Physics of EDMs

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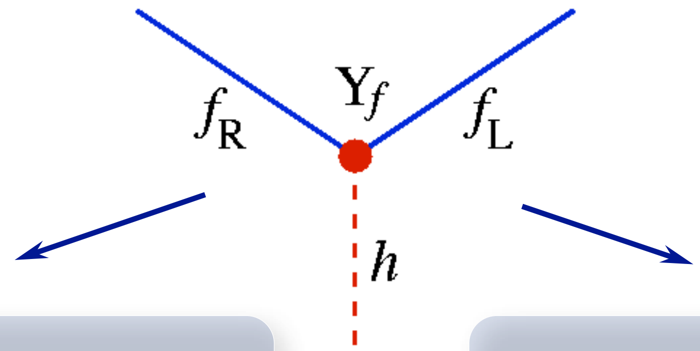
Review: M. Pospelov & AR, Ann. Phys. 318, 119 (2005) [hep-ph/0504231]
D. McKeen, M. Pospelov & AR, arXiv:1208.4597, 1303.1172

Physics of EDMs

Recent FNAL workshop

CP Violation in the Standard Model



$$\sin(\delta_{KM}) \propto \mathrm{Arg\,Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$\delta_{KM} \sim O(1)$

Explains CP-violation in K and B meson mixing and decays

$$\bar{\theta}_{QCD} \sim \mathrm{Arg\,Det}[Y_u Y_d]$$

(in a convenient basis)

$\theta < 10^{-10}$!

Constrained experimentally (strong CP problem)

Do we anticipate other CP-odd sources ?

- Required by baryogenesis (Sakharov conditions)
- Generic with extra degrees of freedom

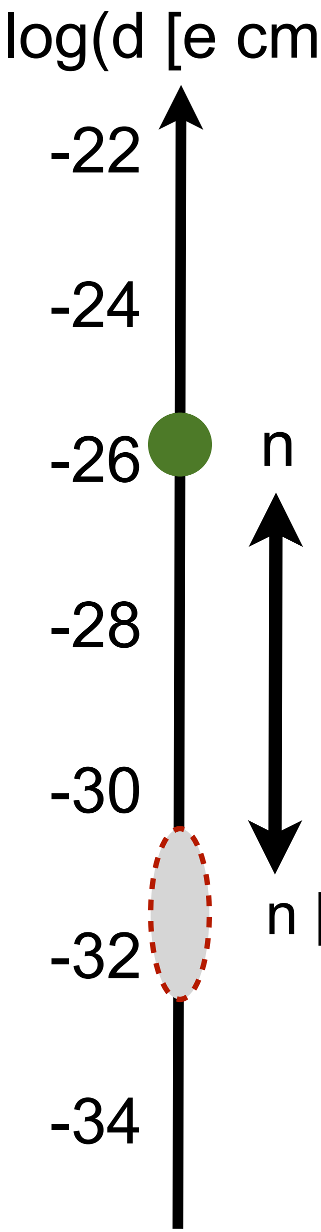
Experimental EDM Limits

$$H = -d\vec{E} \cdot \frac{\vec{S}}{S}$$

- EDMs are powerful (amplitude-level) probes for new flavour-diagonal (T,P) violating sources
- Best current limits from neutrons, para- and dia-magnetic atoms and molecules

Neutron EDM	$\lvert d_n \rvert < 3 \times 10^{-26} e\, cm$	[Baker et al. ‘06]
Thallium EDM (paramagnetic)	$\lvert d_{Tl} \rvert < 9 \times 10^{-25} e\, cm$	[Regan et al. ‘02]
YbF “EDM” (paramagnetic)	$\lvert “d_{YbF}” \rvert < 1.4 \times 10^{-21} e\, \mathrm{cm}$	[Hudson et al. ’11]
Mercury EDM (diamagnetic)	$\lvert d_{Hg} \rvert < 3 \times 10^{-29} e\, cm$	[Griffith et al. ’09]

SM (CKM) background



SM (CKM) contribution is (at least) 4-5 orders of magnitude below the current neutron sensitivity, and even lower for the atomic EDMs

➠ negligible CKM background

n [in SM, via CKM phase ∝J ~ Im(VVVV)]

[Khriplovich & Zhitnitsky '82;
McKellar et al '87;
Mannel & Uraltsev '12]

Schematic new physics sensitivity

Negligible SM (CKM) contribution ➠ EDMs are rather special in having clean (dim-6) amplitude-level sensitivity to new physics

- Generic corrections to the SM:

$$\Delta\Gamma, \Delta\sigma \sim \mathrm{Re}(A_{\mathrm{SM}} A^*_{\mathrm{NP}}) + \delta^{\mathrm{error}}_{\mathrm{SM}}$$

linear dependence on A_{NP}, but sensitivity limited by SM precision

- Tests of SM forbidden/suppressed processes:
  - often quadratic in the amplitude, e.g. LFV

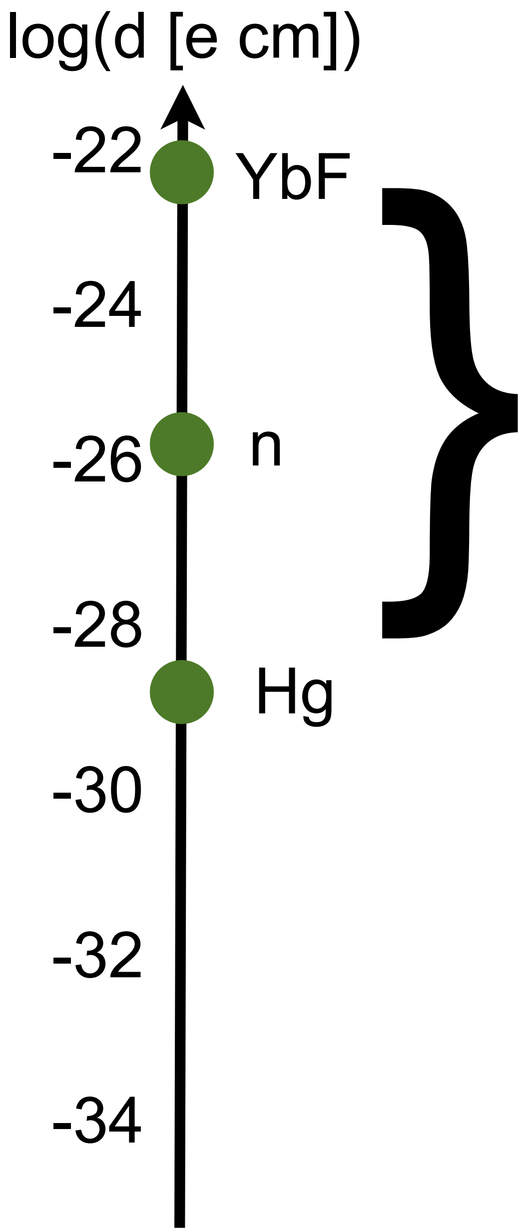
$$\Delta\Gamma \sim |A_{\mathrm{NP}}|^2$$

  - EDMs are linear!

$$\Delta d \sim A_{\mathrm{NP}}$$

➠ Better reward for improvements in experimental sensitivity

Schematic view of the bounds



Difference of more than 6 orders of magnitude, but the sensitivity to underlying CP-odd sources is actually very similar...

