Probing new CP-odd physics with EDMs

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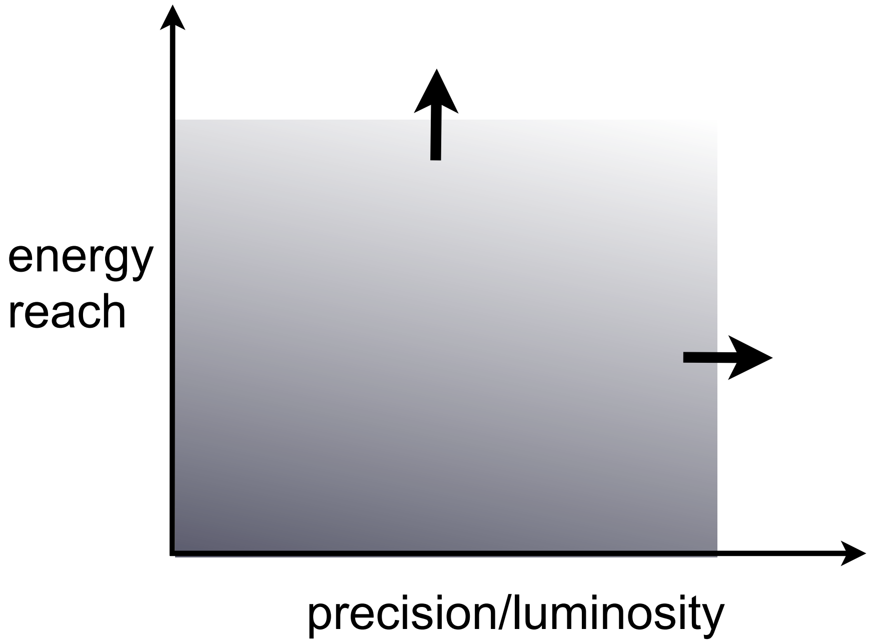
with M. Pospelov

[For a review, see hep-ph/0504231]

Precision Tests as Probes for New Physics

Searches for new physics (at energy scale Λ):



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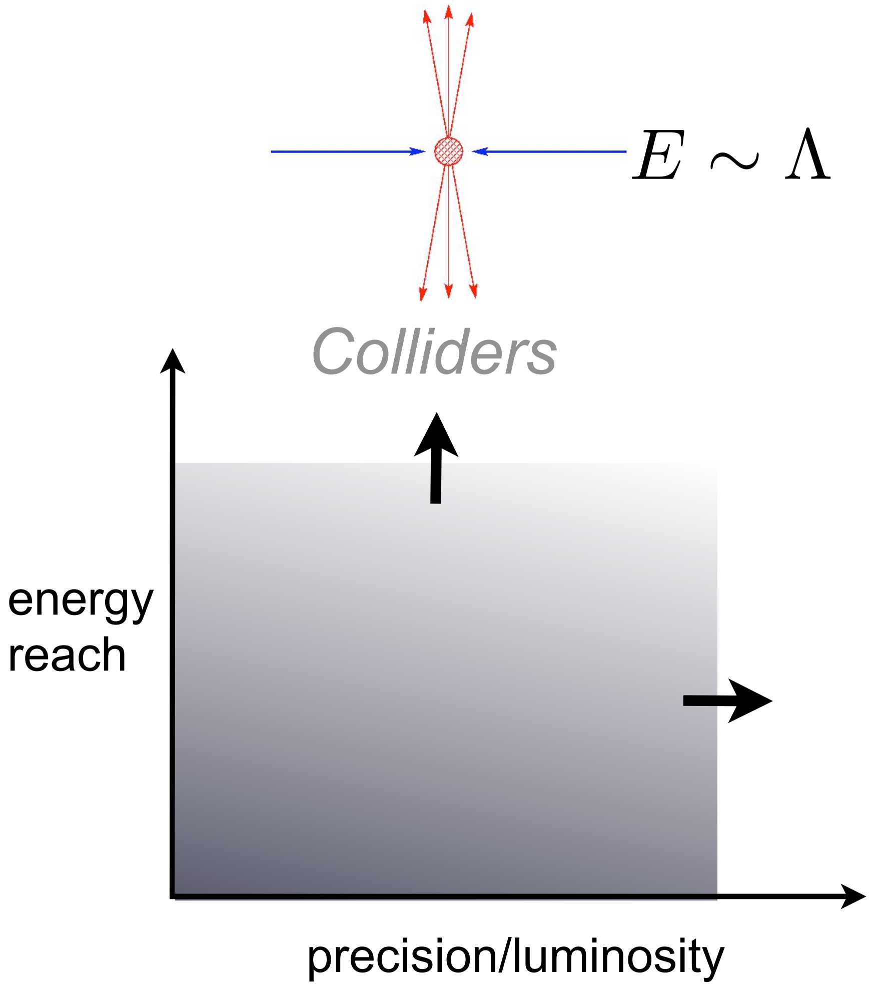

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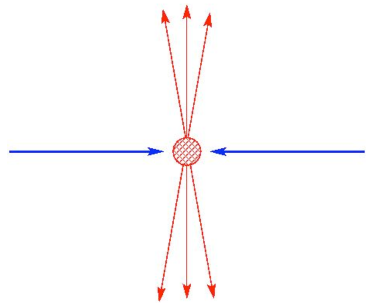
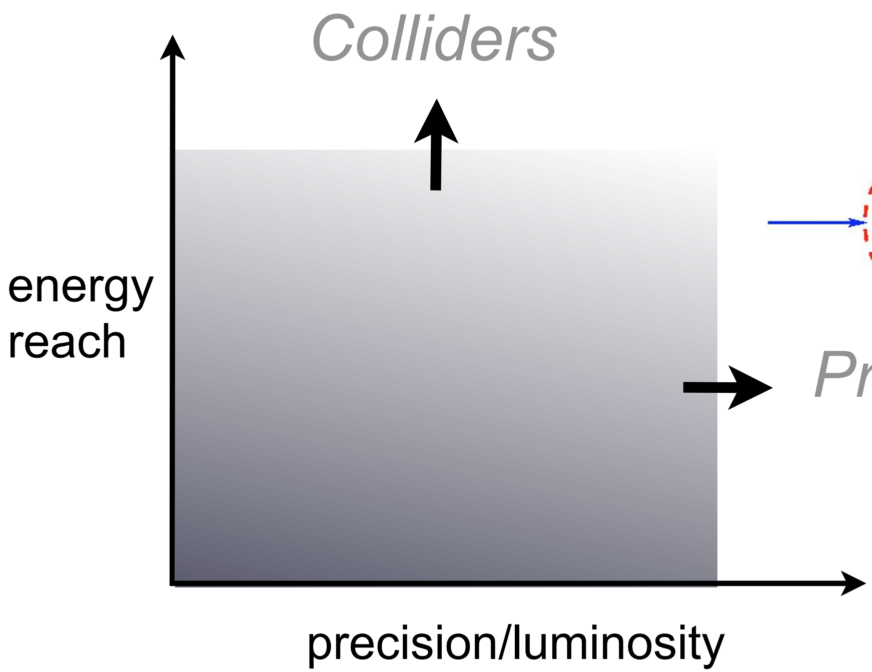
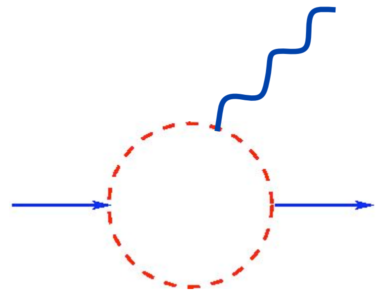


$$E \sim \Lambda$$



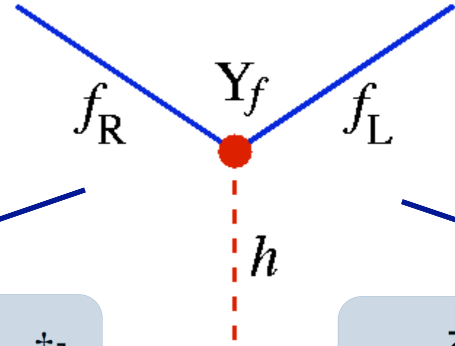


$$\frac{\Delta E}{E} \sim \left(\frac{m}{\Lambda}\right)^n$$

Especially powerful for tests of "*<u>symmetries</u>*" of the SM: e.g. Baryon no., Lepton no., Flavour, T (or CP), etc.

$$\text{e.g. } M_\nu = \frac{v^2}{\Lambda \sim 10^{14}\,\text{GeV}} Y$$

CP Violation in the Standard Model



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

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

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

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

(in a convenient basis)

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

Constrained experimentally (strong CP problem)

Do we anticipate other CP-odd sources ?

