

Probing CP Violation with EDMs (in the LHC Era)

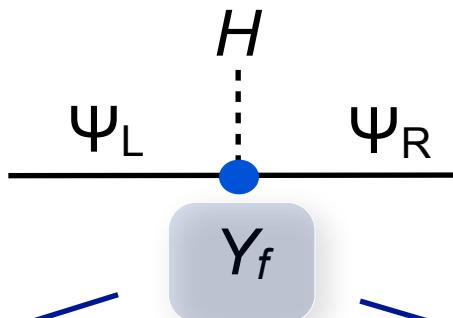
Adam Ritz
University of Victoria



D. McKeen, M. Pospelov & AR, arXiv:1208.4597, 1303.1172

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

CP Violation in the Standard Model



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

$$\sin(\bar{\theta}_{\text{QCD}}) \sim \text{ArgDet}[Y_u Y_d]$$

(in a basis where $\theta_0 \rightarrow 0$)

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

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

$$\theta_{\text{QCD}} < 10^{-10} !$$

Constrained experimentally
(strong CP problem)

Do we anticipate other CP-odd sources ?

- Required for 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 (T,P) violating sources, motivated e.g. by baryogenesis.
- Best current limits from neutrons, para- and dia-magnetic atoms and molecules

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

(Future) Experimental EDM Limits

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

(Posters: Aoki, Chowdhuri, Fertl, Grujic, Hardiman, Helaine, Ingleby, Ito, Kasprzak, Katayama, Leung, Pataguppi, Zsigmond)

Talks by: Filippone, Serebrov, Masuda, Federov

Talk by: Sakemi

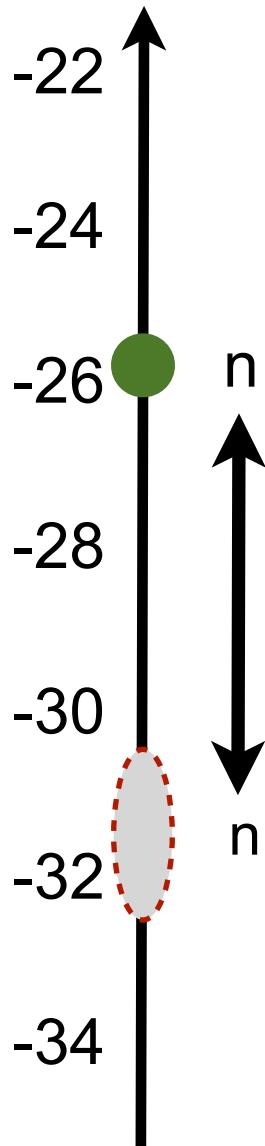
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Talks by: Sauer, Gabrielse

Talks by: Chupp, Ichikawa, Pretz (nuclear)

SM (CKM) background

$\log(d [e \text{ cm}])$

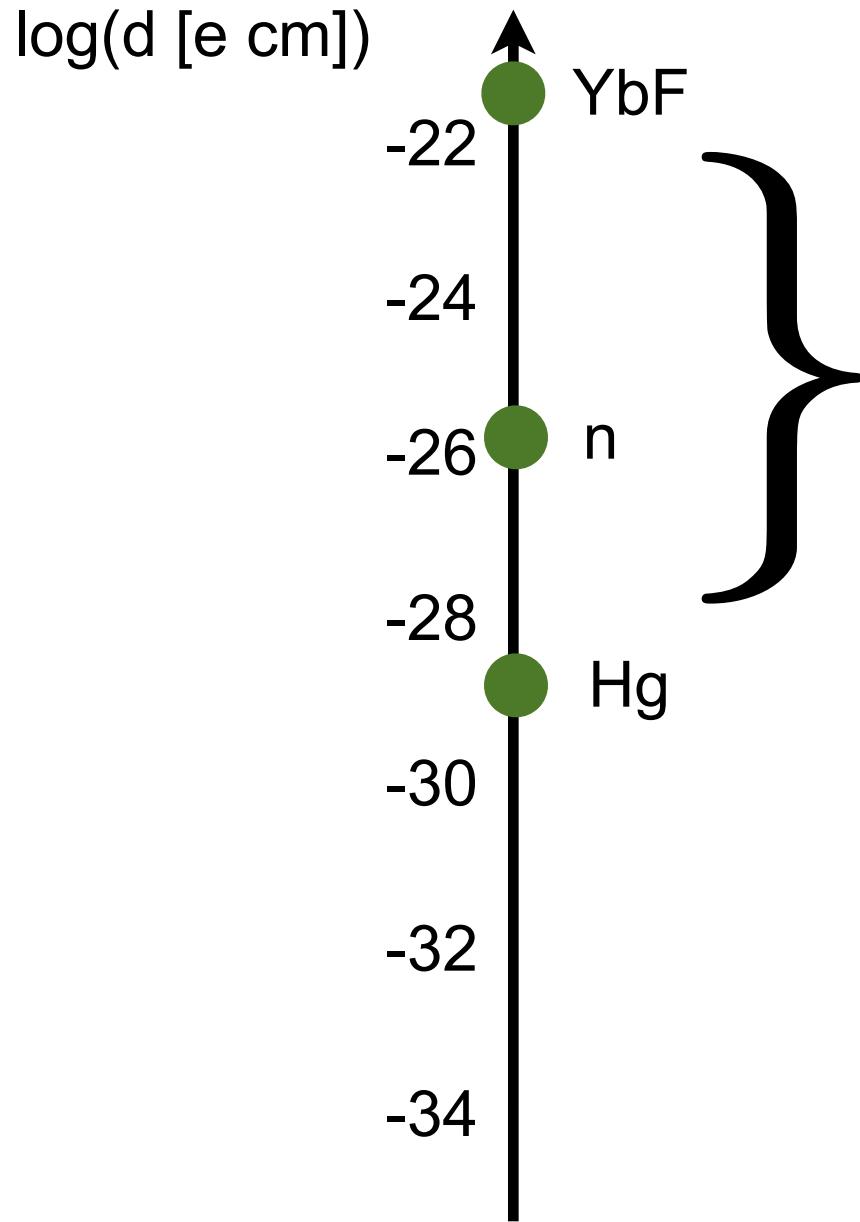


SM (CKM) contribution is (at least)
4-5 orders of magnitude below the
current neutron sensitivity, and
even lower for the atomic EDMs