CP-odd operator expansion (at ~1GeV)

(Flavor-diagonal) CP-violating operators at ~1GeV

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

$$\mathcal{L}_{\dim 4} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\bar{\theta} = \theta_0 - \text{ArgDet}(M_u M_d) \equiv \theta_0 - \theta_q$$

CP-odd operator expansion (at ~1GeV)

(Flavor-diagonal) CP-violating operators at ~1GeV

$$\mathcal{L}_{\rm eff} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

$$d_i \sim c Y_i \frac{v}{\Lambda^2}$$

$$\mathcal{L}_{\rm dim\,4} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\mathcal{L}_{\text{“dim 6”}} \supset \sum_{q=u,d,s} \left(d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l$$

$$\mathcal{L}_{\rm dim\,6} \supset w g_s^3 G G \tilde{G} + \sum_{q,\Gamma} C_{qq} (\bar{q} \Gamma q)_{LL} (\bar{q} \Gamma q)_{RR}$$

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$$C_{ij} \sim c Y_i Y_j \frac{v^2}{\Lambda^4}$$

CP-odd operator expansion (at ~1GeV)

(Flavor-diagonal) CP-violating operators at ~1GeV

$$\mathcal{L}_{\rm eff} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

$$d_N \bar{N} F\sigma\gamma_5 N + \bar{g}^{(1)}_{\pi NN} \pi^0 \bar{N} N + \cdots$$

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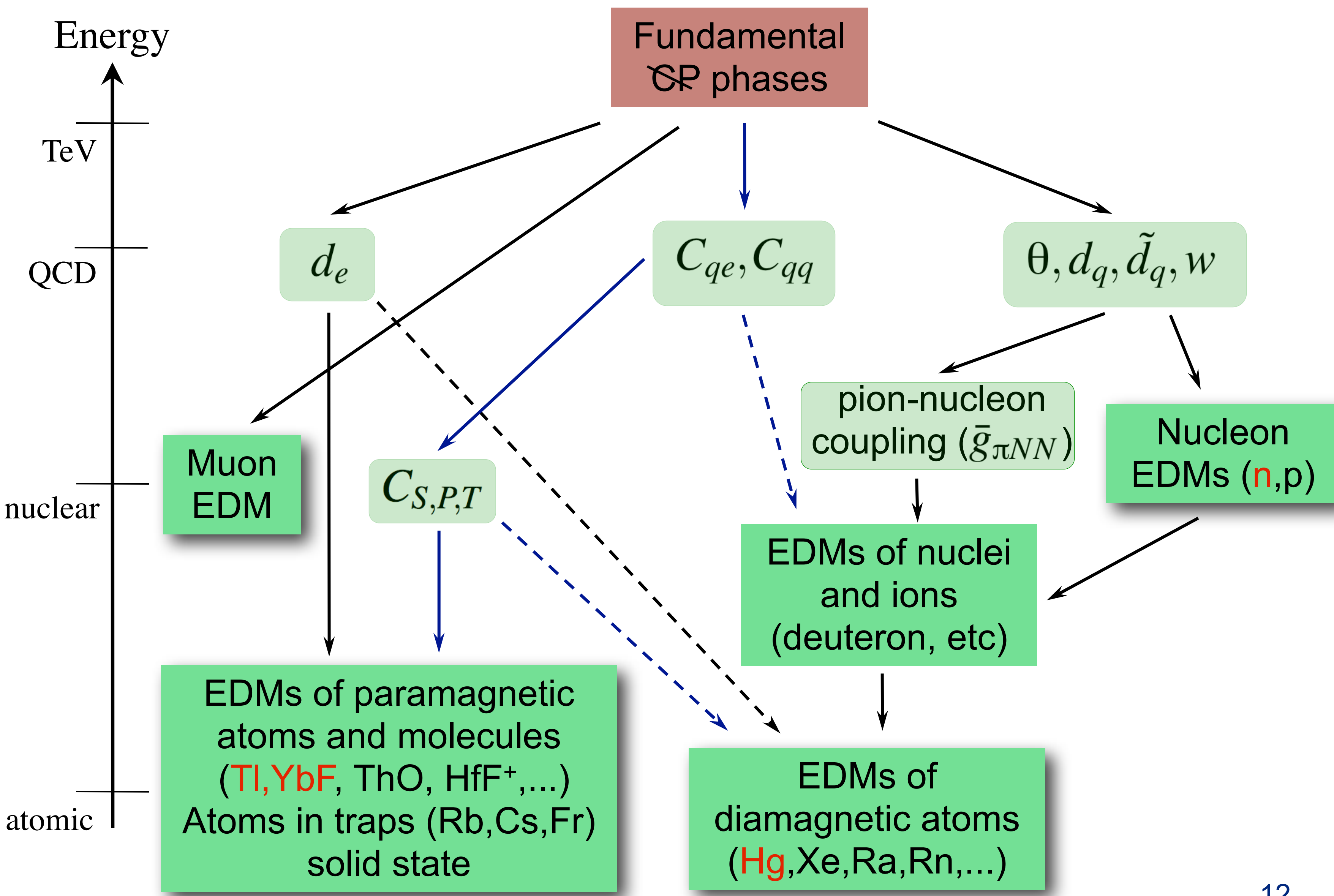
$$C_S \bar{N} N \bar{e} i\gamma_5 e + \cdots$$

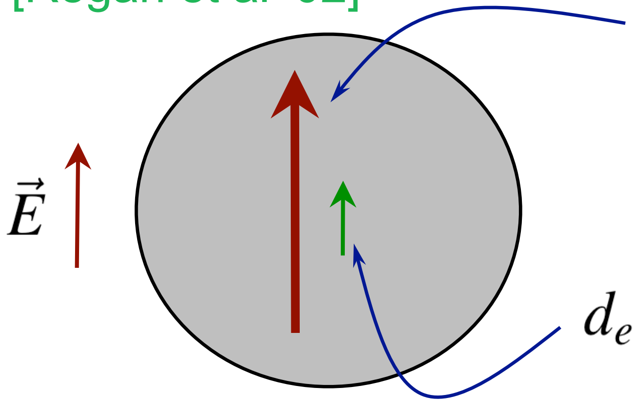
EFT hierarchy



Paramagnetic EDMs - "Schiff enhancement"

Atoms (e.g. Tl [Berkeley]) (relativistic violation of Schiff screening)

[Regan et al '02]



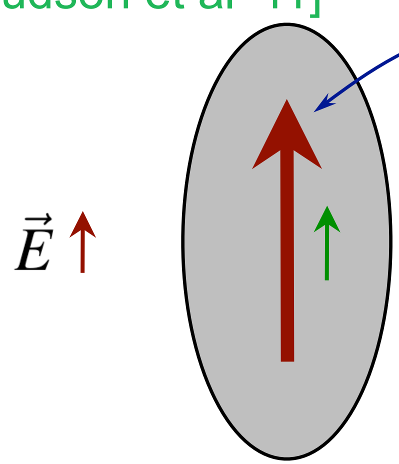
[Salpeter '58; Sandars '65]

≈ 585 [Liu & Kelly '92]

$$d_{Tl} \sim -20\alpha^2 Z^3 d_e + \mathcal{O}(C_S)$$

Polar molecules (e.g. YbF [Imperial]) [also ThO [Harvard/Yale]]

[Hudson et al '11]



Nonlinear function of E_{ext}

$$\Delta E_{\rm YbF} \sim \mathcal{E}_{\rm eff}(E_{\rm ext}) d_e + \mathcal{O}(C_S)$$

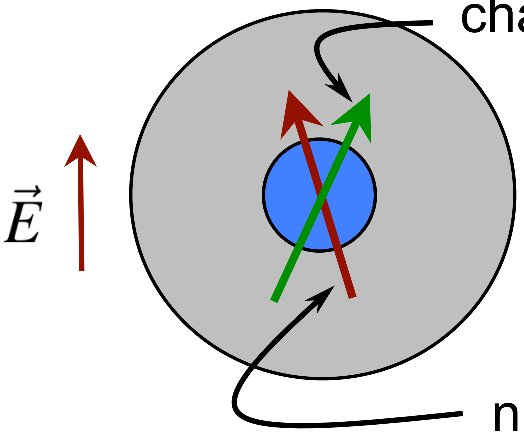
$$\text{“}d_{\rm YbF}\text{”} \sim 10\alpha^2 Z^3 \frac{M_{\rm mol}}{m_e} d_e + \mathcal{O}(C_S)$$

[Sushkov & Flambaum, '78]

Diamagnetic EDMs - “Schiff suppression”

Atoms (e.g. Hg [Washington]) (finite size violation of Schiff screening)

[Griffith et al ’09]



$$d_{Hg} \sim 10 Z^2 (R_N/R_A)^2 d_{\rm nuc}$$

$O(10^{-3})$

$$d_{\rm Hg} \sim -3 \times 10^{-17} S[e\,{\rm fm}^2] + \mathcal{O}(d_e, C_{qe}, C_{qq})$$

[Flambaum et al ’86; Dzuba et al. ’02]

Schiff moment [Schiff ‘63]

$$S = S(\bar{g}^{(i)}_{\pi NN}, d_N, ...)$$

[Flambaum et al. ‘86; Dmitriev & Senkov ‘03; de Jesus & Engel ’05; Ban et al ‘10]

- Octopole enhancements (e.g. Ra, Rn) [R. Holt, Z.-T. Lu, et al, T. Chupp et al]
  - Schiff moment O(100-1000) larger than Hg

[Flambaum et al.]