- Required by baryogenesis
- Generic with more fields (eg MSSM)

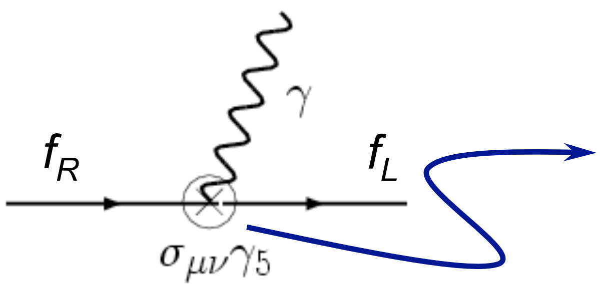
CP-violation and EDMs

Within the SM, CP-violation is hidden behind the flavour structure $J_{CP} \sim 10^{-5}\sin(\delta_{KM})$

[Jarlskog '85]

$\Longrightarrow$

Look for new sources of CP-violation in flavour diagonal channels, with small SM bkgd



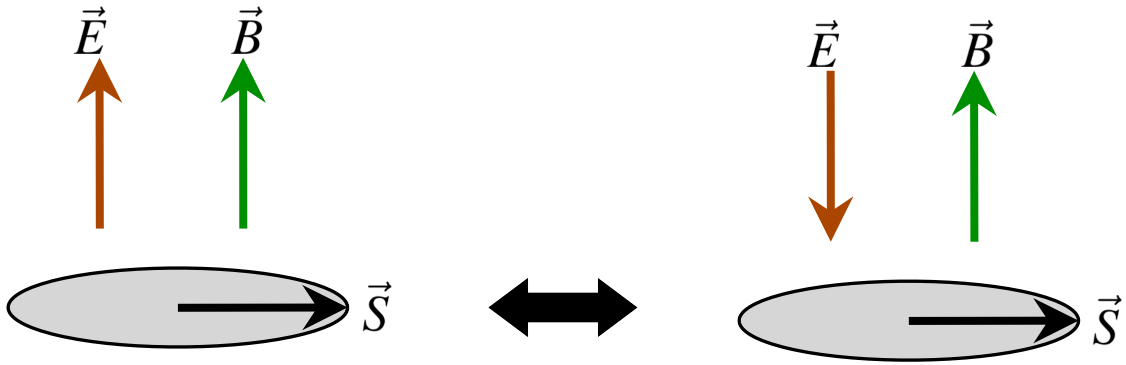
$$H = -d\vec{S}\cdot\vec{E}$$

Sensitivity through EDMs of neutrons, and para- and dia-magnetic atoms and molecules (violate T,P)

Currently, all experimental data $\Rightarrow$ EDMs vanish to very high precision leading to very strong constraints on new physics.

Sensitivity

- Measure Larmor precession frequency in (anti-)aligned E and B fields



$\hbar\omega_L^1 = 2\mu \cdot B + 2d \cdot E$

$\hbar\omega_L^2 = 2\mu \cdot B - 2d \cdot E$

$$d = \frac{\hbar}{4E}(\omega_L^1 - \omega_L^2) \sim (\text{loop})\frac{m_f}{\Lambda_{\text{CP}}^2}$$

$$\text{Given } E \sim 10\, kV/cm,\ \delta\omega \sim 10^{-6}\,\text{Hz} \implies \Lambda_{\text{CP}} \sim 1\,\text{TeV}$$

Experimental Status

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]
Mercury EDM (diamagnetic)	$\lvert d_{Hg} \rvert < 2 \times 10^{-28} e\ cm$	[Romalis et al. '00]

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$$\mathcal{O}(10^4) \times e\, l_p \;!!$$

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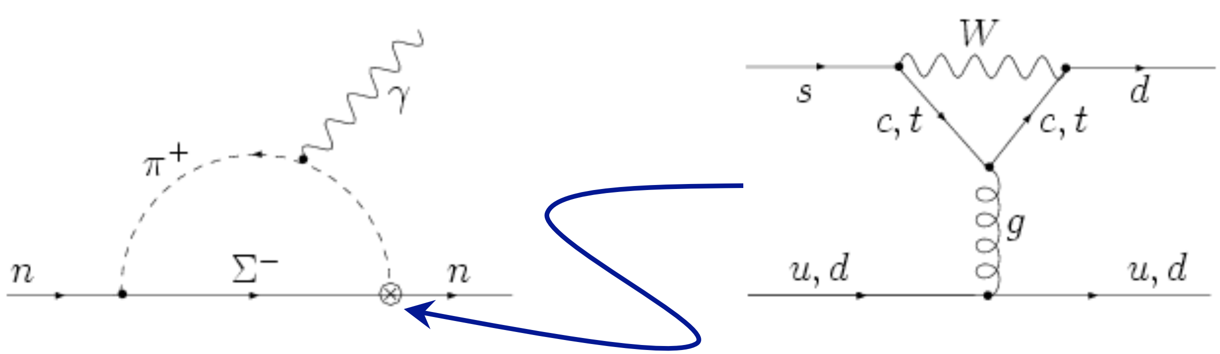
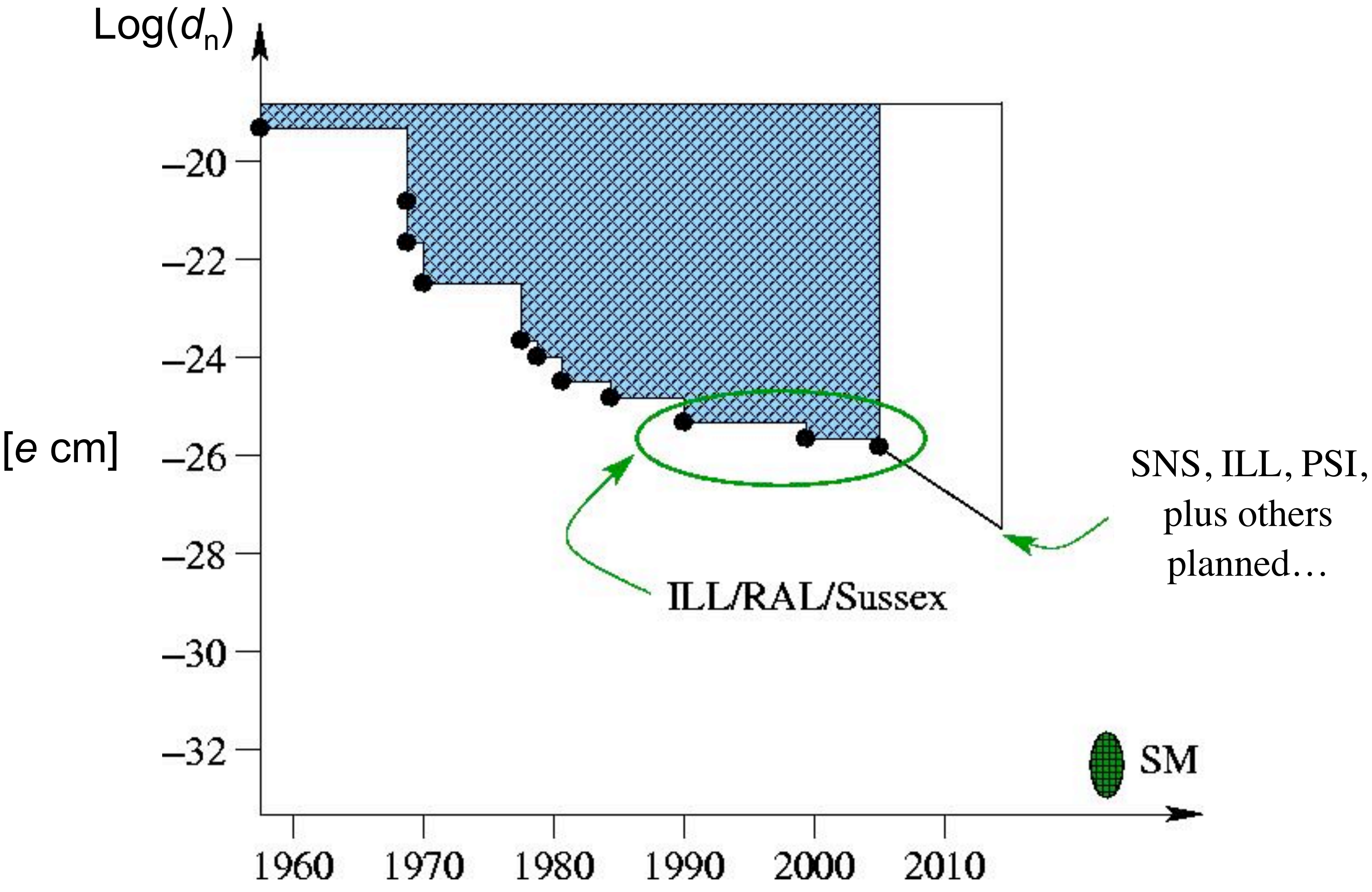
Small SM background (via CKM phase)