➡ negligible CKM background

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

Schematic view of the bounds



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

CP-odd operator expansion (at $\sim 1\text{GeV}$)

(Flavor-diagonal) CP-violating operators at $\sim 1\text{GeV}^{(*)}$

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

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

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

*NB: Basis at $\sim 1\text{GeV}$ simpler than EW scale, as we can integrate out W,Z,h

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

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

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

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

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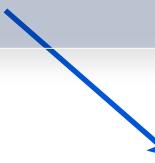
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$$C_{ij} \sim c Y_i Y_j \frac{v^2}{\Lambda^4}$$

CP-odd operator expansion (at $\sim 1\text{GeV}$)

(Flavor-diagonal) CP-violating operators at $\sim 1\text{GeV}$

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

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

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

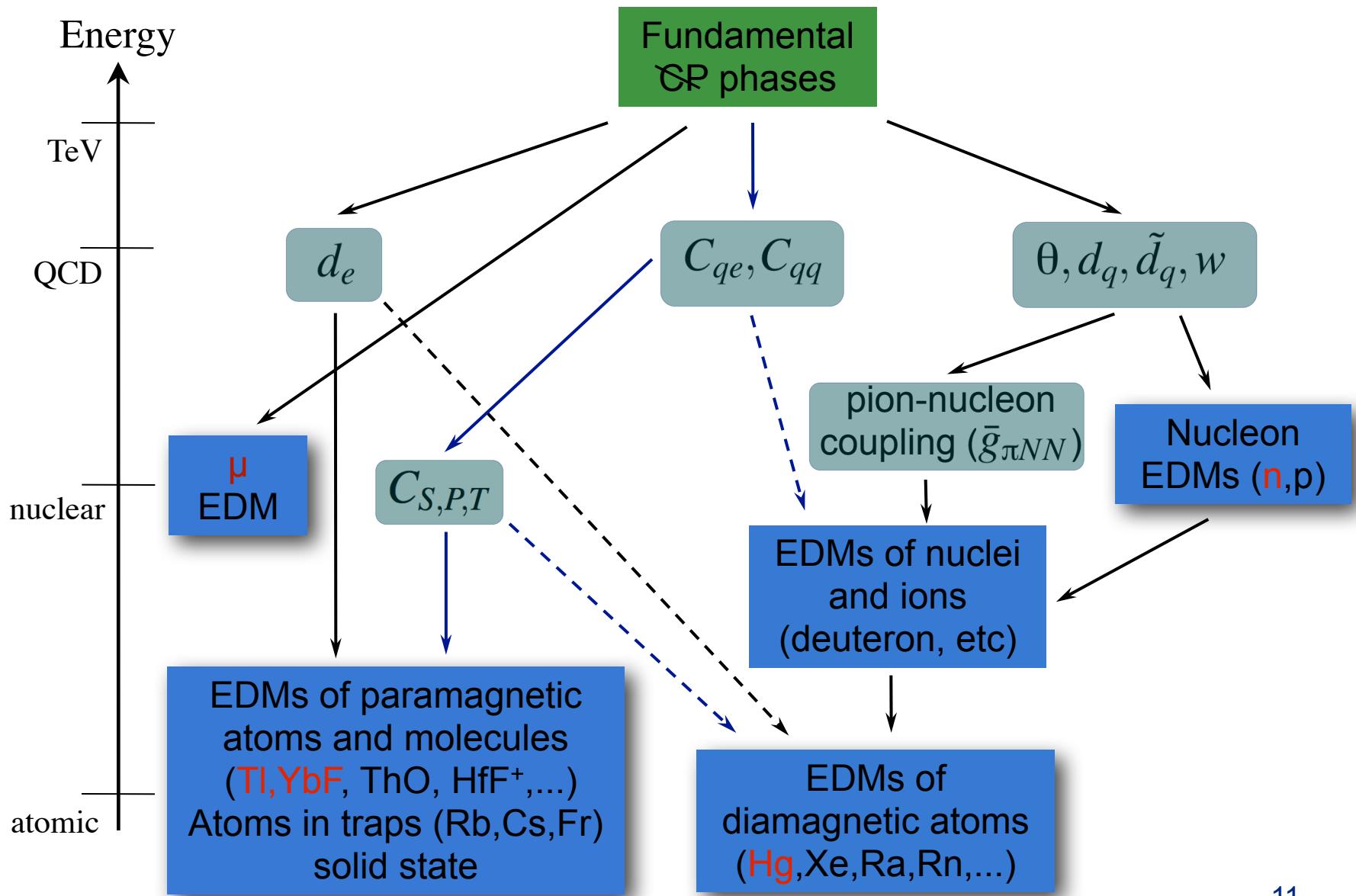
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$$C_S \bar{N} N \bar{e} i \gamma_5 e + \dots$$

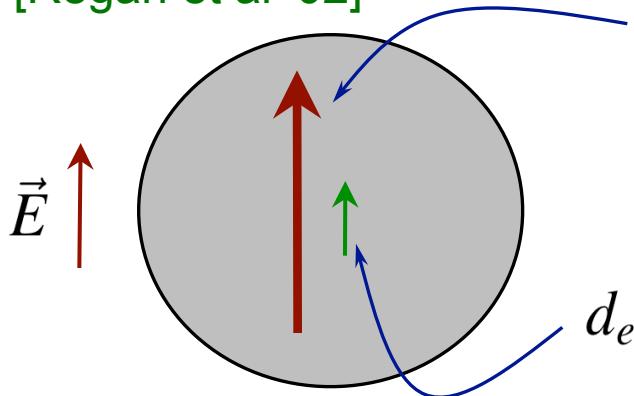
EFT hierarchy



Paramagnetic EDMs - “Schiff enhancement”

Atoms (e.g. Tl [Berkeley])

[Regan et al '02]