Nuclear EDMs - avoiding Schiff screening

- Neutron EDM via UCN bottles [...., PSI, Sussex/ILL, ORNL, Osaka/TRIUMF]

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- Nuclear EDMs (e.g. p,D,^{3}He,...) in storage rings [BNL, FNAL? COSY/Julich]

$$d_{Hg} \sim 10 Z^2 (R_N/R_A)^2 d_{\rm nuc}$$

O(10^{-3}) suppression could be avoided with a direct measurement of the nuclear EDM.

Nuclear EDMs - avoiding Schiff screening

- Neutron EDM via UCN bottles [...., PSI, Sussex/ILL, ORNL, Osaka/TRIUMF]
- Nuclear EDMs (e.g. p,D,^{3}He,...) in storage rings [BNL, FNAL? COSY/Julich]
  - [Best current limit on muon EDM]

$$|d_\mu| < 2 \times 10^{-19}\, e\mathrm{cm}$$

[Muon g-2 Collab, BNL '09]

  - e.g. proton - similar sensitivity to the neutron (d ↔ u)
  - e.g. deuteron

via η-π mixing

$$d_D = (d_n + d_p)(\bar{\theta}, d_q, \tilde{d}_q) + d_D^{\pi NN}(\bar{\theta}, \tilde{d}_q)$$

$$\approx -2 \times 10^{-14} \bar{g}^{(1)}_{\pi NN}(\bar{\theta}, \tilde{d}_q) e\,\mathrm{cm} + \mathcal{O}(\bar{g}^{(0)}_{\pi NN})$$

[Lebedev, Olive, Pospelov, AR '04]

$$\approx -5e(\tilde{d}_d - \tilde{d}_u) + \cdots$$

[Khriplovich & Korkin '00; Liu & Timmermans '04; de Vries et al '11]

  - extended to other light nuclei (e.g. ^{3}H, ^{3}He) in recent work

[Stetcu et al '08, de Vries et al '11]

Dependences

1. Tl EDM & YbF "EDM" (paramagnetic) (atomic/molecular)

$$d_{Tl} \sim -585 d_e - 2e \sum_{q=d,s,b} C_{qe}/m_q$$

[Liu & Kelly '92; Khatsymovsky et al. '86]

$$\text{“}d_{YbF}\text{”} \sim 1.4 \times 10^6 d_e + \mathcal{O}(C_S)$$

Nonlinear function of E_{ext} [Kozlov et al. 94-98]

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2. neutron/proton EDM (chiralPT, NDA, QCD sum rules, …) $\Rightarrow |\theta| < 10^{-10}$

$$d_n(\bar{\theta}) \sim 3 \times 10^{-16} \bar{\theta}\, e\text{cm} \qquad d_p(\bar{\theta}) \sim -4 \times 10^{-16} \bar{\theta}\, e\text{cm}$$

$$d_n^{(PQ)} \sim (0.4 \pm 0.2)[4d_d - d_u + 2.7e(\tilde{d}_d + 0.5\tilde{d}_d) + \cdots] + \mathcal{O}(d_s, w, C_{qq})$$

$$d_p^{(PQ)} \sim (0.4 \pm 0.2)[4d_u - d_d - 5.3e(\tilde{d}_u + 0.13\tilde{d}_d) + \cdots] + \mathcal{O}(d_s, w, C_{qq})$$

[Pospelov & AR '99,'00]

NB: precision limited by: sum rules analysis, s-quark content, nucleon coupling,... [Hisano et al '12]

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[Pospelov & AR '99,'00]

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3. Hg EDM (diamagnetic) (atomic+nuclear+QCD)

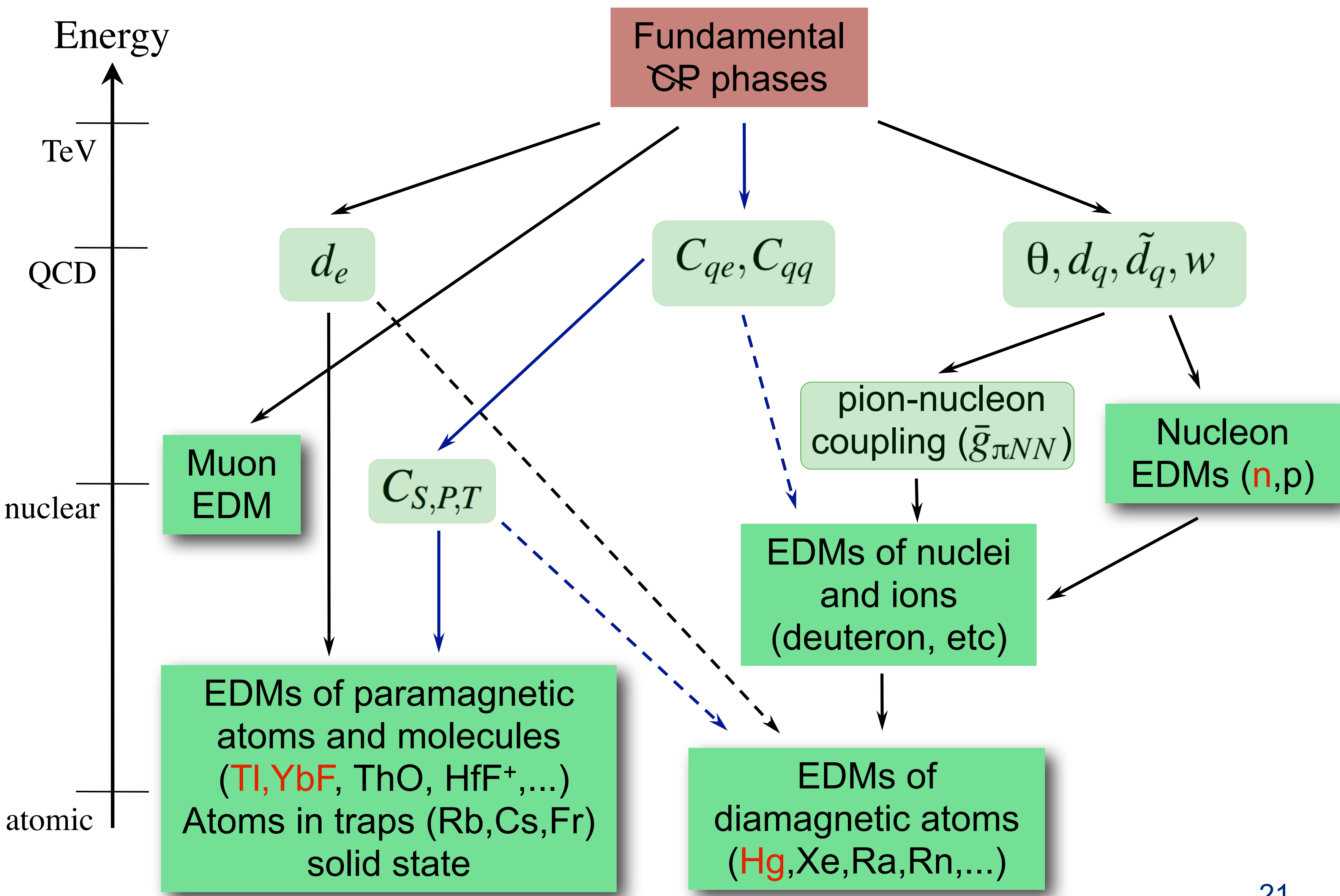
$$d_{Hg} \sim 10^{-3} d_{\rm nuc} \sim -3 \times 10^{-17} S(\bar g_{\pi NN}^{(0,1,2)}, d_n, d_p)\,[e\,\mathrm{fm}^3] + \mathcal{O}(d_e, C_{qq})$$