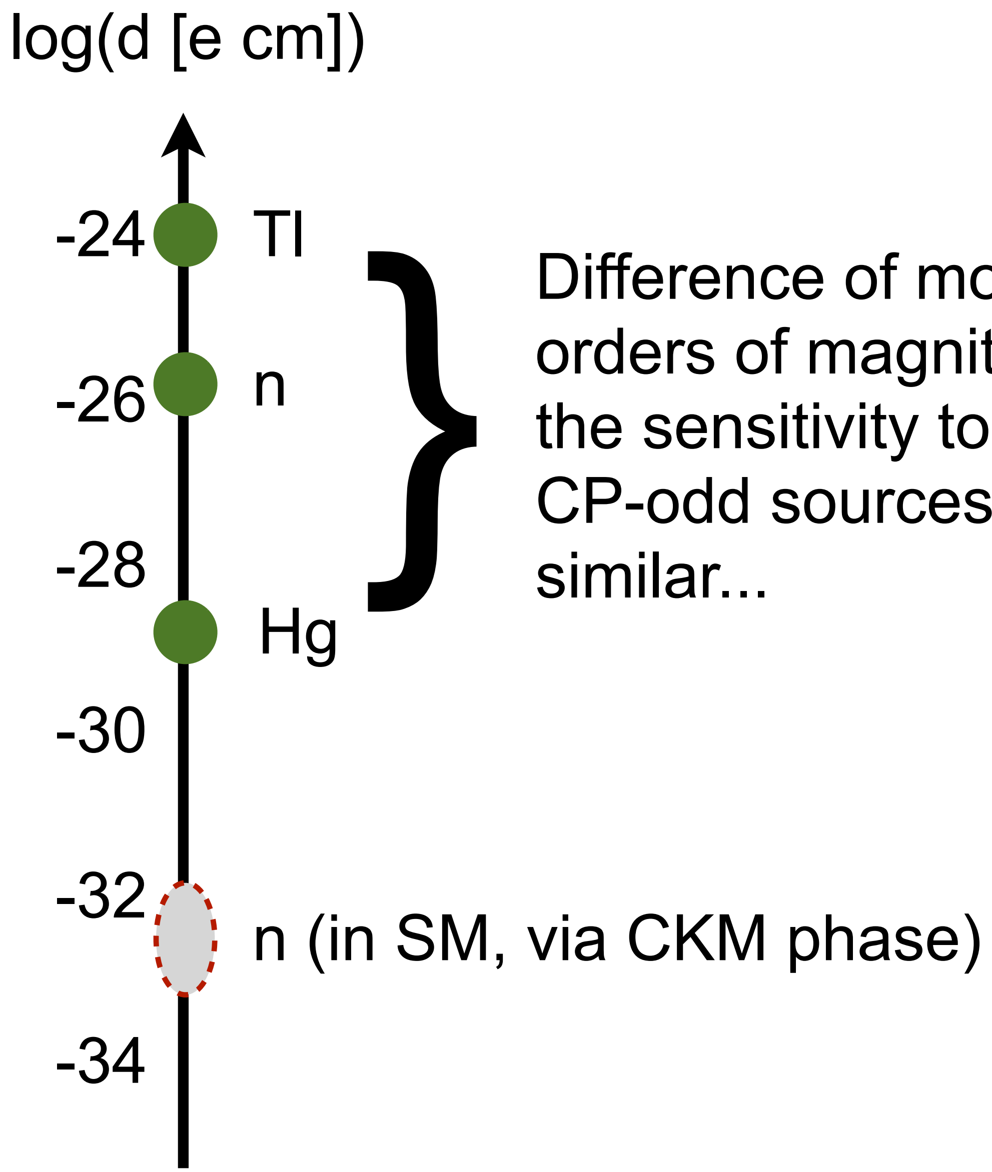
$$d_n \sim 10^{-32} e\, cm$$

[Khriplovich & Zhitnitsky ‘86]

Progress in the neutron EDM bound



Schematic view of the bounds



Difference of more than 4 orders of magnitude, but the sensitivity to underlying CP-odd sources is very similar...

Classification of CP-odd operators at 1GeV

Effective field theory is used to provide a model-independent parametrization of (flavor-diagonal) CP-violating operators at 1GeV

$$\mathcal{L} = \sum_i \frac{c_i}{M^{d-4}} O_d^{(i)}$$

Dimension 4: $\bar{\theta}\alpha_s G\tilde{G}$

$$\bar{\theta} = \theta_0 + ArgDet(M_q)$$

Dimension "6": $\sum_{q=u,d,s} d_q \bar{q} F\sigma\gamma_5 q + \sum_{q=u,d,s} \tilde{d}_q \bar{q} G\sigma\gamma_5 q + d_e \bar{e} F\sigma\gamma_5 e + w g_s^3 G G\tilde{G}$

Dimension "8": $\sum_{q=u,d,s} C_{qq}\bar{q}q\bar{q}i\gamma_5 q + C_{qe}\bar{q}q\bar{e}i\gamma_5 e + \cdots$

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

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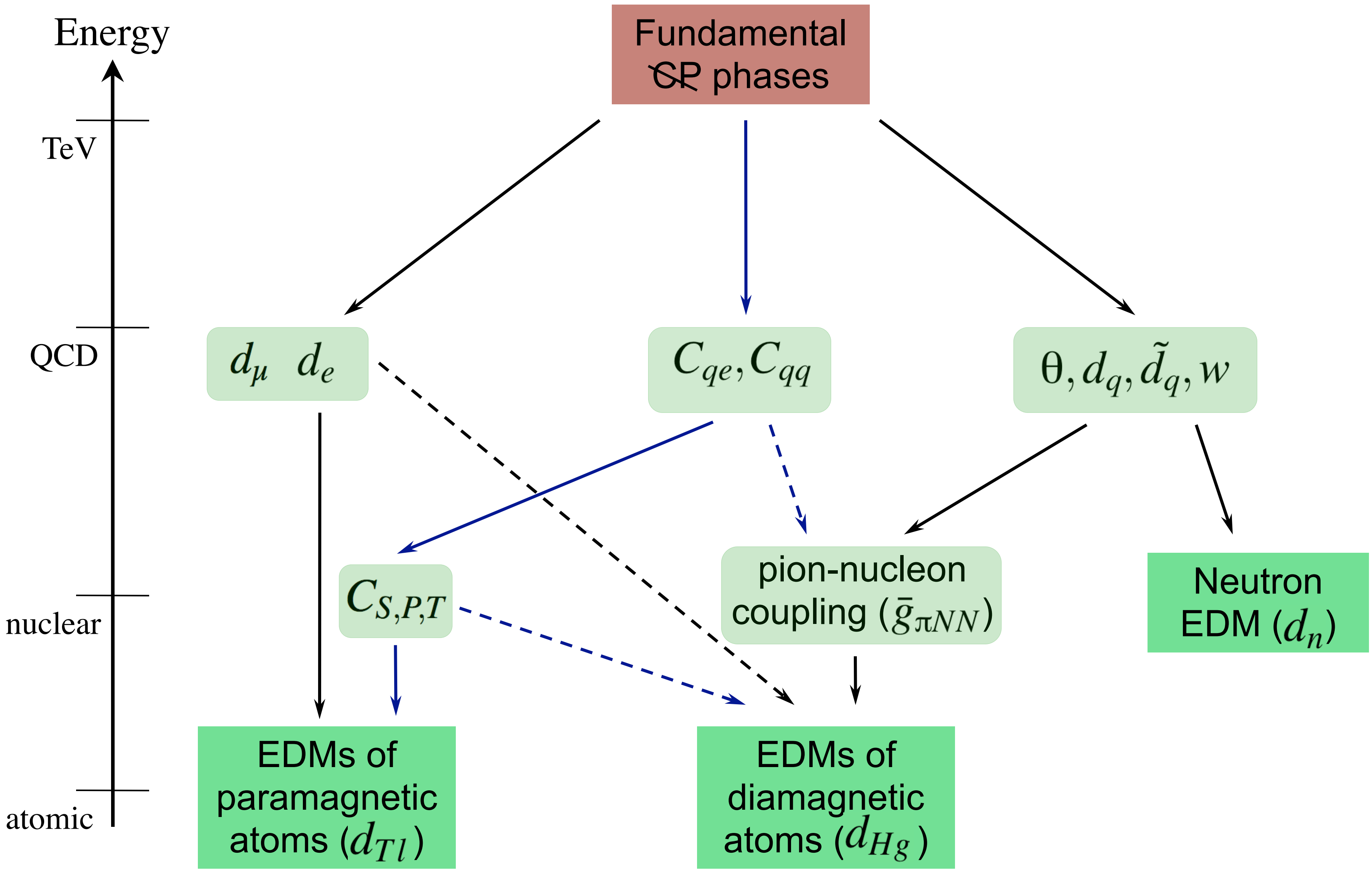
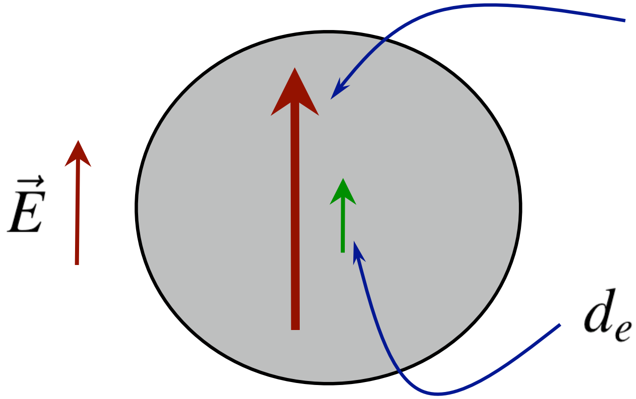
$$C_S \bar{N} N \bar{e} i\gamma_5 e$$

Origin of the EDMs



Atomic Schiff screening factors

Paramagnetic EDMs (relativistic violation of Schiff screening)

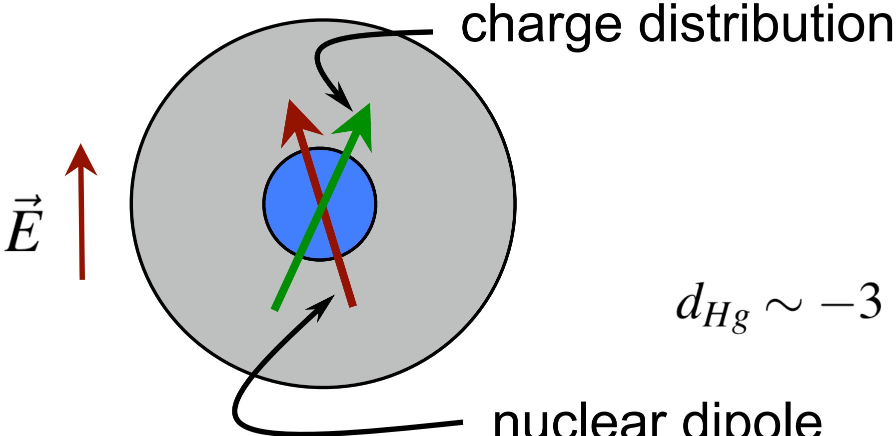


$$d_{Tl} \sim -10\alpha^2 Z^3 d_e$$

$$10\,\alpha^2 Z^3 \approx 585$$

[Liu & Kelly '92]

Diamagnetic EDMs (finite size violation of Schiff screening)



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

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

$$d_{Hg} \sim -3 \times 10^{-17} S\ fm^{-3} + O(d_e, C_{qq})$$ [Dzuba et al '02]

Schiff moment [Schiff '63]