(relativistic violation of Schiff screening)

$$\alpha^2 Z^3 \vec{E}$$

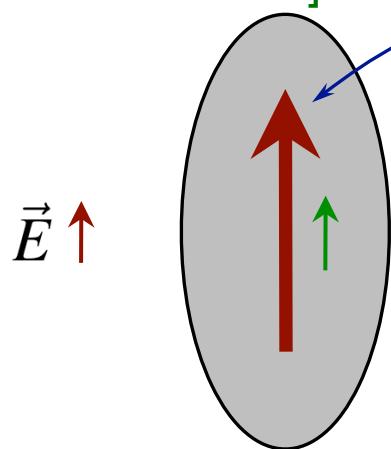
[Salpeter '58;
Sandars '65]

≈ 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}

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

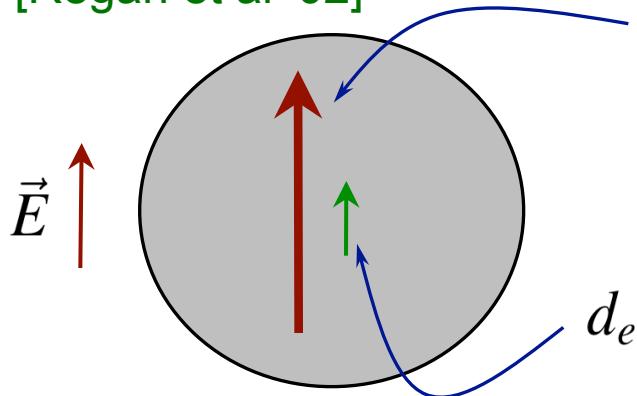
$$\text{“}d_{\text{YbF}}\text{”} \sim 10\alpha^2 Z^3 \frac{M_{\text{mol}}}{m_e} d_e + \mathcal{O}(C_S)$$

[Sushkov &
Flambaum, '78]

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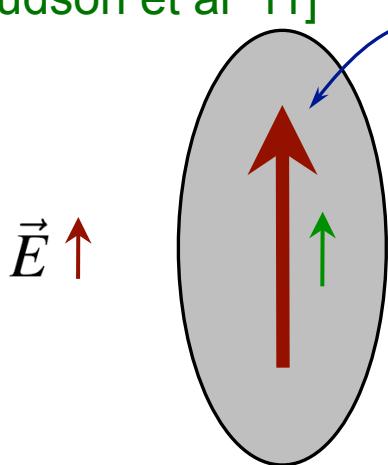
$$d_{\text{Tl}} \sim -585 d_e - e(43 \text{ GeV}) C_S^{(0)}(C_{qe}) + \dots$$

[Liu & Kelly '92]

[Bouchiat '75;
Khatsymovsky et al. '86]

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

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$$\mathcal{E}_{\text{eff}}(E_{\text{ext}})$$

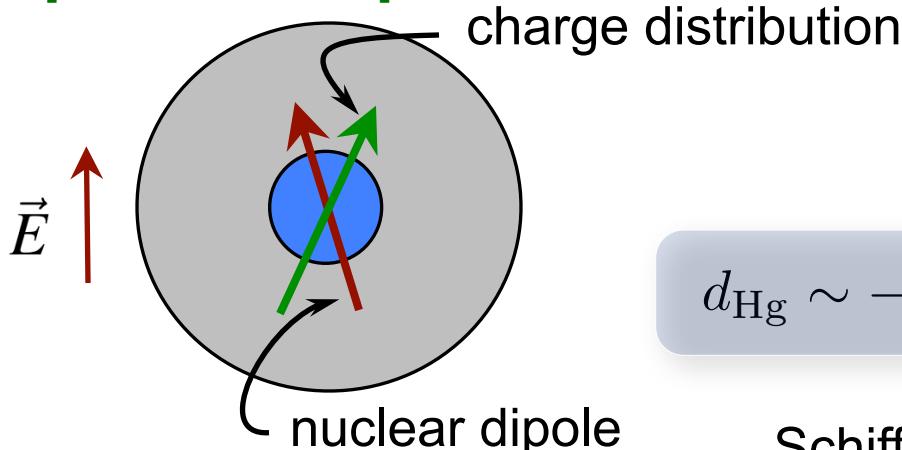
$$\Delta E_{\text{YbF}} \sim -1.5 \times 10^{10} \text{ eV} \left(\frac{d_e}{e \text{ cm}} \right) + \mathcal{O}(C_S(C_{qe}))$$

$$\text{“}d_{\text{YbF}}\text{”} \sim -1.4 \times 10^6 d_e - e(60 \text{ TeV}) C_S^{(0)}(C_{qe}) + \dots$$

[Kozlov et al. 94-98; Quiney et al '98;
Parpia '98; Chaudhuri & Nayak '08]

Diamagnetic EDMs - “Schiff suppression”

Atoms (e.g. Hg [Washington]) (finite size violation of Schiff screening)
[Griffith et al '09]



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

$$O(10^{-3})$$

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

Schiff moment [Schiff '63]

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

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

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

$$\sim -0.06 g_{\pi NN} \bar{g}_{\pi NN}^{(1)} \text{ fm}^3 + \dots$$

NB: precision concerns?

$$\bar{g}_{\pi NN}(\tilde{d}_q) \sim (1-6)(\tilde{d}_u - \tilde{d}_d) + \mathcal{O}(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w)$$

[Pospelov '01]

- 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, SNS, PNPI, TRIUMF, TUM, J-PARC...]
(Calculations using: chiralPT, NDA, QCD sum rules, ...)

$$d_n(\bar{\theta}) \sim 3 \times 10^{-16} \bar{\theta} \text{ ecm} \Rightarrow |\theta| < 10^{-10}$$

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

[Pospelov
& AR
'99,'00]

NB: precision limited by: sum rules analysis, s-quark content,
nucleon coupling,...