[Dzuba et al. '02; Flambaum et al. '86; Dmitriev & Senkov '03; de Jesus & Engel '05; Ban et al '10]

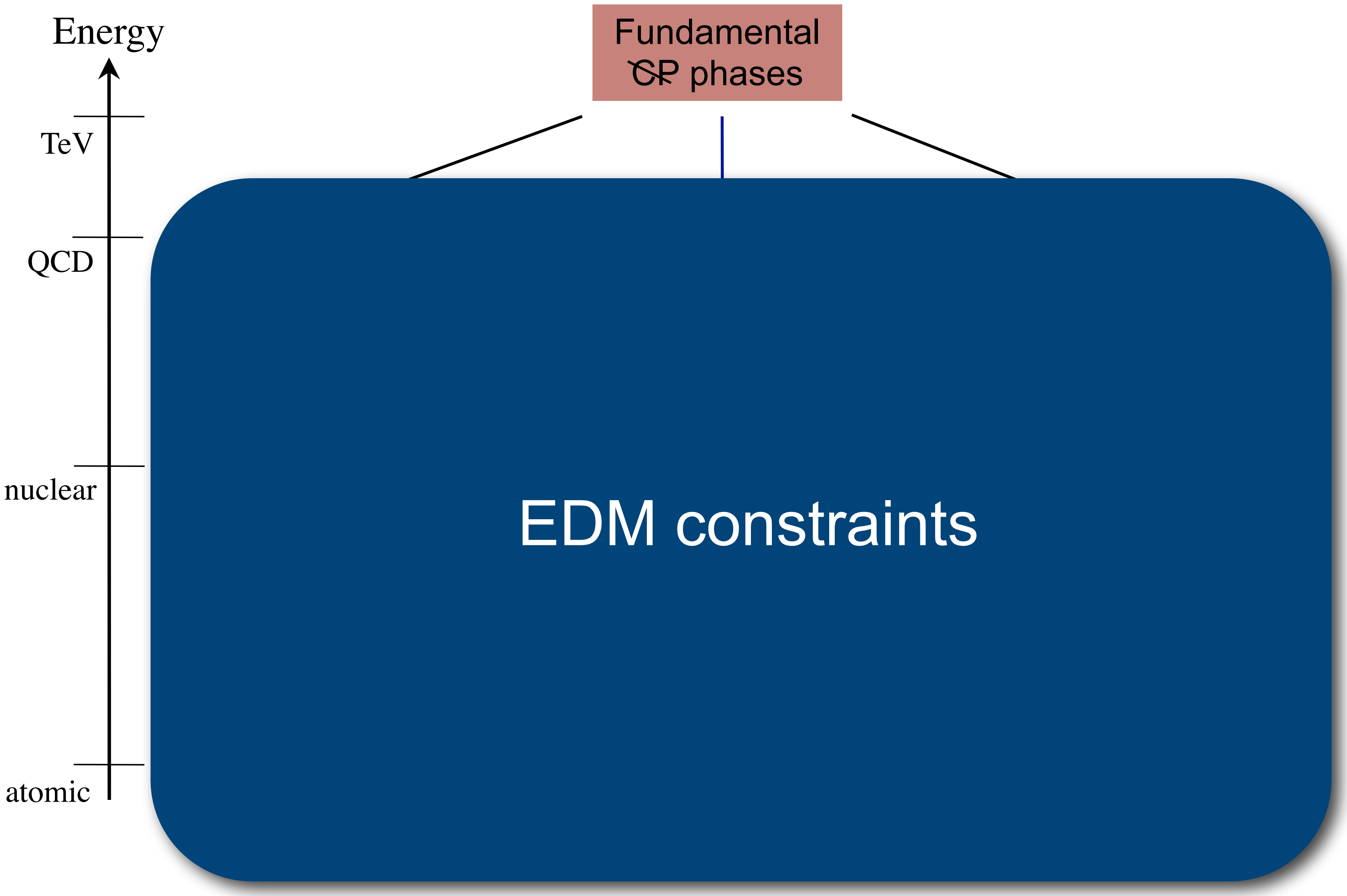
NB: Precision limited by: (i) $S(\bar g_{\pi NN}^{(0)}, \bar g_{\pi NN}^{(1)}, \bar g_{\pi NN}^{(2)})$ [Ban et al '10]

(ii) $\bar g_{\pi NN}^{(1)}(\tilde d_q) \sim (1-6)(\tilde d_u - \tilde d_d) + O(\tilde d_u + \tilde d_d, \tilde d_s, w)$ [Pospelov '01]

EFT hierarchy



Constraints on CP-violation



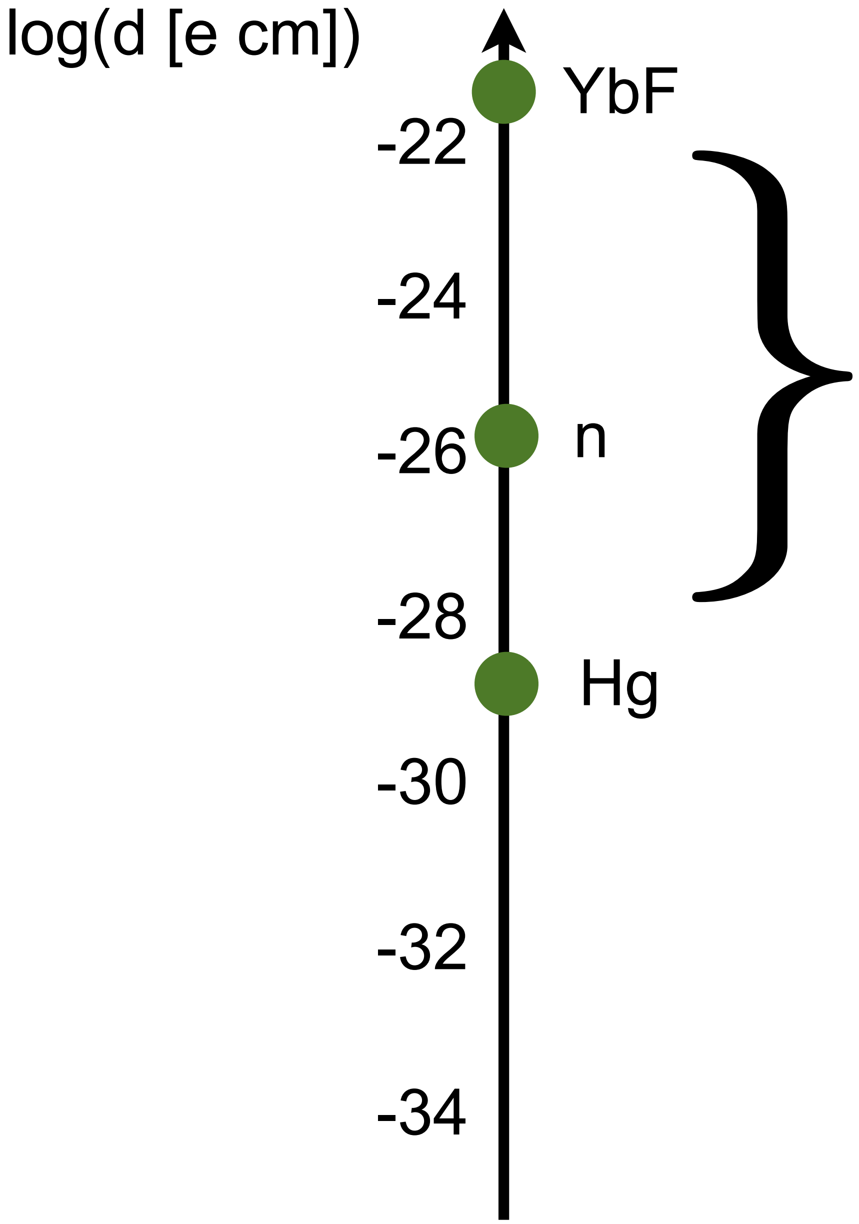
Resulting Bounds on fermion EDMs & CEDMs