Computations

1. Tl EDM (paramagnetic) (atomic)

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

$\alpha^2 Z^3$

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

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

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

[Pospelov & AR '99,'00]

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

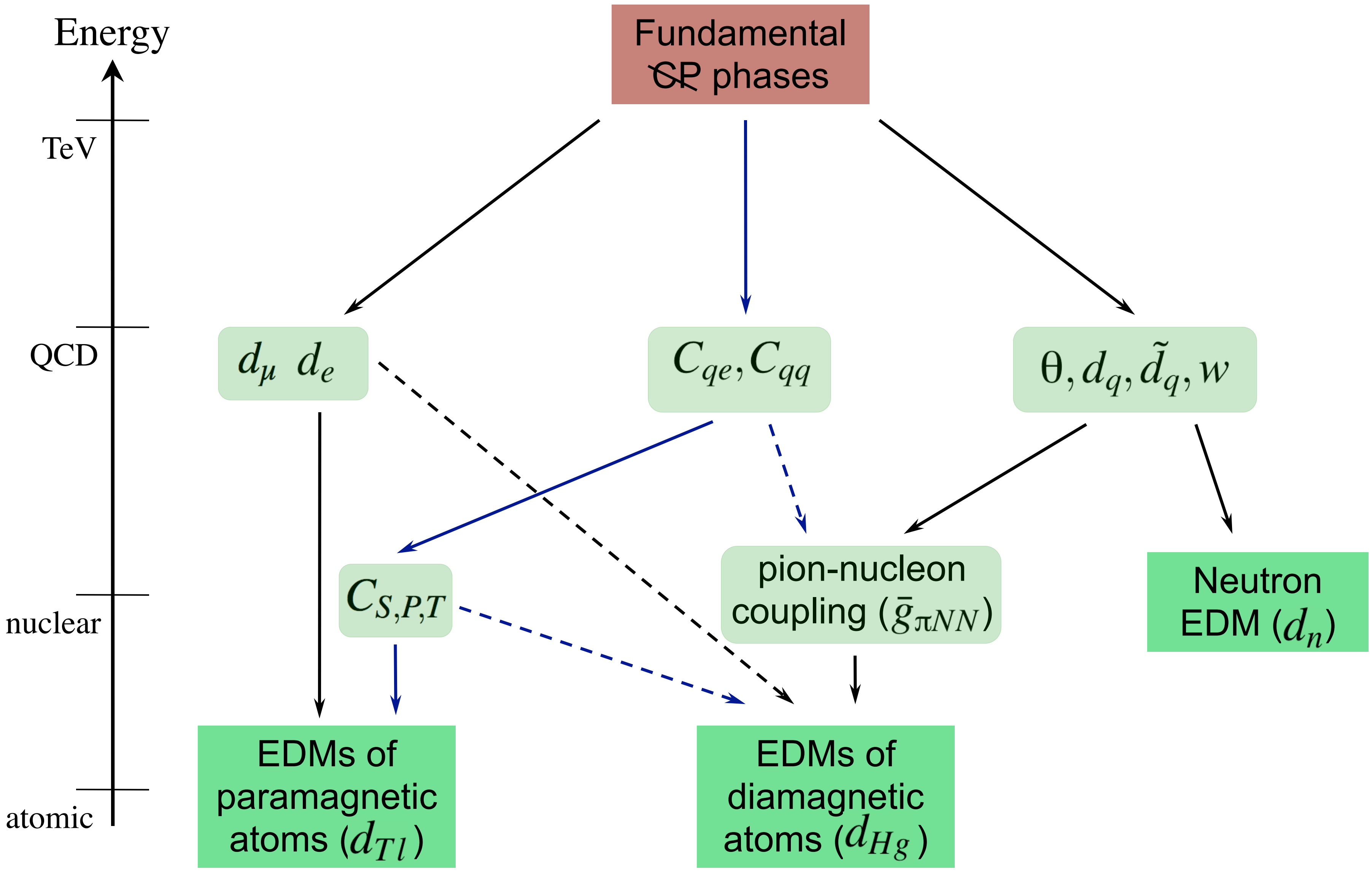
$$d_{Hg} \sim 10^{-3} d_{nuc} \sim -3 \times 10^{-17} S\, fm^{-3} + O(d_e, C_{qq})$$

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

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

[Pospelov '01]

Current status



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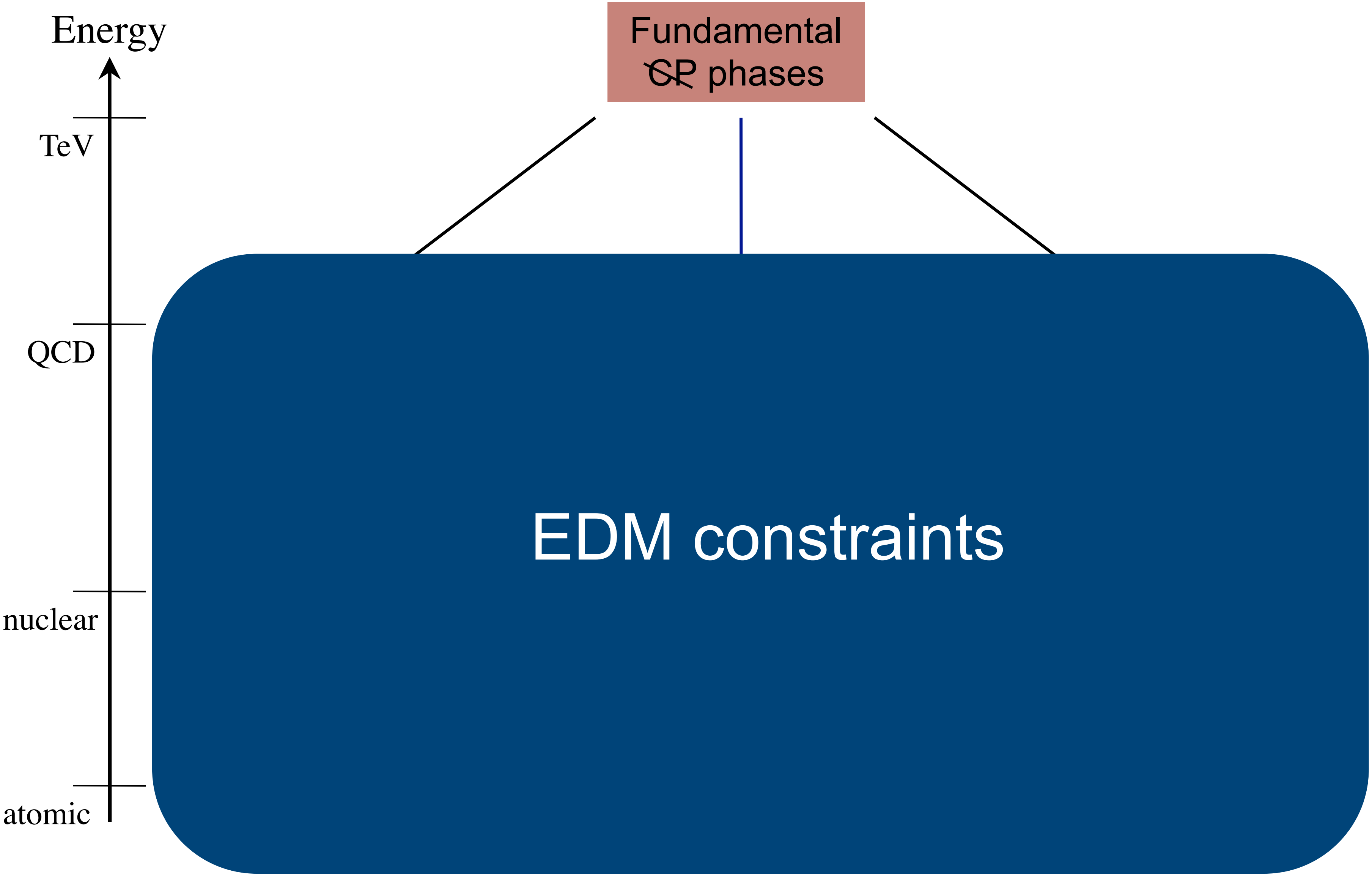
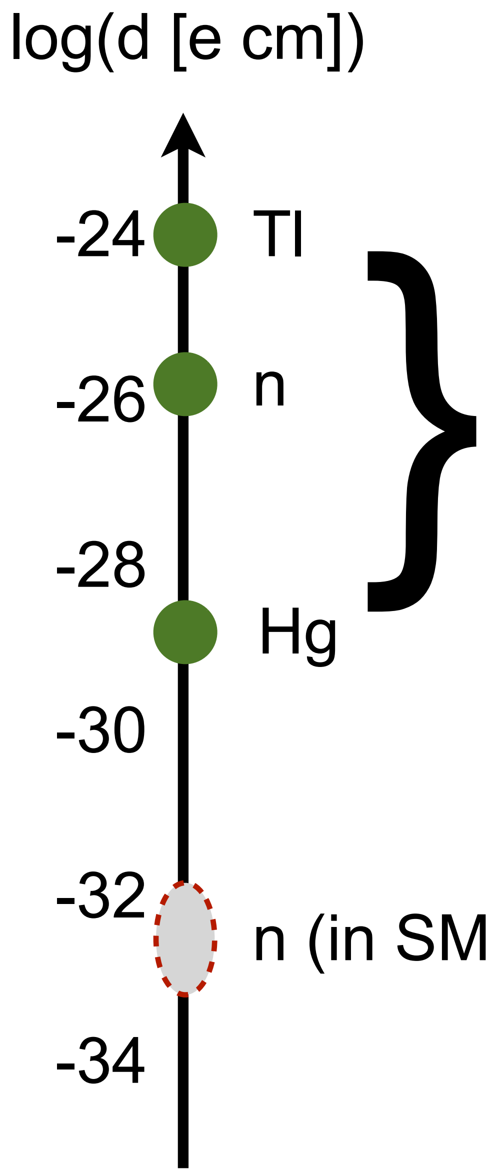