[Hisano
et al '12]

Nuclear EDMs - avoiding Schiff screening

- Neutron EDM via UCN bottles [...., PSI, Sussex/ILL, SNS, PNPI, TRIUMF, TUM, J-PARC...]
- Nuclear EDMs (e.g. p,D, ${}^3\text{He}$,...) in storage rings [BNL, FNAL? COSY/Julich]

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



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, SNS, PNPI, TRIUMF, TUM, J-PARC...]
- Nuclear EDMs (e.g. p,D, $^3\text{He}, \dots$) in storage rings [BNL, FNAL? COSY/Julich]

- proton - similar sensitivity to the neutron ($d \leftrightarrow u$)

$$d_p(\bar{\theta}) \sim -4 \times 10^{-16} \bar{\theta} \text{ ecm} \quad [\text{Pospelov \& AR '99, '00}]$$

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

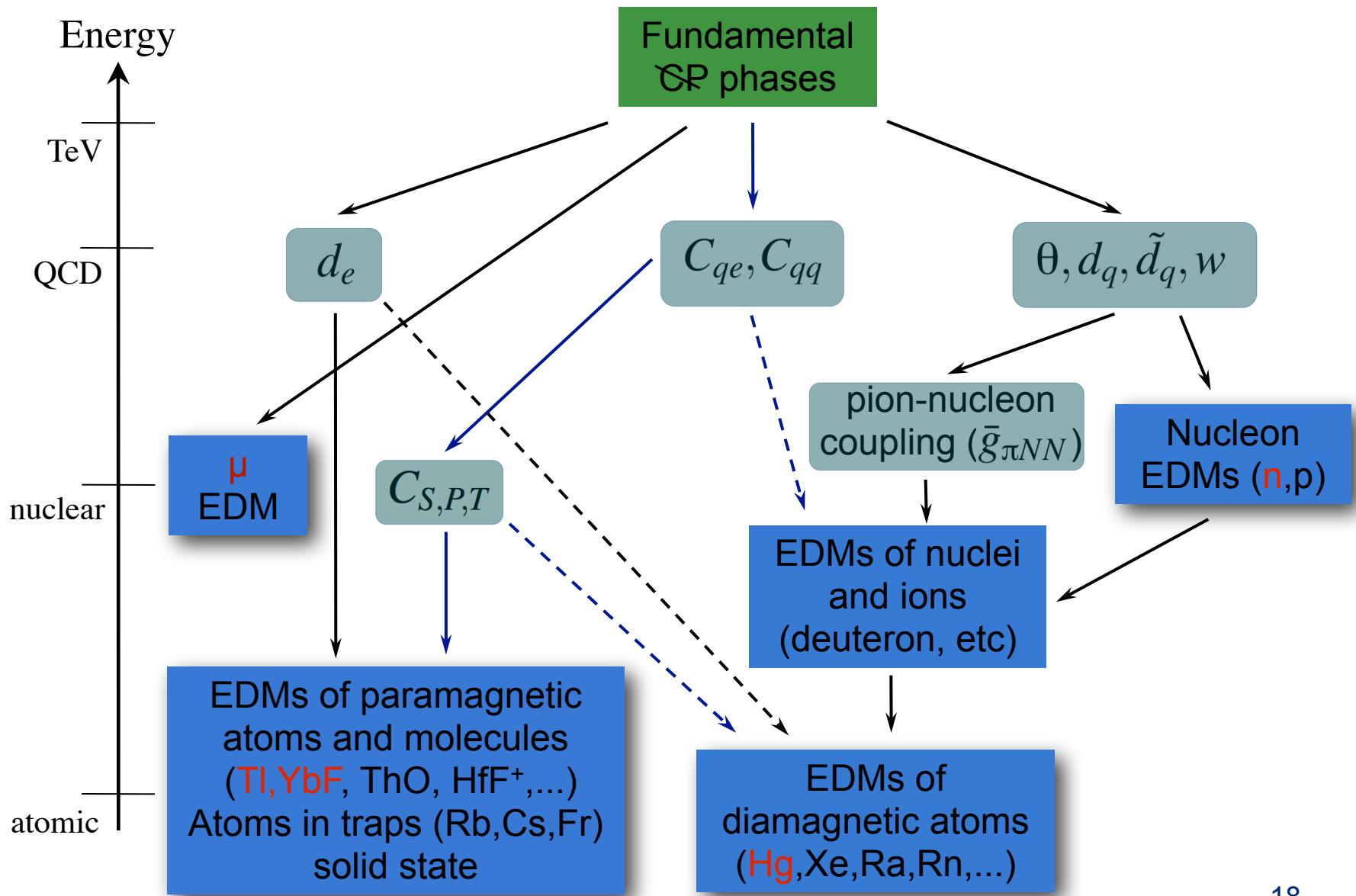
- deuteron

$$\begin{aligned} d_D &= (d_n + d_p)(\bar{\theta}, d_q, \tilde{d}_q) + d_D^{\pi NN}(\bar{\theta}, \tilde{d}_q) \\ &\approx -2 \times 10^{-14} \bar{g}_{\pi NN}^{(1)}(\bar{\theta}, \tilde{d}_q) \text{ e cm} + \mathcal{O}(\bar{g}_{\pi NN}^{(0)}) \\ &\approx -5e(\tilde{d}_d - \tilde{d}_u) + \dots \quad [\text{Lebedev, Olive, Pospelov, AR '04}] \\ &\quad [\text{Khriplovich \& Korkin '00; Liu \& Timmermans '04;} \\ &\quad \text{de Vries et al '11; Bsaisou et al '12}] \end{aligned}$$