YbF EDM [±20%]	$|d_e + \mathcal{O}(C_{eq})| < 1.1 \times 10^{-27} e\, cm$
Tl EDM [±20%]	$\left| d_e + e(26\,\mathrm{MeV})^2 \left(3\frac{C_{ed}}{m_d} + 11\frac{C_{es}}{m_s} + 5\frac{C_{eb}}{m_b}\right)\right| < 1.6 \times 10^{-27} e\, cm$
Neutron EDM [±50%?]	$\left|e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25 d_u) + O(\tilde{d}_s, w, C_{qq})\right| < 2 \times 10^{-26} e\ cm$
Hg EDM [±O(few)?]	$e|\tilde{d}_d - \tilde{d}_u + \mathcal{O}(d_e, \tilde{d}_s, C_{qq}, C_{qe})| < 6 \times 10^{-27} e\,\mathrm{cm}$

Generic scaling: $d_f \sim (couplings) \times \frac{m_f}{\Lambda_{CP}^2}$

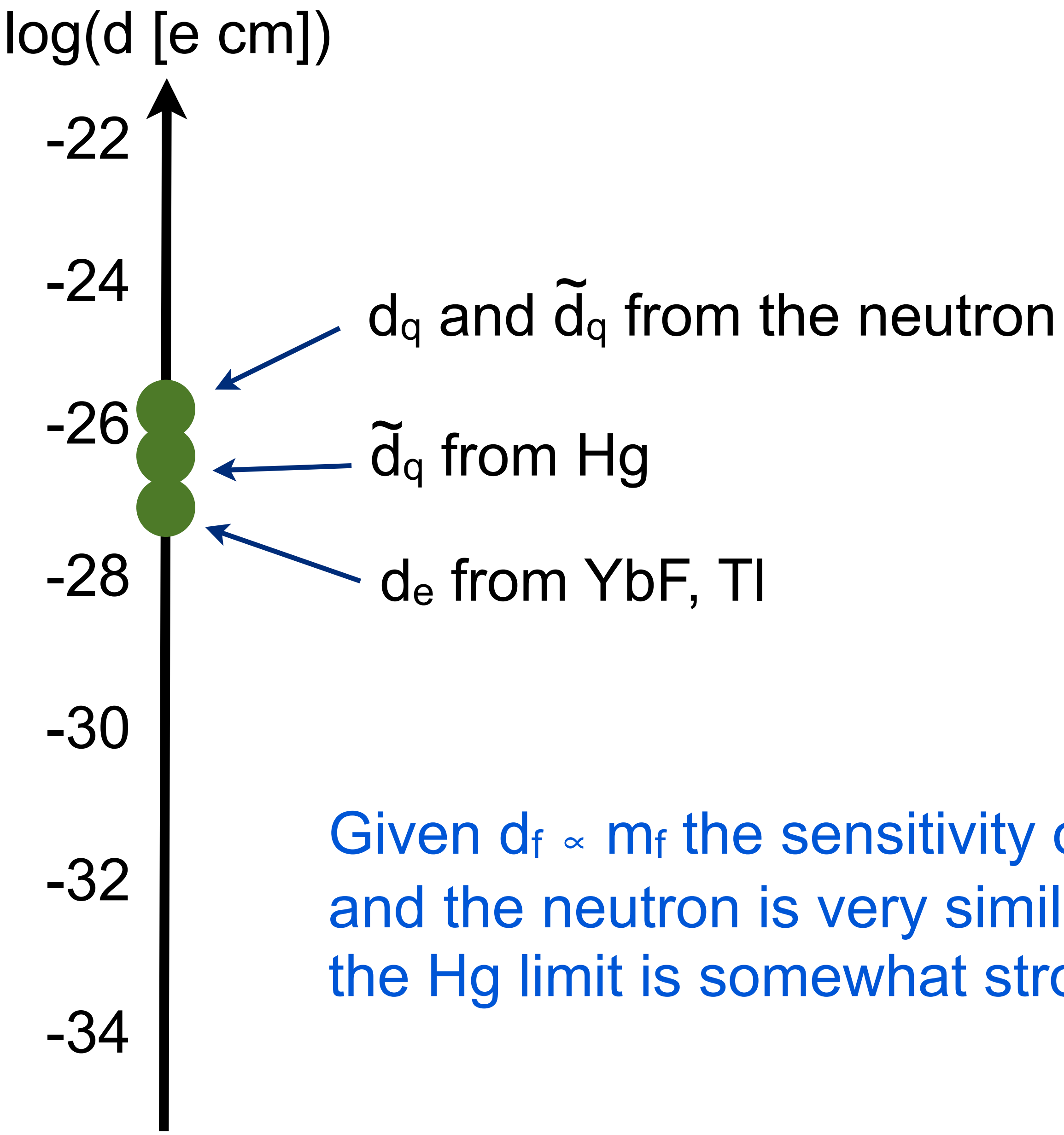
See also recent compilation of limits: [Engel, Ramsey-Musolf, van Kolck '13]

Summary of the bounds



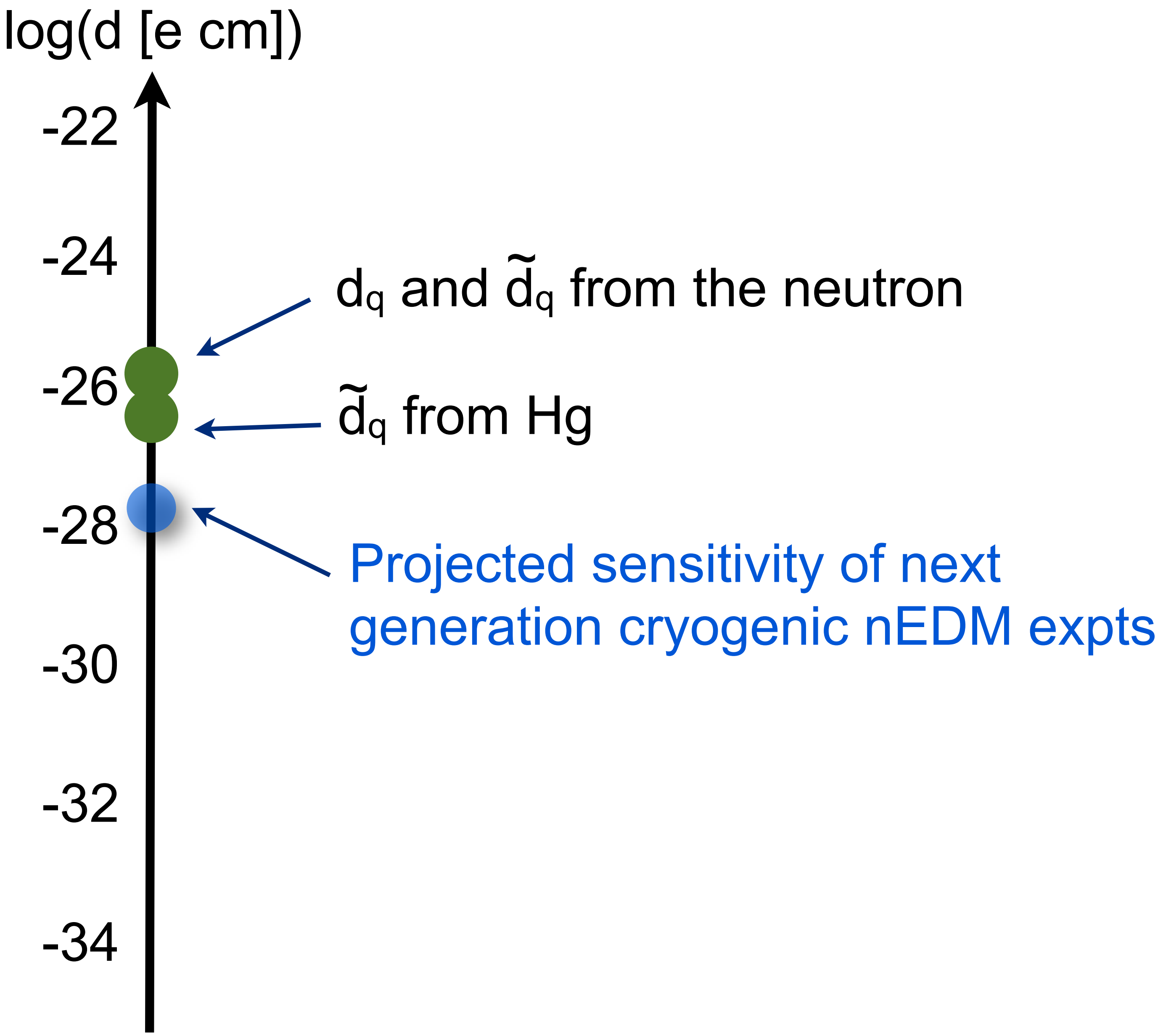
Difference of more than 6 orders of magnitude, but the sensitivity to many underlying CP-odd sources is similar...