Resulting Bounds on fermion EDMs & CEDMs

Tl EDM (±20%)	$\left\| d_e + e(26MeV)^2 \left(3\frac{C_{ed}}{m_d} + 11\frac{C_{es}}{m_s} + 5\frac{C_{eb}}{m_b}\right) \right\| < 1.6 \times 10^{-27}\, e\ cm$
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 (±100%)	$e\|\tilde{d}_d - \tilde{d}_u + O(d_e, \tilde{d}_s, C_{qq}, C_{qe})\| < 3 \times 10^{-27} e\ cm$

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

Summary of the bounds



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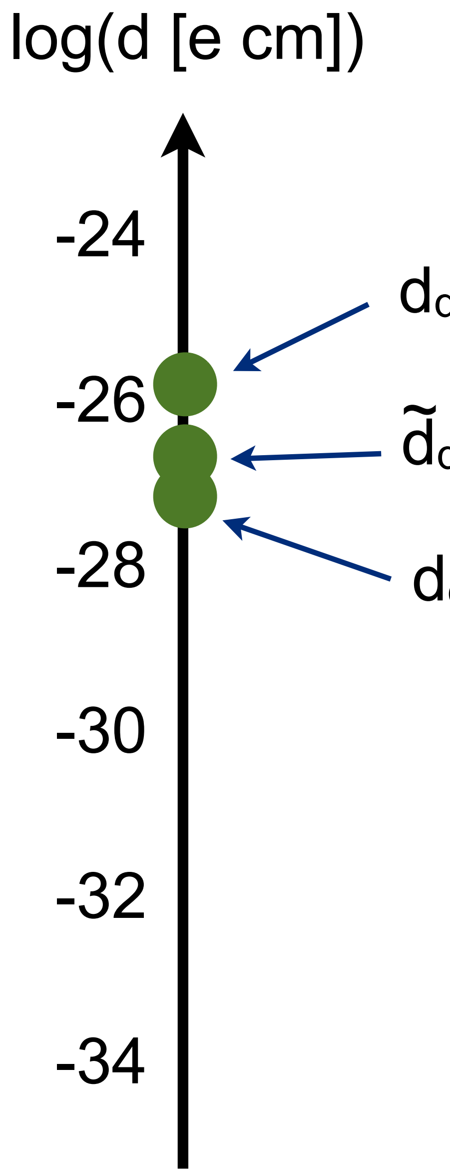


Given $d_f \propto m_f$ the sensitivity of Tl and the neutron is very similar, with the new limit from Hg somewhat stronger

Constraints on TeV-scale models

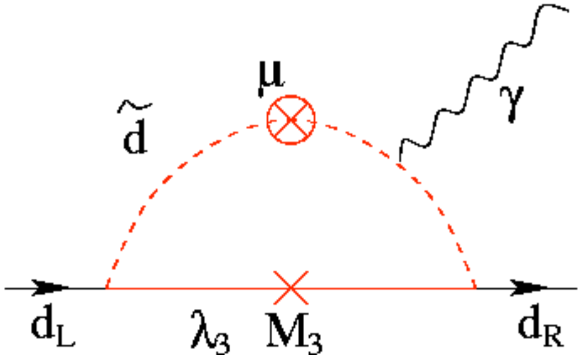
- E.G. MSSM: In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

Complex ⇒ CP-odd phase

$$\Delta\mathcal{L} \sim -\mu\, \bar{\tilde{H}}_1 \tilde{H}_2 + B\mu\, H_1 H_2 + h.c. - \frac{1}{2}\left(M_3\, \bar{\lambda}_3\lambda_3 + M_2\, \bar{\lambda}_2\lambda_2 + M_1\, \bar{\lambda}_1\lambda_1\right) + h.c. - A^d_{ij}\, H_1 \tilde{q}_{Li} \tilde{q}_{Rj} + h.c + \cdots$$

With a universality assumption, 2 physical CP-odd phases $\{\theta_\mu, \theta_A\}$

- EG:1-loop EDM contribution:

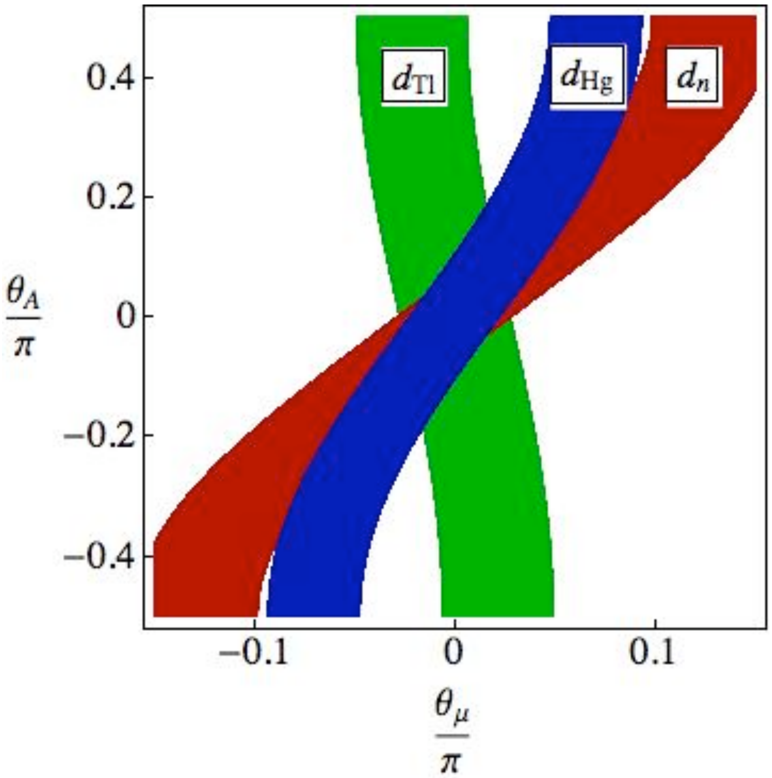


[Ellis, Ferrara & Nanopoulos '82]

$$\frac{d_d}{m_d} \sim \frac{1}{16\pi^2}\frac{\mu m_{\tilde{g}}}{M^4}\sin\theta_\mu$$

M ~ sfermion mass

SUSY CP Problem



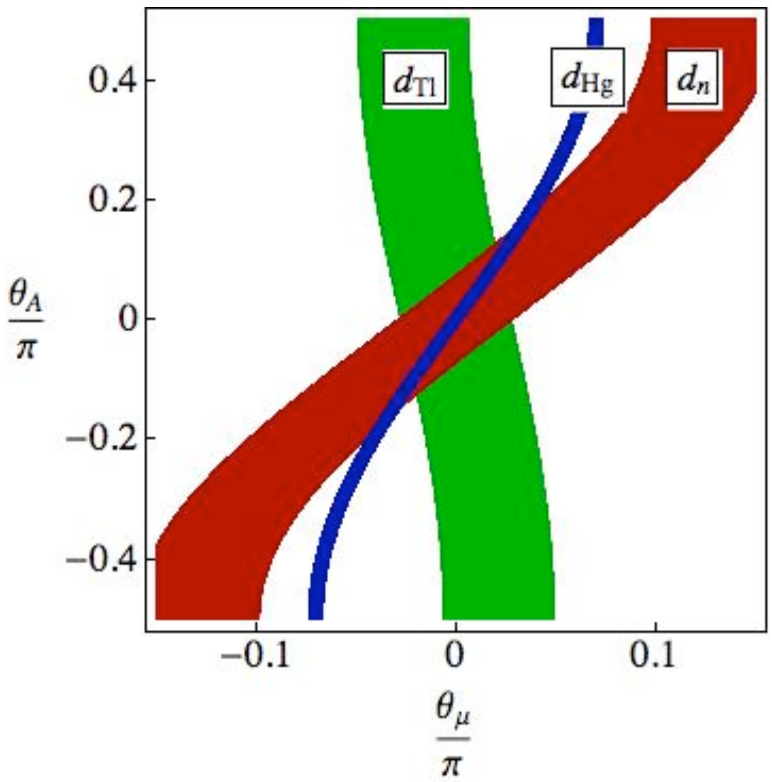
$$M_{susy} = 1\,TeV$$

Generic Implications ⇒ Soft CP-odd phases *O(10^{-2} - 10^{-3})*

[Olive, Pospelov, AR, Santoso '05]

[Also: Barger et al '01, Abel et al '01, Pilaftsis '02, Argyrou et al '08, Ellis et al '08]

SUSY CP Problem



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Generic 2-loop Sensitivity to O(1) phases

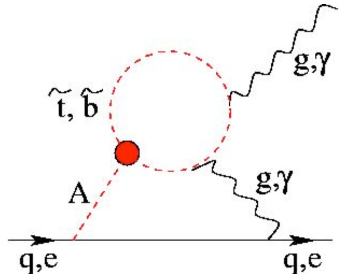
(MSSM)
parameter space
for EW-scale new
physics

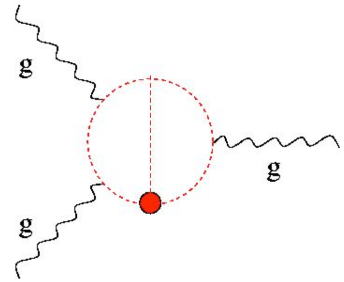
$$phases < O(10^{-3}) - O(1)$$

Generic 2-loop Sensitivity to O(1) phases

Decoupling 1st/2nd generation

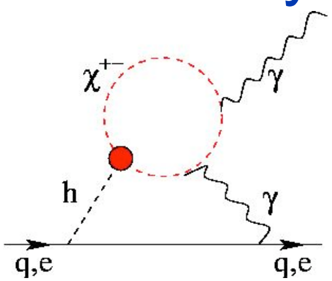
[Chang, Keung & Pilaftsis '98]