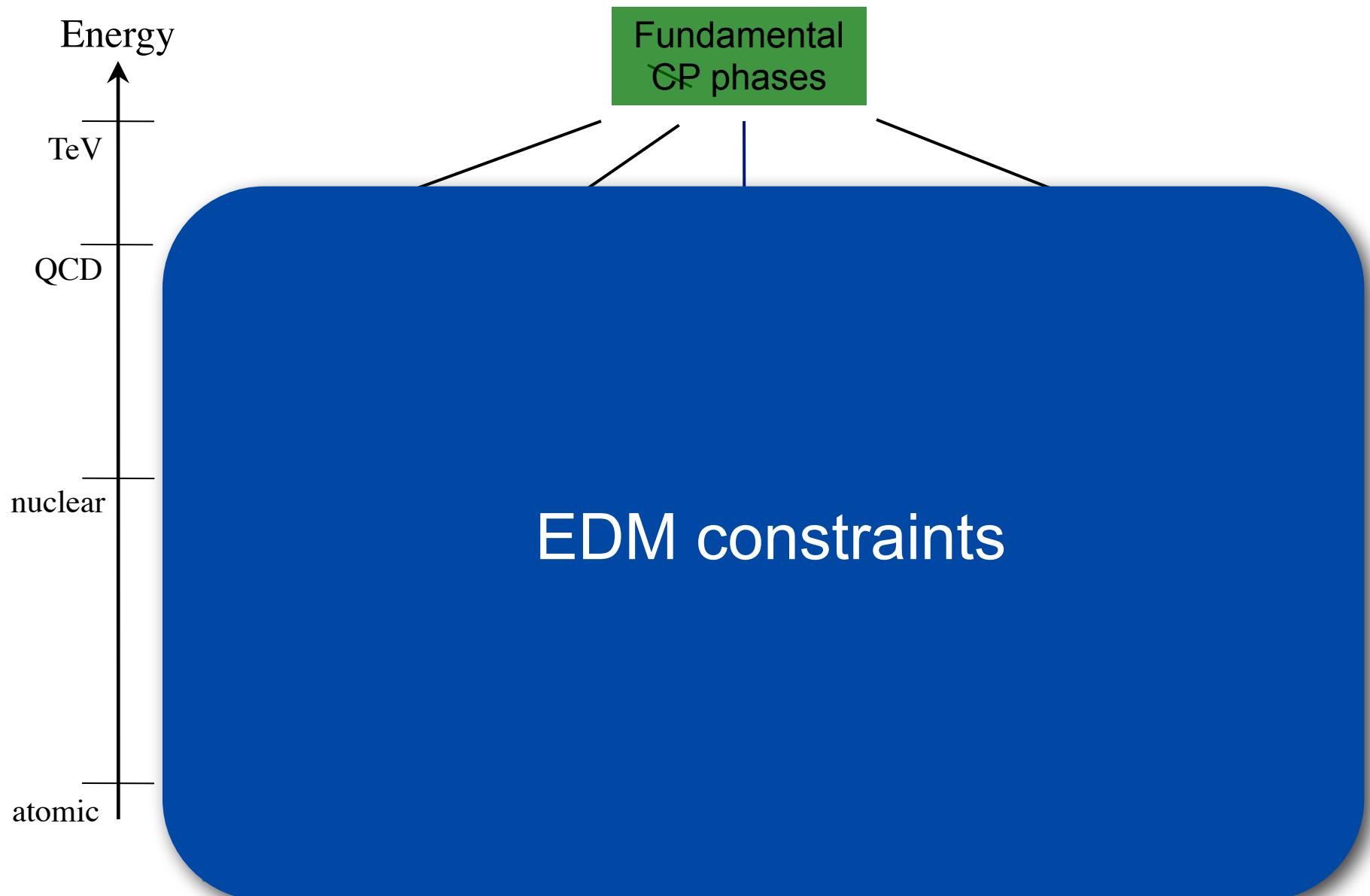
via η - π mixing

- extended to other light nuclei (e.g. ^3H , ^3He) in recent work
[Stetcu et al '08, de Vries et al '11]

EFT hierarchy



Constraints on CP-violation



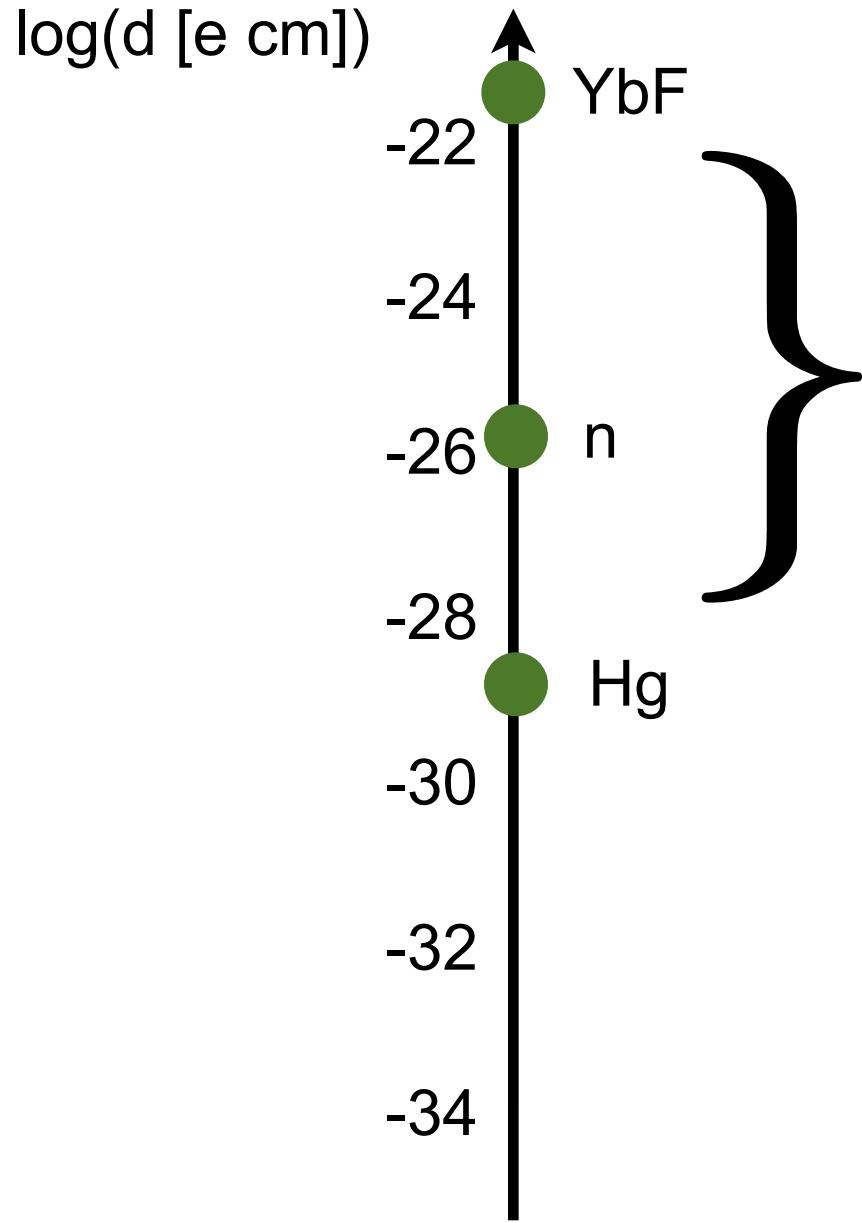
Resulting Bounds on fermion EDMs & CEDMs