Summary of the bounds



Given $d_f \propto m_f$ the sensitivity of Tl and the neutron is very similar; the Hg limit is somewhat stronger

Summary of the bounds



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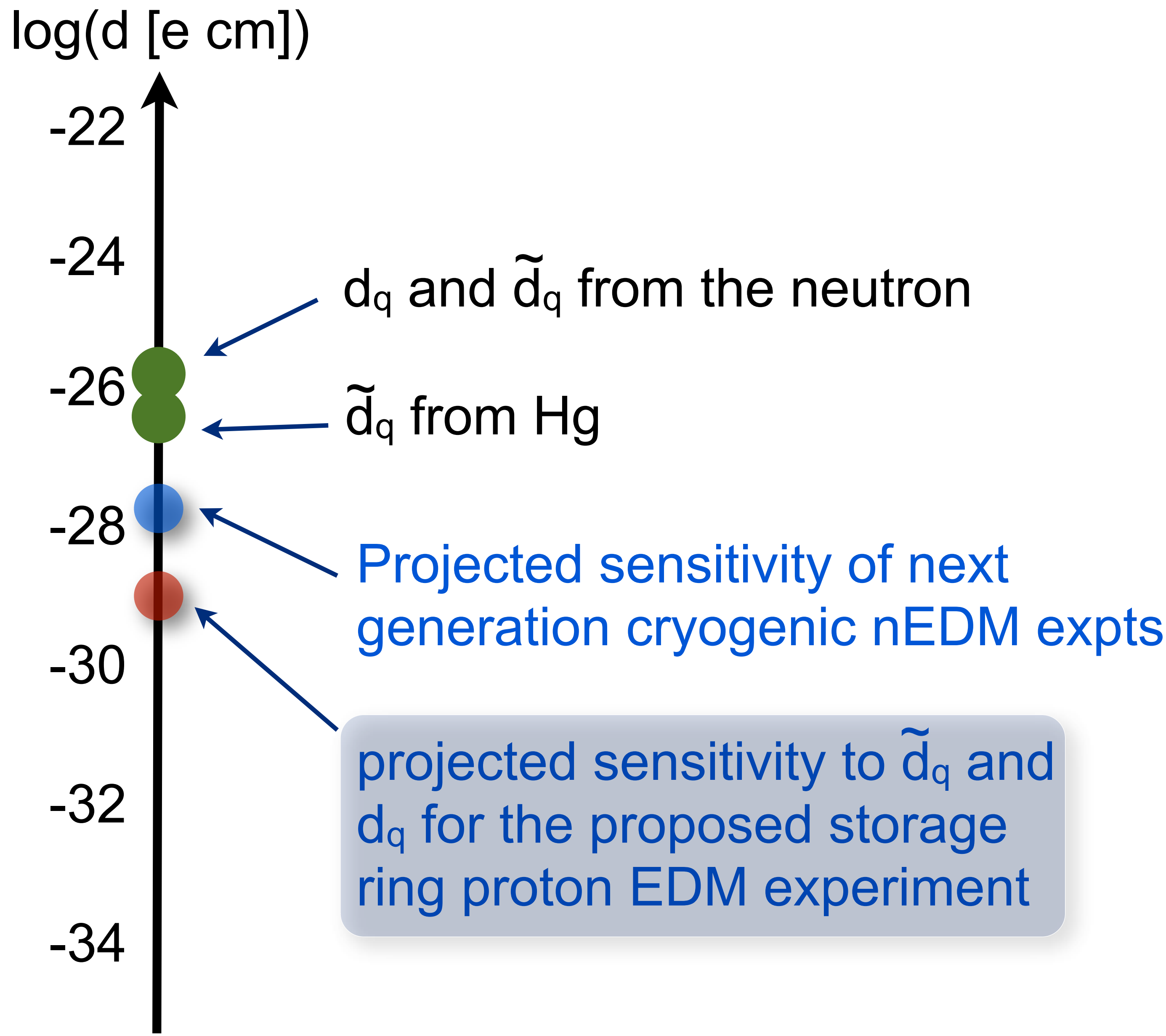
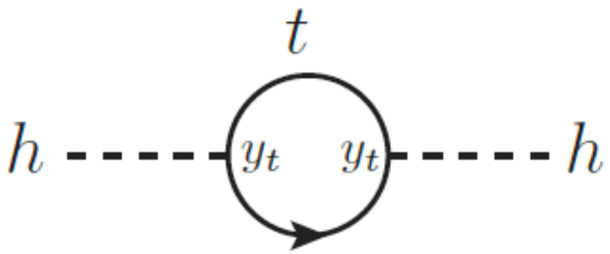


LHC-era tests of CP-violating new physics

Expectation of new EW-scale physics is (or was) primarily associated with stabilising the Higgs sector...



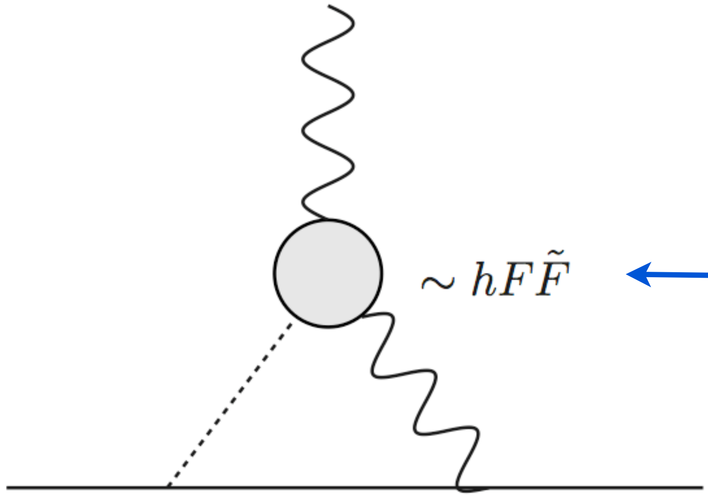
- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...

$\Rightarrow$ EDMs at 2-loops

E.g. - CP-odd Higgs couplings

- Hints in 2012 that Br(h→γγ) > $\mathrm{Br_{SM}}$ (still present in ATLAS data)
- EDMs significantly constrain any CP-odd contribution to h→γγ

$$\Delta\mathcal{L} = \frac{1}{e^2\tilde{\Lambda}^2} H^\dagger H \left(a_h g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu} + b_h g_2^2 W_{\mu\nu}\tilde{W}^{\mu\nu} \right) \longrightarrow \frac{\tilde{c}_h v}{\tilde{\Lambda}^2} h F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$



This interaction corrects the Higgs width, but also generates 2-loop EDMs!