[Weinberg '89; Dai et al. 90]

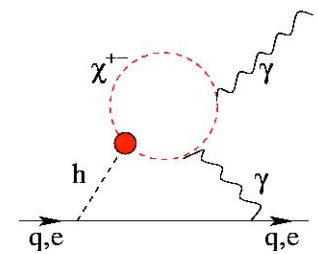
SUSY EW baryogenesis



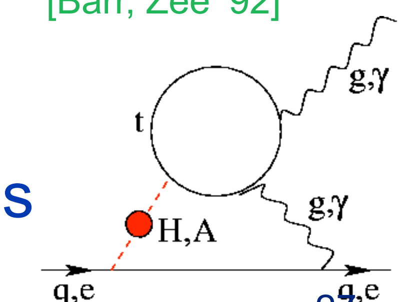
(MSSM) parameter space for EW-scale new physics

$$phases < O(10^{-3}) - O(1)$$

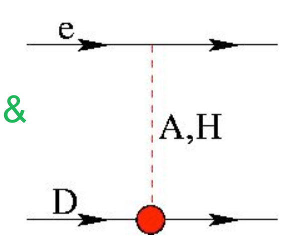
heavy sfermions (split SUSY)



[Barr, Zee '92]



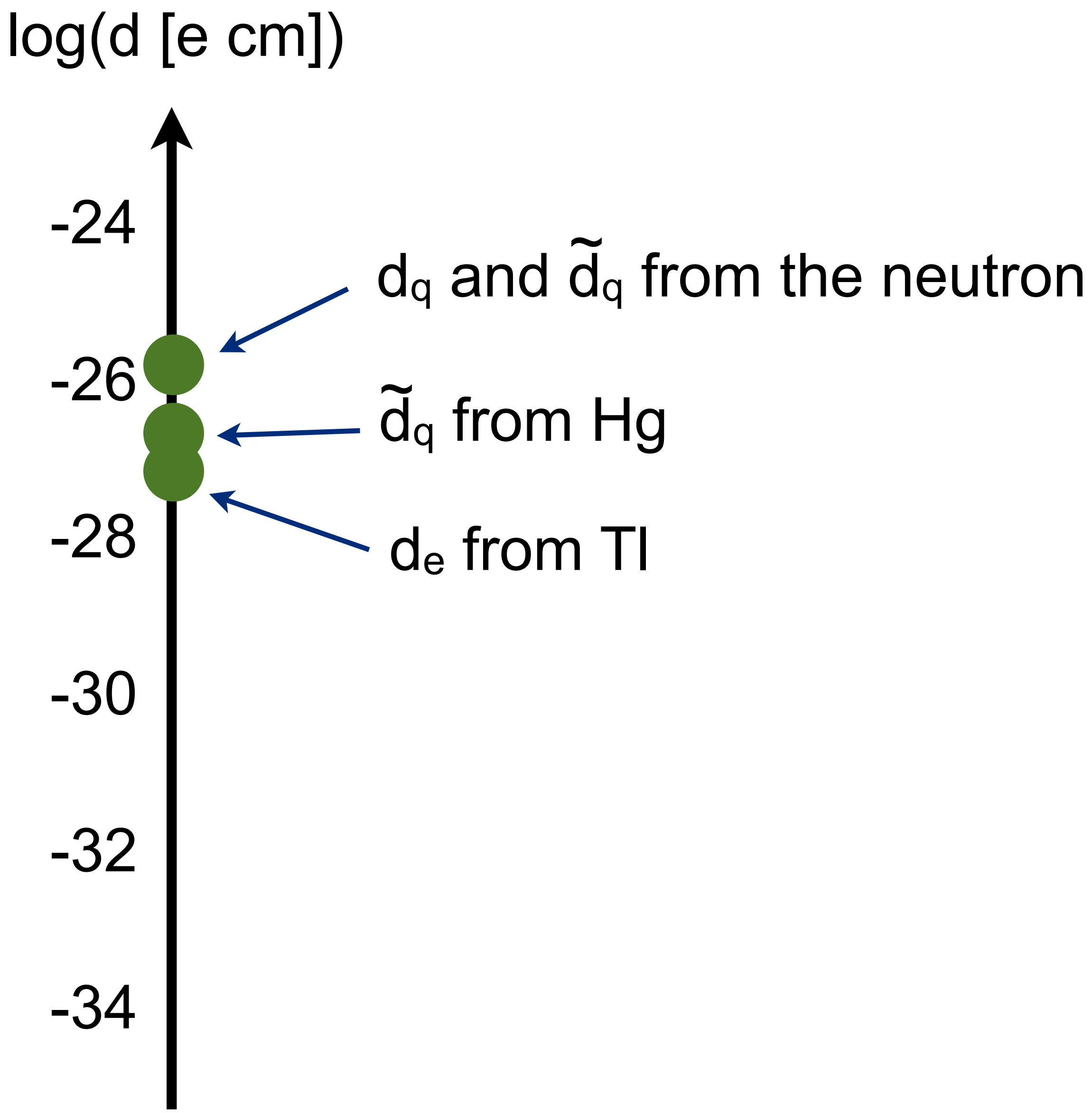
[Barr '92; Lebedev & Pospelov '02]



large tanβ

heavy 'inos (2 HDM)

Generic Sensitivity at 2-loops



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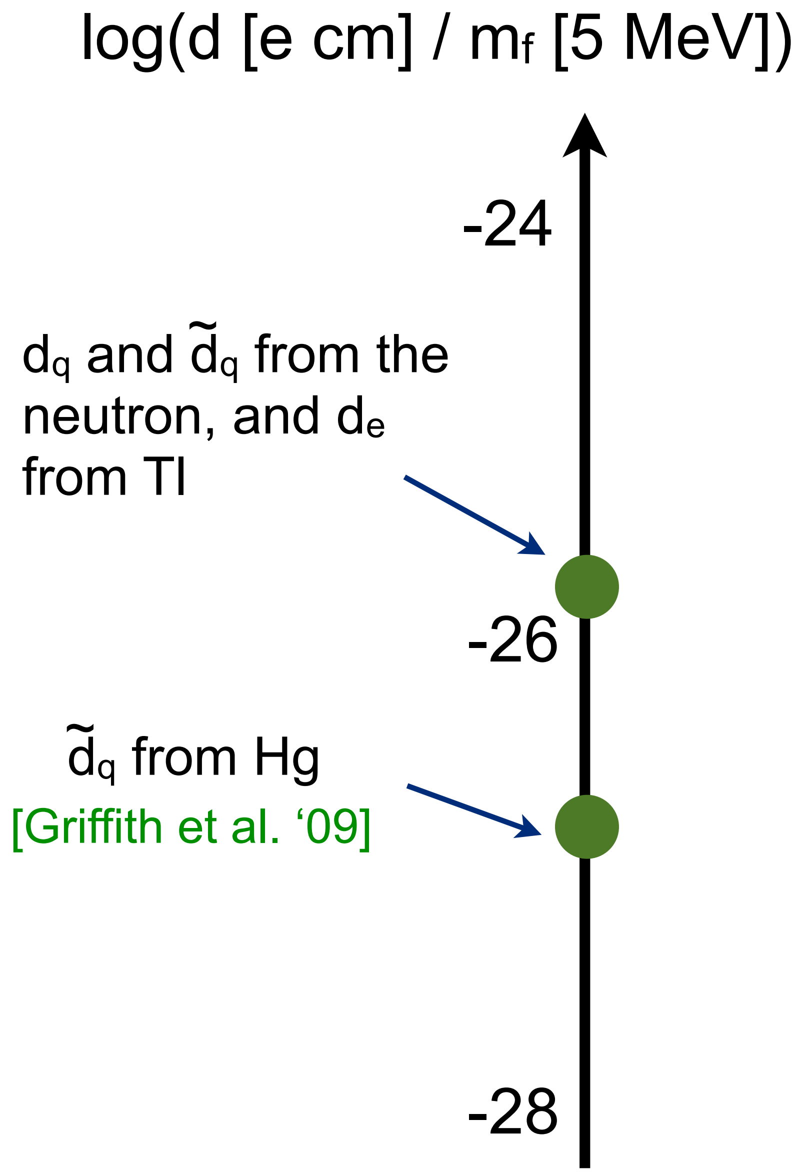