YbF EDM [$\pm 20\%$]	$\left d_e + e(21 \text{ MeV})^2 \left(3 \frac{C_{ed}}{m_d} + 11 \frac{C_{es}}{m_s} + 5 \frac{C_{eb}}{m_b} \right) \right < 1.1 \times 10^{-27} e \text{ cm}$
TI EDM [$\pm 20\%$]	$\left d_e + e(26 \text{ MeV})^2 \left(3 \frac{C_{ed}}{m_d} + 11 \frac{C_{es}}{m_s} + 5 \frac{C_{eb}}{m_b} \right) \right < 1.6 \times 10^{-27} e \text{ cm}$
Neutron EDM [$\pm 50\%?$]	$\left e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25d_u) + \mathcal{O}(\tilde{d}_s, w, C_{qq}) \right < 2 \times 10^{-26} e \text{ cm}$
Hg EDM [$\pm \mathcal{O}(\text{few})?$]	$e \tilde{d}_d - \tilde{d}_u + \mathcal{O}(d_e, \tilde{d}_s, C_{qq}, C_{qe}) < 6 \times 10^{-27} e \text{ cm}$

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

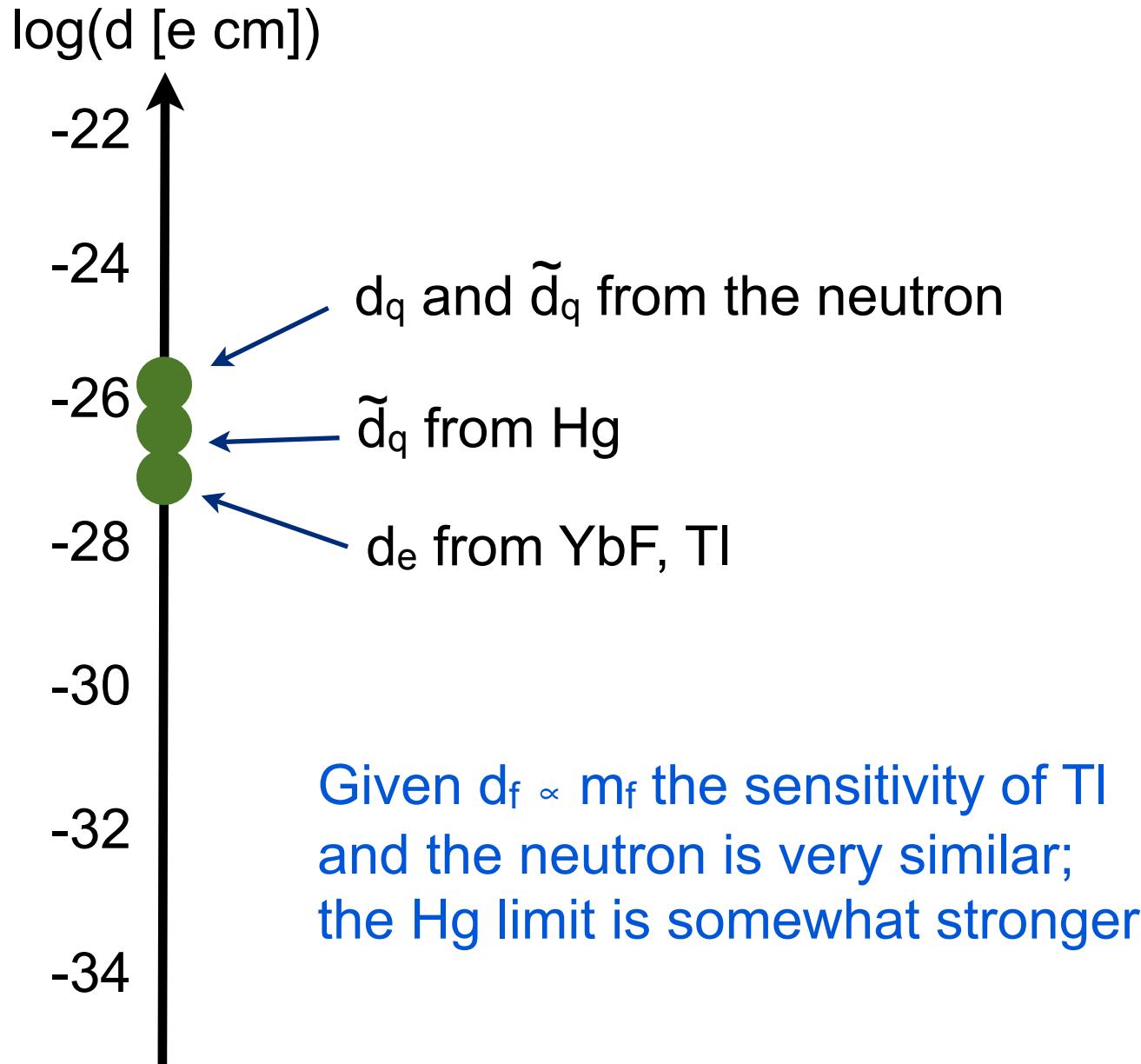
See also recent compilation of limits: [Engel, Ramsey-Musolf, van Kolck '13]

Summary of the bounds



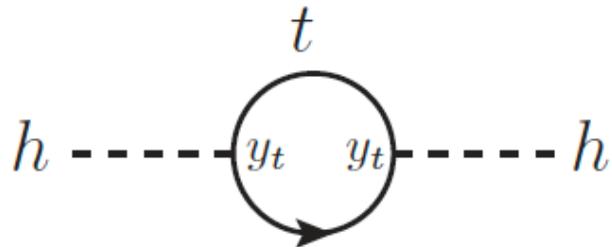
Difference of more than 6 orders of magnitude, but the sensitivity to many underlying CP-odd sources is similar...