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} \simeq 1 + \left| \tilde{c}_h \frac{v^2}{\tilde{\Lambda}^2} \frac{8\pi}{\alpha A_{\mathrm{SM}}} \right|^2$$

Current limit on d_e limits the shift of Br(h→γγ)/$\mathrm{Br_{SM}}$ to O(10^{-4}) !

[McKeen, Pospelov & AR '12]
[Harnik et al '12; Fan & Reece '13]

LHC-era tests of CP-violating new physics

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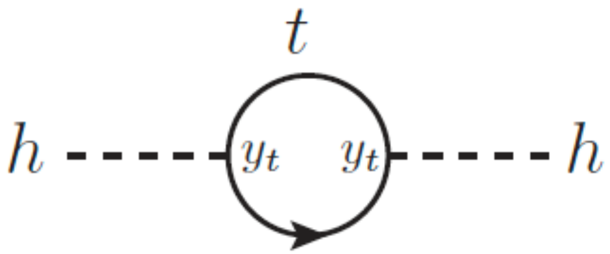

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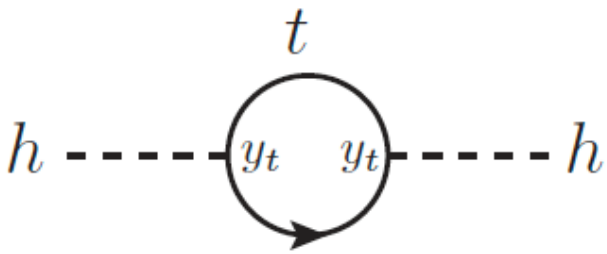


- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...

  ⇒ EDMs at 2-loops

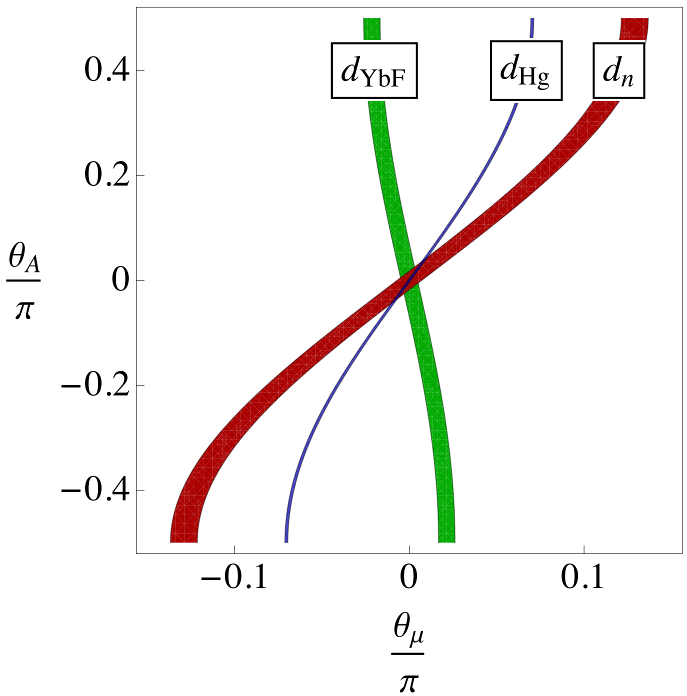
- SUSY provides new physics with strong coupling to 1st generation

  ⇒ EDMs at 1-loop! → SUSY CP problem!

E.g. - SUSY CP Problem (given LHC constraints)

(pre-LHC)

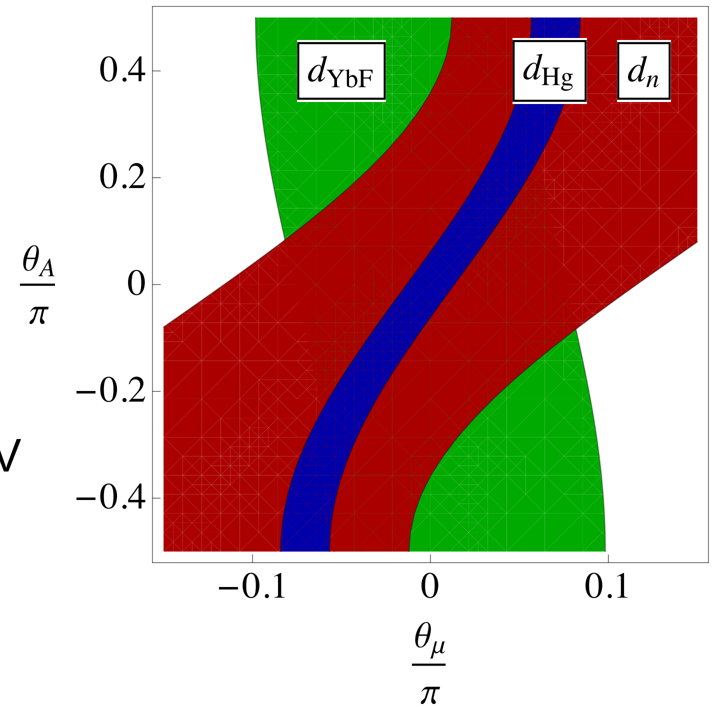
M_{susy} = 500 GeV



1st gen squarks excluded by direct searches at ~1 TeV

(now)