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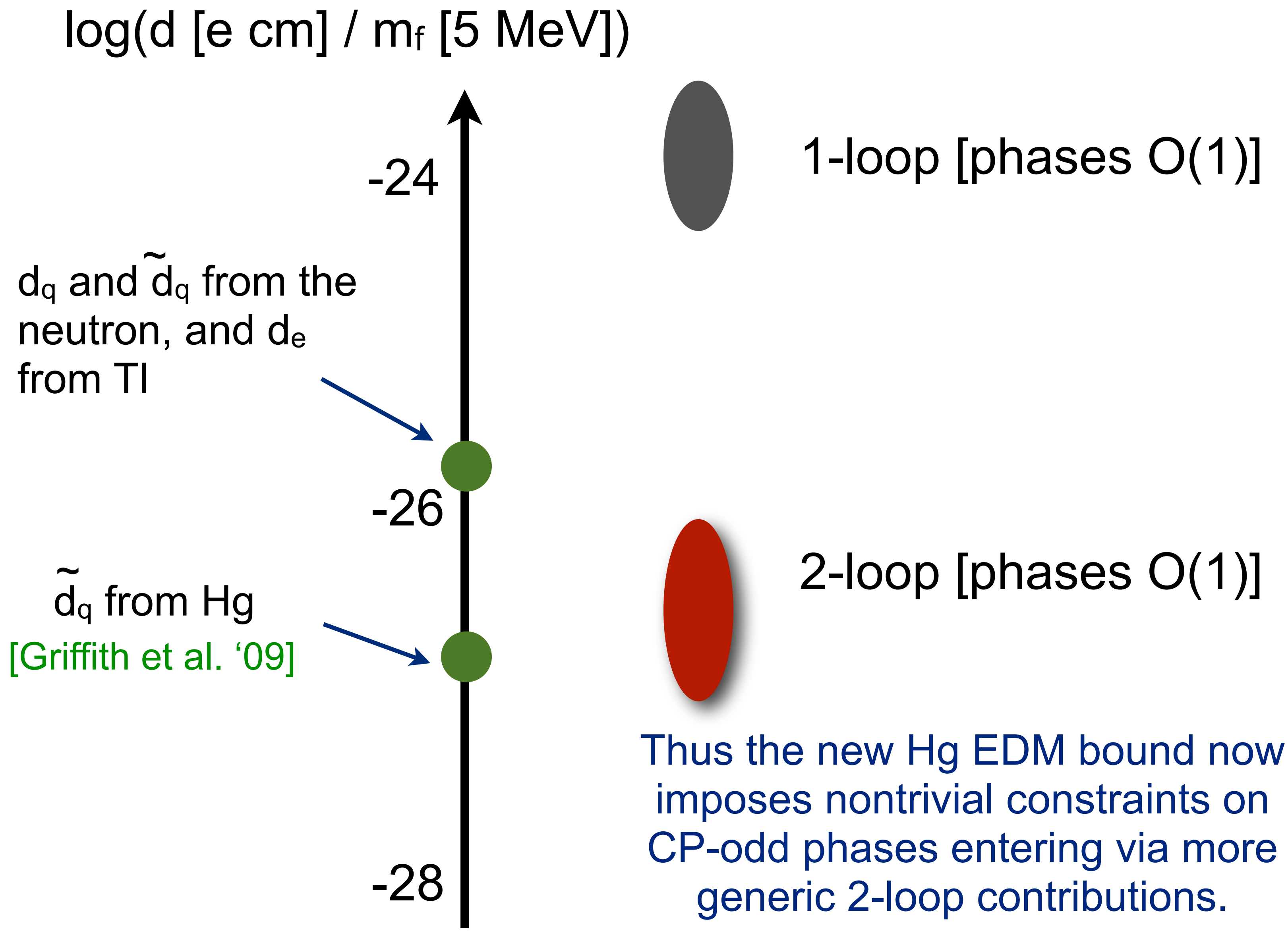


Thus the new Hg EDM bound now imposes nontrivial constraints on CP-odd phases entering via more generic 2-loop contributions.

Concluding Remarks

- Precision tests can play a crucial role in probing fundamental symmetries at scales well beyond the reach of colliders.
- EDMs currently provide stringent constraints on CP-phases in models of new physics, e.g. the soft-breaking sector of the MSSM.

Concluding Remarks

- Precision tests can play a crucial role in probing fundamental symmetries at scales well beyond the reach of colliders.
- EDMs currently provide stringent constraints on CP-phases in models of new physics, e.g. the soft-breaking sector of the MSSM.
- The recent improvement in the Hg EDM bound now implies sensitivity to phases (in the 3rd generation) through 2-loop effects which are quite generic in TeV-scale new physics.

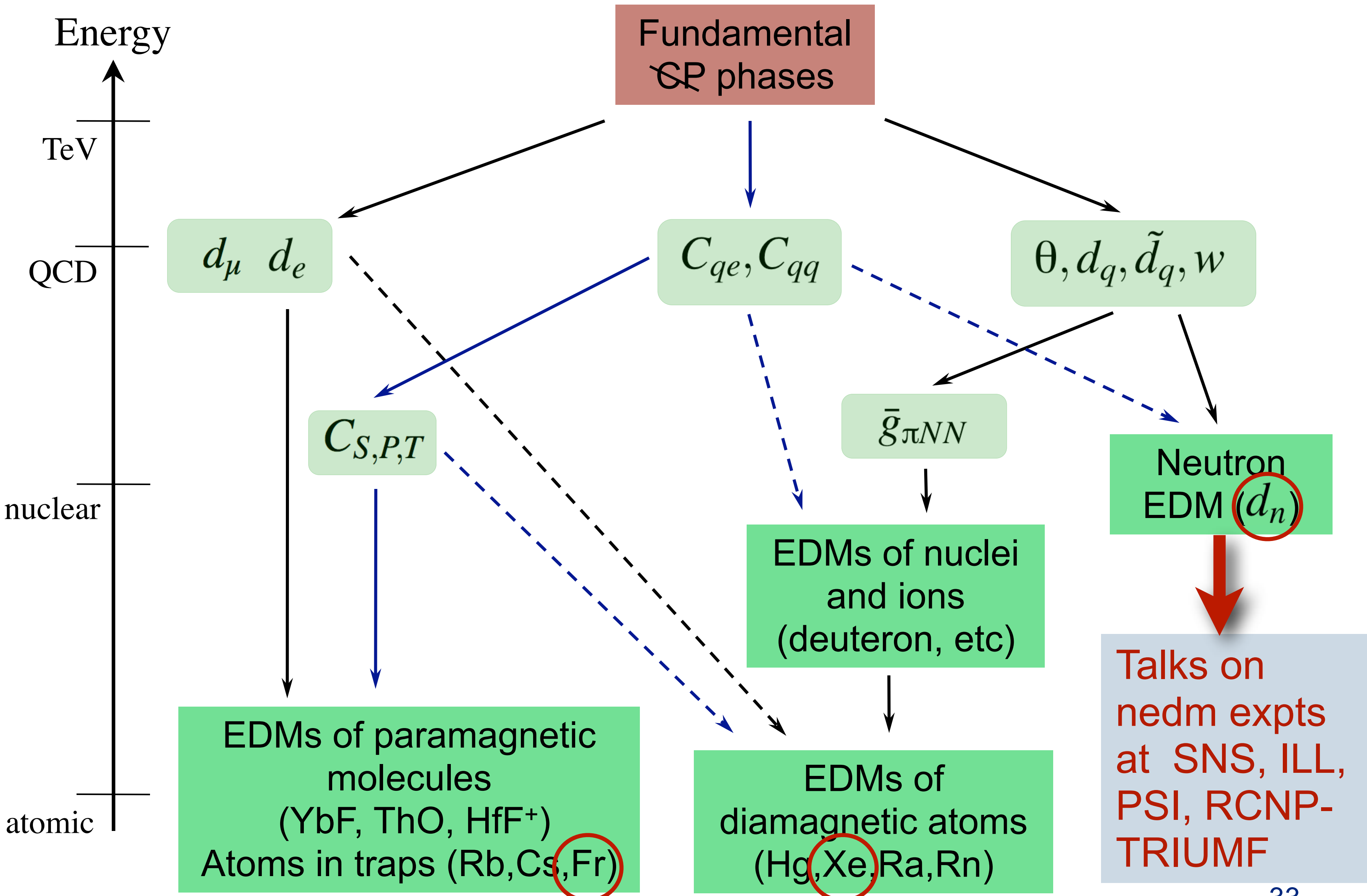
Full suite of next generation EDM experiments will probe these more generic “2-loop” contributions

⇓

Must all diagonal phases be small?

Is (large) TeV-scale CP violation intrinsically hidden by flavor?

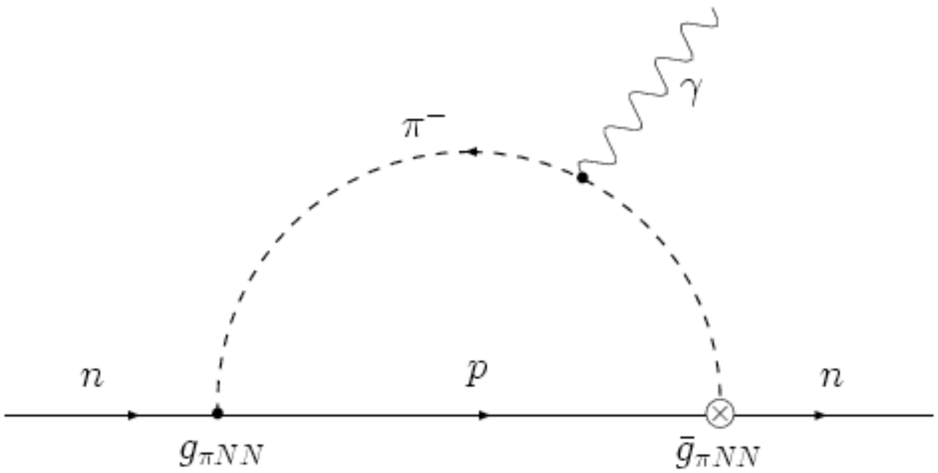
Future Developments…



Extra slides

Calculating the neutron EDM

- Chiral Logarithm: [Crewther, Di Vecchia, Veneziano & Witten '79]



$$d_n(\theta) = c_1 \ln \frac{\Lambda}{m_\pi} + c_2 \longrightarrow |\theta| < 10^{-9}$$