Summary of the bounds



LHC-era tests of CP-violating new physics

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

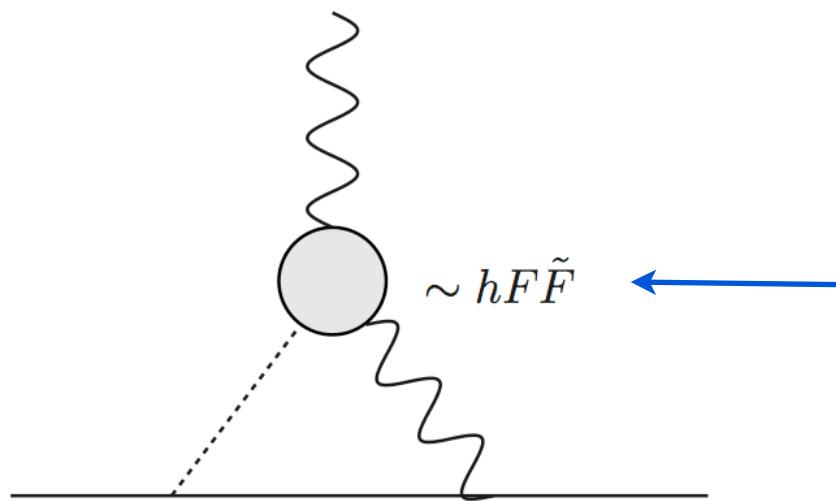


- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...
 ⇒ EDMs at 2-loops

E.g. - CP-odd Higgs couplings

- Hints in 2012 that $\text{Br}(h \rightarrow \gamma\gamma) > \text{Br}_{\text{SM}}$ (still present in ATLAS data)
- EDMs significantly constrain any CP-odd contribution to $h \rightarrow \gamma\gamma$

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



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

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

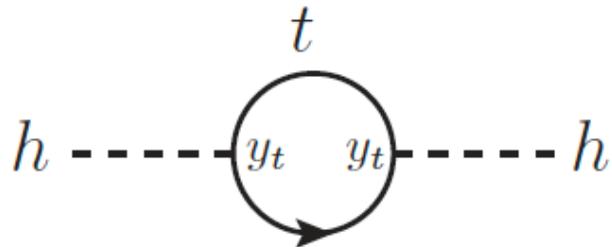
Current limit on d_e limits the shift of $\text{Br}(h \rightarrow \gamma\gamma)/\text{Br}_{\text{SM}}$ to $O(10^{-4})$!

[McKeen, Pospelov & AR '12]

[Harnik et al '12; Fan & Reece '13]

LHC-era tests of CP-violating new physics

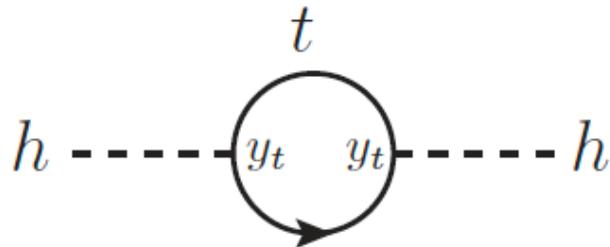
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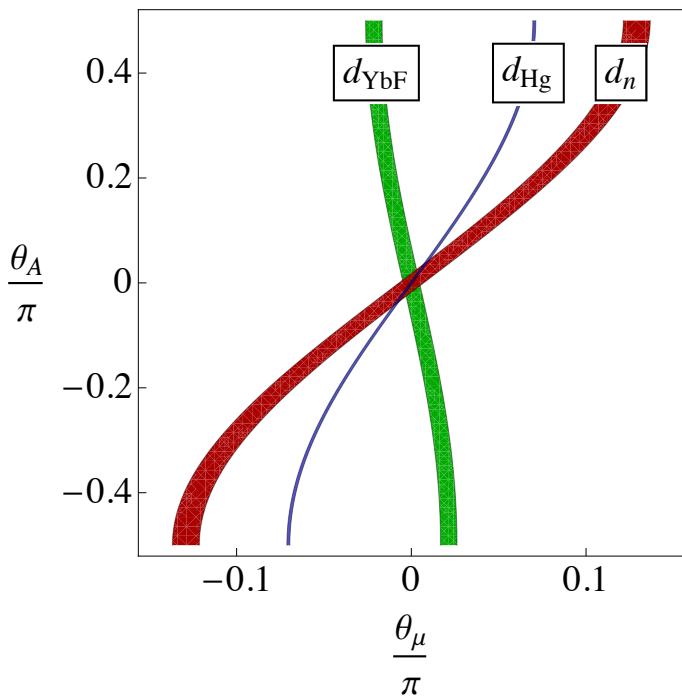


- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...
 ⇒ EDMs at 2-loops
- SUSY provides new physics with strong coupling to 1st generation
 ⇒ EDMs at 1-loop! → SUSY CP problem!

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

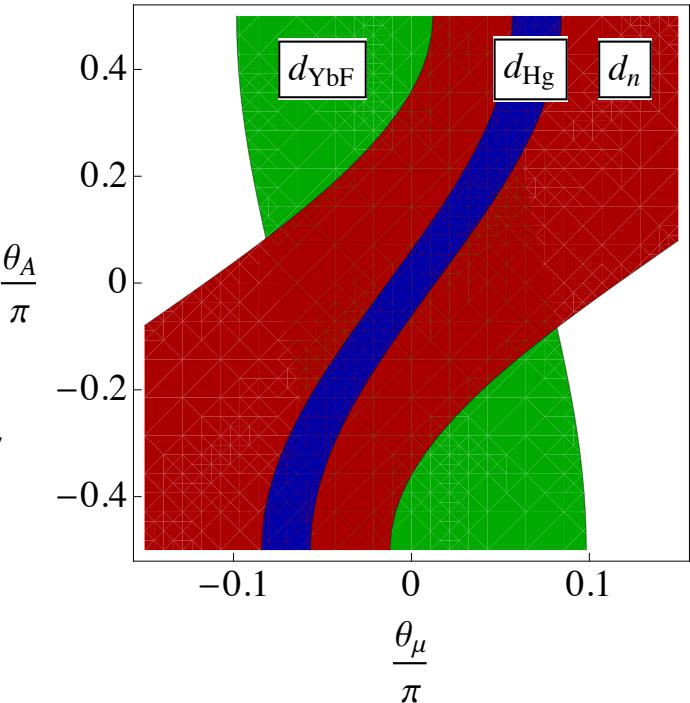
(pre-LHC)

$$M_{susy} = 500 \text{ GeV}$$



(now)

$$M_{susy} = 2 \text{ TeV}$$



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

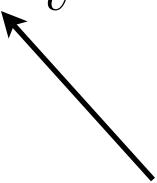
EDMs have for many years required (tuned) $O(10^{-3})$ CP-odd phases for generic weak-scale SUSY. The LHC appears to have “resolved” this by pushing mass limits on 1st generation sfermions above a TeV

