mathrm{cm}.$$

Higgs-gamma loop is too big!

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

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

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

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

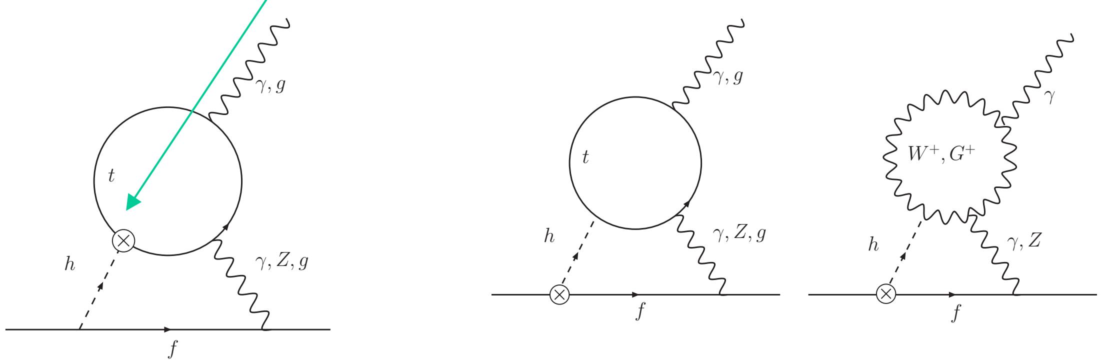
This is very restrictive and one wonders if this would hold outside of the contact operator approximations. *The only way to avoid it is to have more states degenerate with the Higgs.*

Higgs-top CP violation induces EDMs at two loops

CP violation comes from

$$\mathcal{L}_{CP} = y_t Q t_R H + \frac{1}{(M')^2} y_t' Q t_R H (H^\dagger H),$$

when y and y' have relative complex phase. Only the top operator is important for η_B.



The 2-loop contributions to d_f and $\tilde{d}_f$ mediated by the top loop.

$h\bar{t}i\gamma_5 t \;\rightarrow\; hF_{\mu\nu}\tilde{F}_{\mu\nu} \;\rightarrow\; \overline{\psi}i(F\sigma)\gamma_5\psi$

Considered in Huber et al. 2006; limits scenarios of EW baryogenesis based on extra dim=6 terms in the Higgs potential.

Theoretical wish list

1. Schiff moment from pion-nucleon constants

2. Full lattice results for d_n(W.C.), including strangeness. Understanding if such lattice results are reliable.

3. Axion-nucleon CP-violating constant (aNN coherent coupling) from CKM - not done properly.

4. More motivated models with some accessible scales (e.g. something other than 100 TeV SUSY, perhaps motivated by EW baryogenesis.)

Conclusions

1. CKM phase gives too small an EDM, and before experimentally we cross 10^{-29} cm, we can be sure that we are probing new physics.
2. EDMs generated by theta term is too large – one needs to remove theta from the theory by some adjustment mechanism. Neither θ_{QCD} nor ϕ_{CKM} look as viable sources for BAU..
3. Main uncertainty in the EDM business comes not from QCD or nuclear physics, but from us not knowing where New Physics is and how it looks like. But even if it is very heavy – I argue – EDMs are capable of probing scales as high as several 100 TeV. (Example = "minimally unnatural SUSY")
4. Main obstacle now: experimental sensitivity. But we also need theory improvement, notably with Schiff moment induced by pion-nucleon constants.