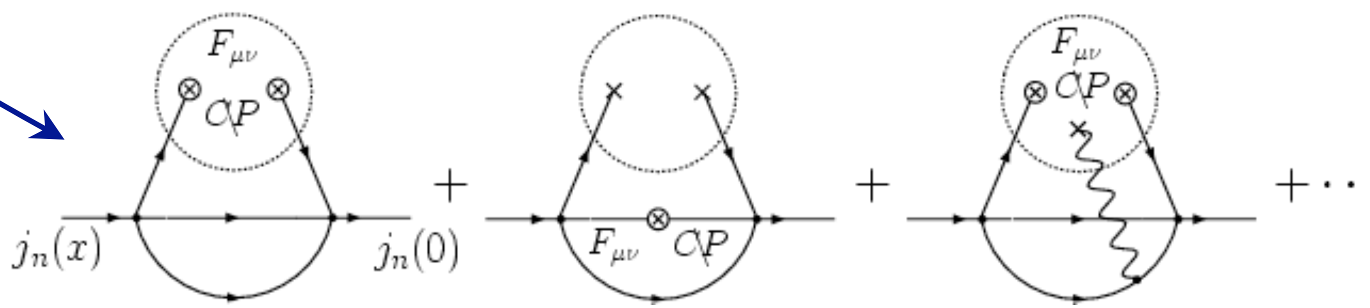
[also Baluni '79]

Calculating the neutron EDM

- QCD Sum Rules: [Pospelov & AR '99-'00]
  - — Neutron current: $j_n \sim d^T C\gamma_5 u d$
  - — Correlator: $\int d^4x e^{ip\cdot x}\langle \bar{j}_n(x), j_n(0)\rangle_{\not{C}P,F} = \Pi_0(p) + \Pi_1^{\mu\nu}(p)F_{\mu\nu} + \cdots$

$$\Pi_1(p,\theta,d_q,\tilde{d}_q)\cdot F \sim \frac{d_n\lambda^2 m_n}{(p^2-m_n^2)^2}\{F\sigma\gamma_5,\not{p}\} + \cdots$$

$d_n\vec{E}\cdot\vec{S}$



Calculating the neutron EDM

- QCD Sum Rules: Results
  - Important condensates: $\begin{cases} \langle \bar{q}\sigma_{\mu\nu}q\rangle_F = \chi e_q F_{\mu\nu}\langle \bar{q}q\rangle \\ \langle \bar{q}G\sigma q\rangle = -m_0^2\langle \bar{q}q\rangle \end{cases}$

$$d_n = (0.4 \pm 0.2)\frac{|\langle \bar{q}q\rangle|}{(225\ MeV)^3}\left[4d_d - d_u + \underbrace{\frac{1}{2}\chi m_0^2(4e_d\tilde{d}_d - e_u\tilde{d}_u)}_{2.7e(\tilde{d}_d + 0.5\tilde{d}_u)} + \cdots\right] + O(d_s, w, C_{qq})$$

Sensitive only to ratios of light quark masses

[Pospelov & AR ‘99,’00]

NB: PQ axion used to remove $\bar{\theta}$

$$\theta_{ind} = \frac{1}{2}m_0^2 \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q}$$

Comments on the SR NEDM calculation

✓

- Chiral properties
- Mixing with CP-conjugate currents
- Generic treatment of all CP-odd sources (…)

✗

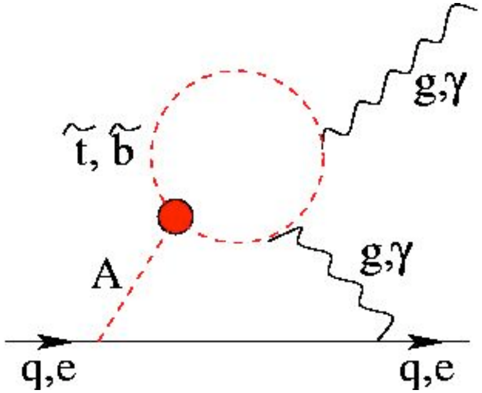
- Dependence on sea-quark EDMs
- Improvements in precision (?)

$$\langle \bar{q}\sigma_{\mu\nu}q\rangle_F = \chi e_q F_{\mu\nu}\langle \bar{q}q\rangle$$
$$\langle \bar{q}G\sigma q\rangle = -m_0^2\langle \bar{q}q\rangle$$

Lattice ?

Generic SUSY CP constraints at 2-loop

[Chang, Keung & Pilaftsis '98]



$$\frac{\tilde{d}_q}{m_q} \sim \frac{\alpha_s Y_t^2 \tan\beta}{128\pi^3 M_{SUSY}^2} \ln\left[\frac{M_{SUSY}^2}{m_A^2}\right] \sin(\theta_A + \theta_\mu)$$

The new Hg EDM bound [Griffith et al. '09] now imposes nontrivial constraints on 2-loop contributions, e.g. for stops with M ~ 100-200 GeV

$$|\theta_{3rd\ gen}| < 0.1$$

SUSY threshold sensitivity

If soft terms (approximately) conserve CP & flavour, what is the sensitivity to irrelevant operators (new thresholds) ?

[Pospelov, AR, Santoso '05, '06]

Dim 5:

$$\mathcal{W} = \mathcal{W}_{MSSM} + \frac{y_h}{\Lambda}(H_u H_d)^2 + \frac{Y^{qe}}{\Lambda} QULE + \frac{Y^{qq}}{\Lambda} QUQD + seesaw + \cancel{baryon}$$

- Contributions to e.g. EDMs will scale as "dim=5"

$$d_f \sim \frac{v_{EW}}{m_{soft}\Lambda}$$

- Sensitivity depends on flavor structure of Y^{ff}

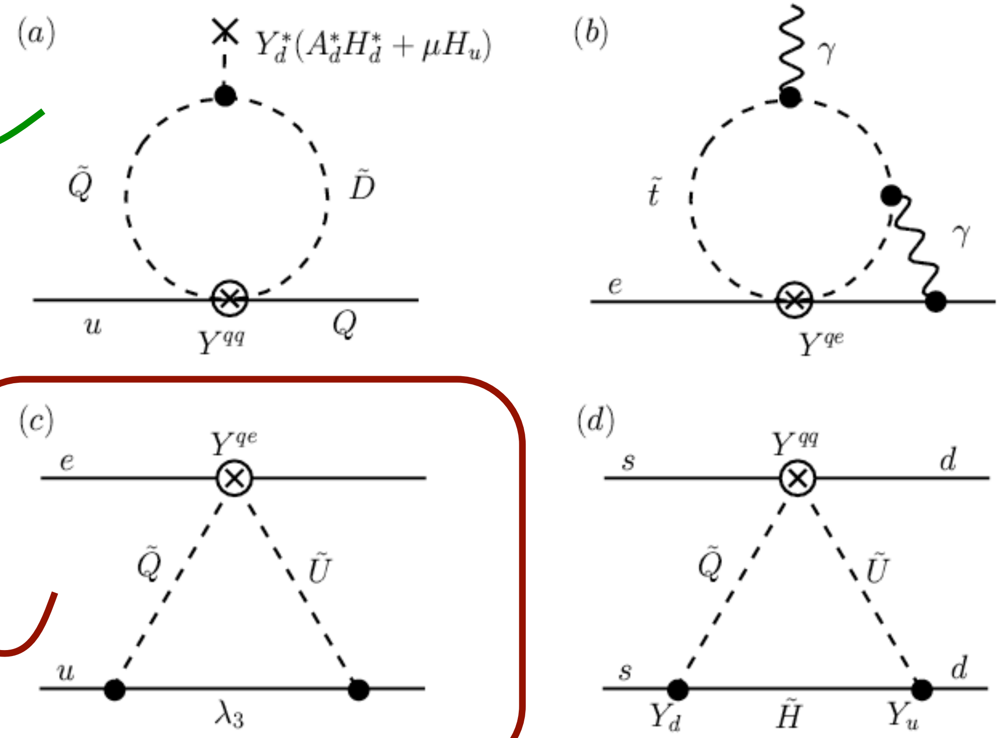
  — we will assume $Y^{ff'} \neq Y_f Y_{f'} \sim 1$

SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

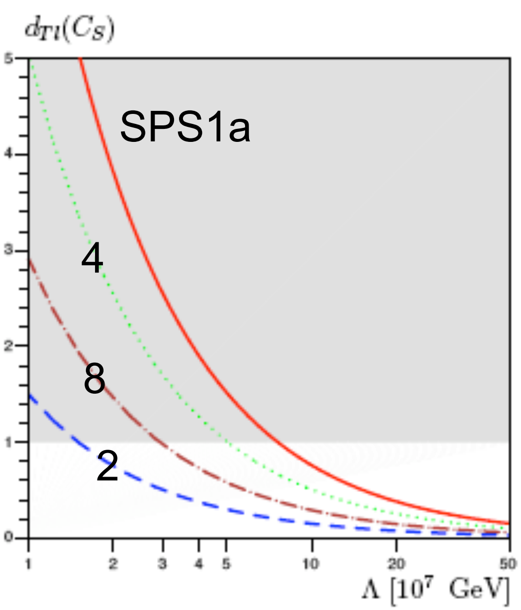
$$\Delta m_e \sim m_e \Rightarrow \Lambda > 10^6 GeV$$

$$d_{Tl}(C_S), d_{Hg}(C_S), \mu \rightarrow e$$
$$\Rightarrow \Lambda > 10^8 GeV$$



SUSY threshold sensitivity

operator	sensitivity to Λ (GeV)	source
Y^{qe}_{3311}	$\sim 10^7$	naturalness of m_e
$\mathrm{Im}(Y^{qq}_{3311})$	$\sim 10^{17}$	naturalness of $\bar{\theta}$, d_n
$\mathrm{Im}(Y^{qe}_{ii11})$	$10^7 - 10^9$	Tl, Hg EDMs
Y^{qe}_{1112}, Y^{qe}_{1121}	$10^7 - 10^8$	$\mu \to e$ conversion
$\mathrm{Im}(Y^{qq})$	$10^7 - 10^8$	Hg EDM
$\mathrm{Im}(y_h)$	$10^3 - 10^8$	d_e from Tl EDM



[Pospelov, AR, Santoso '05, '06]

Models: e.g. MSSM + extended Higgs sector

$$\{N, H'_u, H'_d\}$$