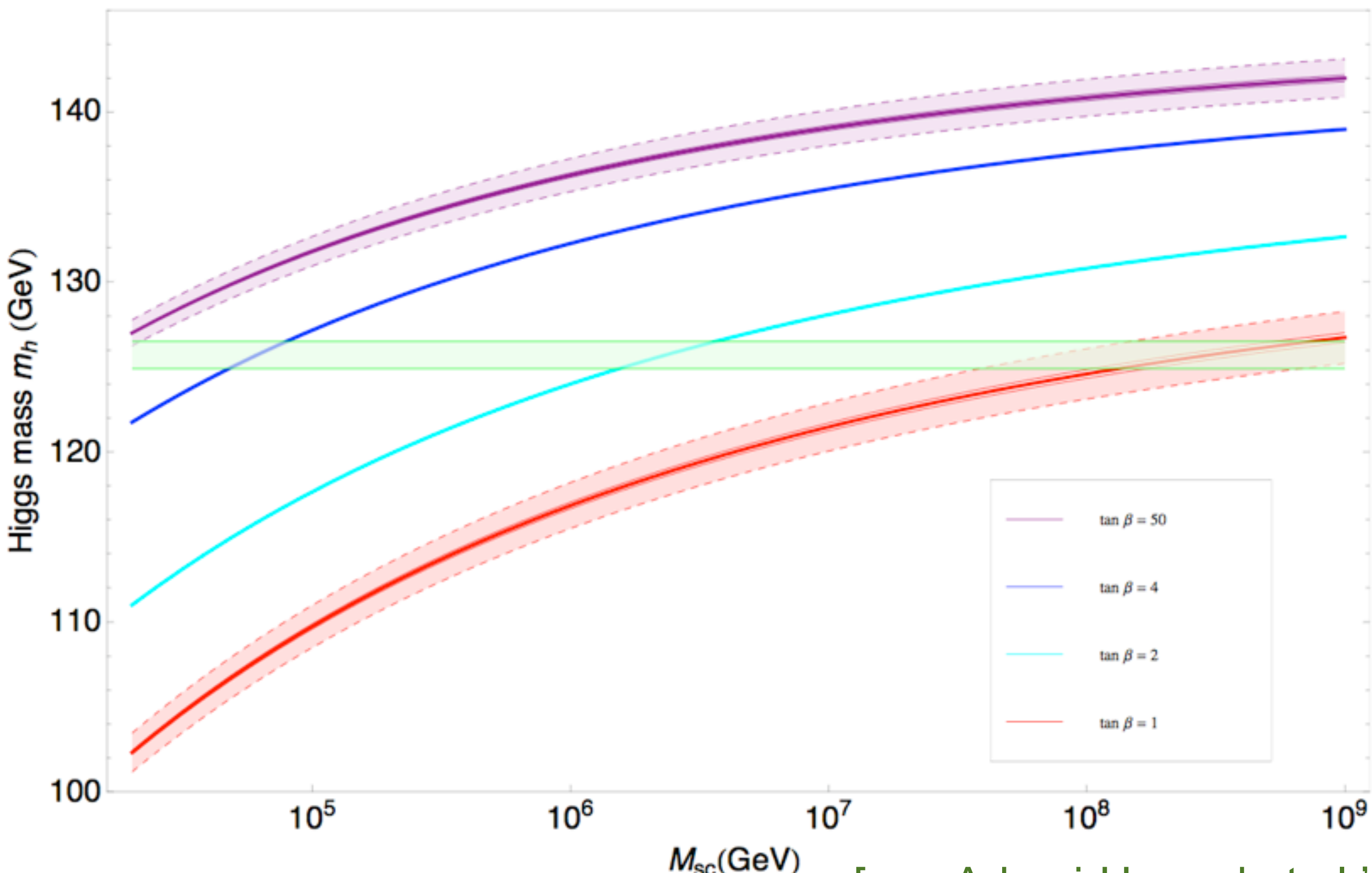
M_{susy} = 2 TeV



EDMs have for many years required (tuned) $O(10^{-3})$ CP-odd phases for generic weak-scale SUSY. The LHC appears to have resolved this by pushing mass limits on 1st generation sfermions above a TeV

E.g. - PeV-scale SUSY sensitivity

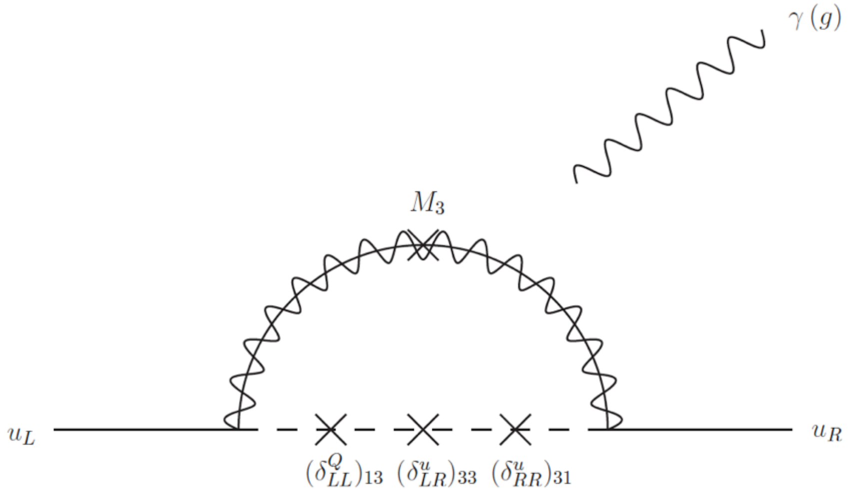
- Within minimal SUSY, $m_h \gg m_Z$ points to PeV-scale s-partners (➠ no soln to hierarchy problem)



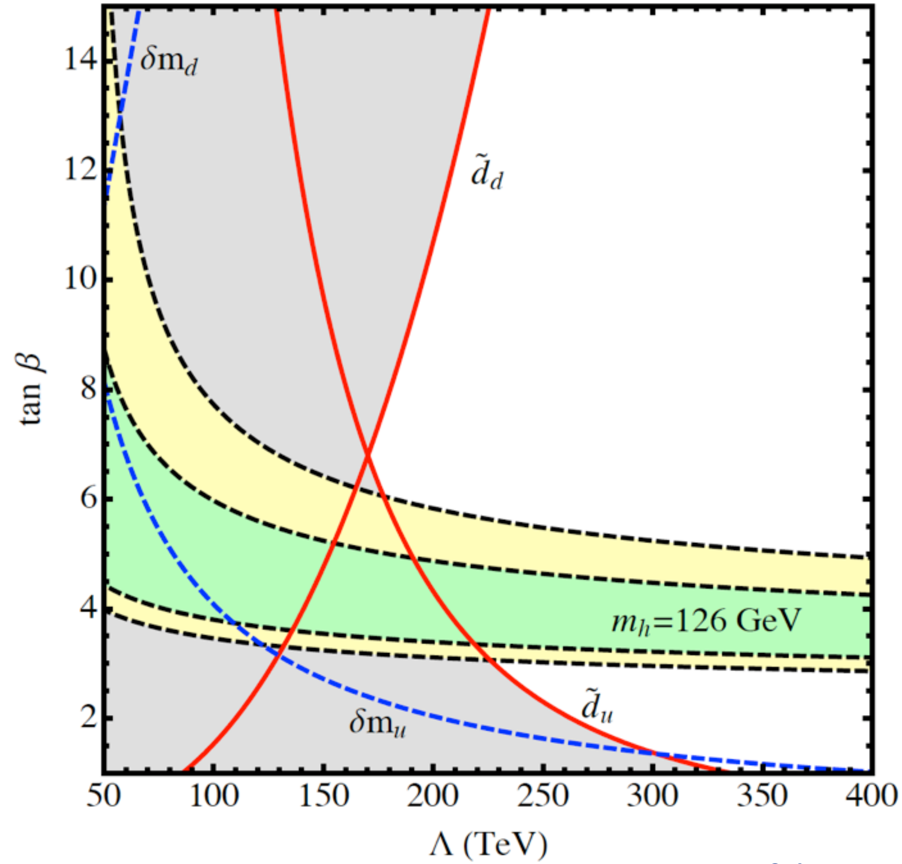
[e.g. Arkani-Hamed et al ’12]

E.g. - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h >> m_Z$ points to PeV-scale s-partners
- The PeV scale allows a generic flavour structure and, with TeV gauginos, hadronic EDMs are one of the few observables able to probe this scale via log-enhanced quark CEDMs



[McKeen, Pospelov & AR '13]



Concluding Remarks

EDMs form an important class of flavour-diagonal CP-odd observables, testing/constraining new physics (motivated by the need for baryogenesis)

- Disentangling multiple CP-odd operators at 1 GeV requires multiple observables
- Storage rings are a novel new technology, which suggest a route around the Schiff screening that “hides” nuclear EDMs

⬇ recent applications

- Useful interplay between EDM constraints and precision tests of CP-odd Higgs couplings
- The SUSY CP problem hinted at by (1-loop) EDMs for more than 20 years has been “confirmed” by the LHC, with no s-partners seen near the weak scale (thus far).

Extra slides

Neutron/Proton EDM Precision

- Issues affecting precision, and tests:
  - numerical coefficients are consistent with NDA, NQM (for d_q), and the chiral log (for θ)
  - another test for $d_n(d_q)$ via (LQCD) nucleon tensor charge

    [e.g. Falk et al '99]

$$\langle N|\frac{1}{2}d_q\bar{q}\tilde{F}\sigma q|N\rangle = \frac{1}{2}d_q\tilde{F}^{\mu\nu}\langle N|\sigma_{\mu\nu}|N\rangle = \frac{1}{2}g_T^q d_q\bar{N}\tilde{F}\sigma N$$

$$\Longrightarrow d_n(d_q) = g_T^d(1\,\mathrm{GeV})d_d + g_T^u(1\,\mathrm{GeV})d_u \sim 1.1d_d - 0.25d_u$$

  - sum-rules fixes ($d_n \sim \langle qq\rangle/\lambda^2$), so the normalization of the coupling matters

$$\lambda \sim 0.025\,\mathrm{GeV}^3$$

from analysis of CP-even sum rules for m_n, sigma term, etc (or lattice result for tensor charge above)

[Pospelov & AR '99,'00]

$$\lambda \sim 0.044 \pm 0.01\,\mathrm{GeV}^3$$

from LQCD [Aoki et al '08] run down from 2 GeV, *BUT* <qq> is also larger with LQCD values for m_q

[Hisano et al '12, Fuyuto et al '12]

  - higher order dependence on s-quark EDM?