E.g. - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h \gg m_Z$ points to PeV-scale s-partners
(\Rightarrow tuning, no soln to “little hierarchy” problem)

[e.g. Arkani-Hamed et al '12]

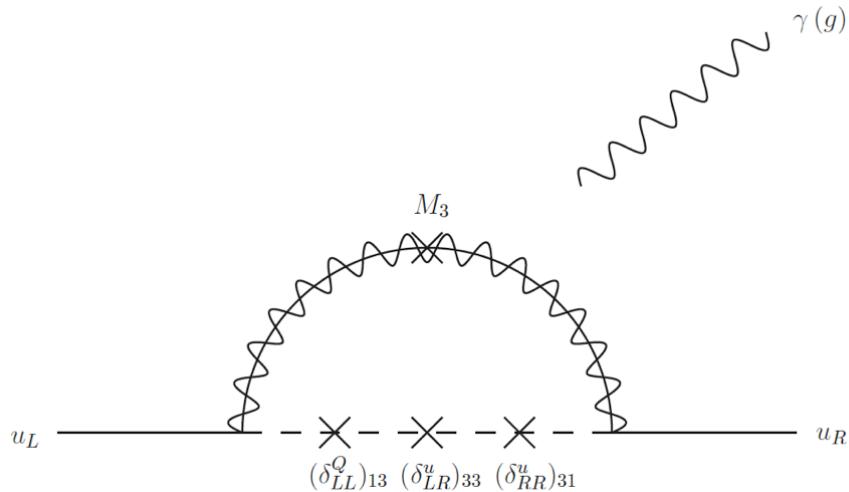
$$m_h^2 \sim M_Z^2 + \frac{3}{\sqrt{2}\pi^2} G_F m_t^4 \ln \frac{m_{\tilde{t}}^2}{v^2}$$



Need a large log correction
 $\Rightarrow m_{\text{squark}} > 100\text{-}1000 \text{ TeV}$

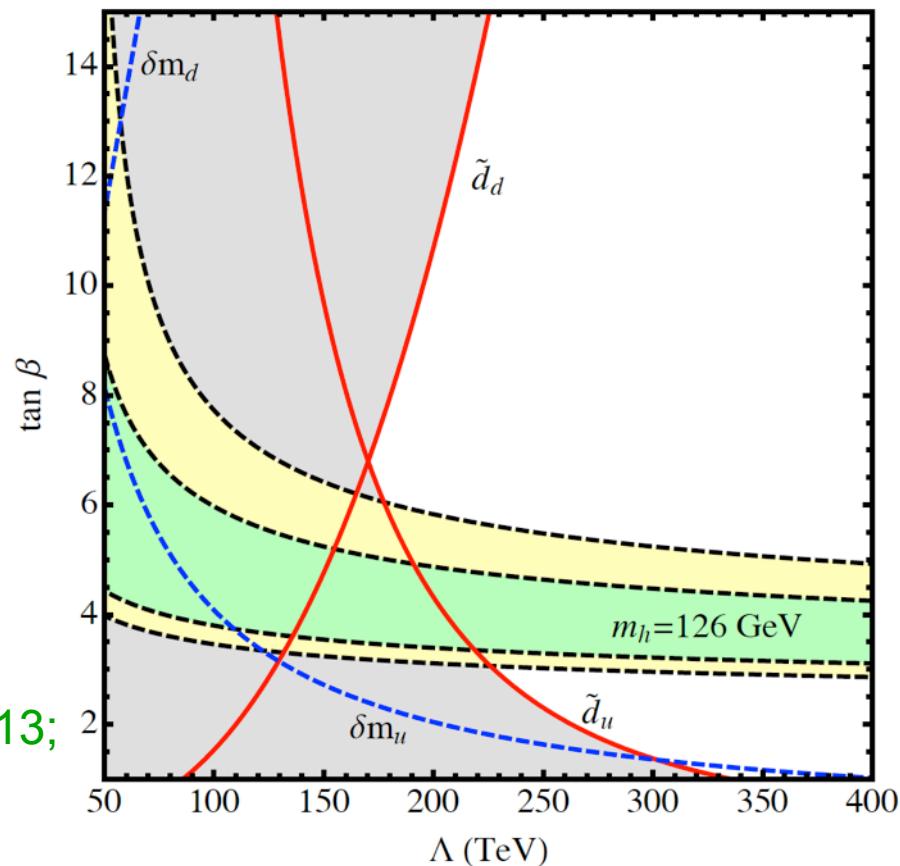
E.g. - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h \gg m_Z$ 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]

[also recent work by Altmannshofer et al '13;
Fuyuto et al '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



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 squarks seen near the weak scale (thus far). EDMs probe the very high (PeV) sfermion scales characteristic of the “large” observed Higgs mass

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]
$$\langle N | \frac{1}{2} d_q \bar{q} \tilde{F} \sigma q | N \rangle = \frac{1}{2} d_q \tilde{F}^{\mu\nu} \langle N | \sigma_{\mu\nu} | N \rangle = \frac{1}{2} g_T^q d_q \bar{N} \tilde{F} \sigma N$$
$$\implies d_n(d_q) = g_T^d(1 \text{ GeV}) d_d + g_T^u(1 \text{ GeV}) d_u \sim 1.1 d_d - 0.25 d_u$$

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

$$\lambda \sim 0.025 \text{ GeV}^3$$

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

[Pospelov & AR '99, '00]

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

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

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

- higher order dependence on s-quark EDM?