Electric dipole moments as probes of new physics

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Based on work with:

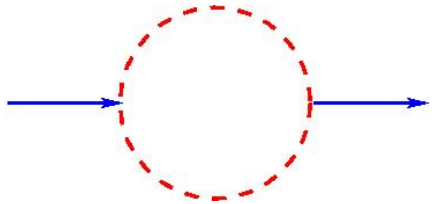
M. Pospelov,

S. Huber & Y. Santoso

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

Precision Tests as Probes for New Physics

Precision searches for new physics (at energy scale Λ):



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

Especially powerful for tests of "*fundamental symmetries*":
e.g. T (or CP), Lepton no., Flavour, Lorentz, etc.

e.g: lepton number violation

The Standard Model (above the EW scale) allows a *single* dimension five operator:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{Y}{\Lambda}\bar{L}_L^c \tilde{H}\tilde{H}^T L_L + [dim \geq 6]$$

$$M_\nu = \frac{v^2}{\Lambda}Y$$

data $\Rightarrow \Lambda \approx 10^{11} - 10^{15}$ GeV

CP-violation and EDMs

- Thus far (?), $\not{CP}$ in K and B-meson mixing and decays is consistent with a single source

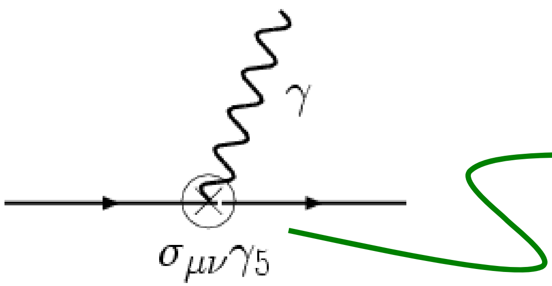
  - SM CKM phase $\delta_{KM} \sim O(1)$

- $\not{CP}$ apparently hidden behind the flavour structure

$$\Rightarrow \quad J_{CP} \sim 10^{-5} \sin(\delta_{KM})$$

Q: Are CP and flavour intrinsically linked ?

$\Rightarrow$ Look for $\not{CP}$ in flavour diagonal channels



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

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

CP-violation and EDMs

Motivation:

- Baryogenesis requires extra ~~CP~~
- SM also has an additional ~~CP~~ source $\bar{\theta}$
- Most "UV completions" of SM (e.g. MSSM) provide additional sources of ~~CP~~

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

NB: EDMs are observables accessible at the amplitude level, and so decouple more weakly than e.g. LFV observables

Plan

- Current status of EDM bounds
- A review of (hadronic) EDM calculations
- EDMs vs supersymmetry
  - — Review of the (current) SUSY CP problem
  - — Constraints on new CP-odd thresholds
- EDMs vs baryogenesis
- Concluding remarks

Experimental Status

Neutron EDM	$\vert d_n\vert < 3\times 10^{-26} e\ cm$	[Baker et al. '06]
Thallium EDM (paramagnetic)	$\vert d_{Tl}\vert < 9\times 10^{-25} e\ cm$	[Regan et al. '02]
Mercury EDM (diamagnetic)	$\vert d_{Hg}\vert < 2\times 10^{-28} e\ cm$	[Romalis et al. '00]

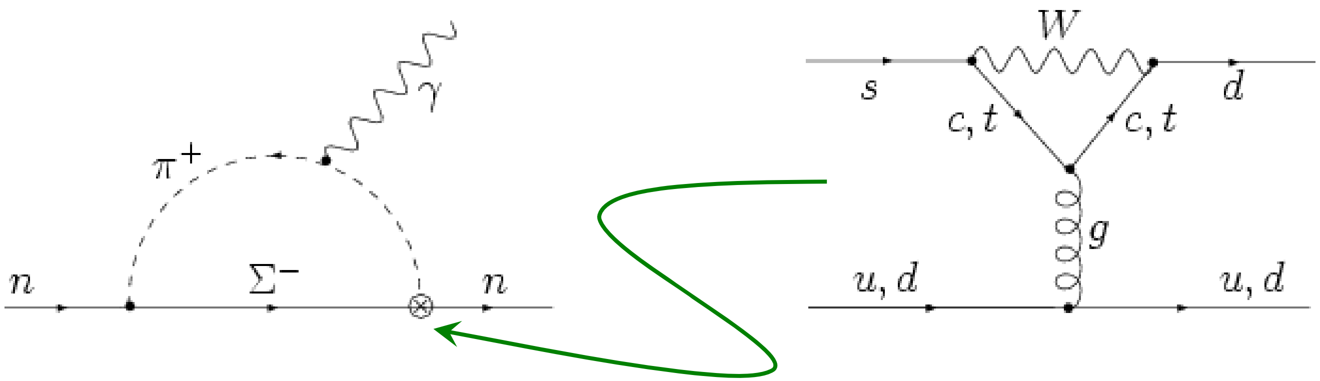
(Optimistically) anticipate $\mathcal{O}(10^{-2} - 10^{-3})$ gain in sensitivity for each channel

$\rightarrow$ see the rest of this meeting!

Experimental Status

<u>Small</u> SM background (via CKM phase)

EG: for the neutron EDM



$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[Khriplovich & Zhitnitsky '86]

Classification of CP-odd operators at 1GeV

Effective field theory is used to provide a model-independent parametrization of 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": $\sum_{q=u,d,s} C_{qq} \bar{q} q \bar{q} i \gamma_5 q + C_{qe} \bar{q} q \bar{e} i \gamma_5 e + \cdots$

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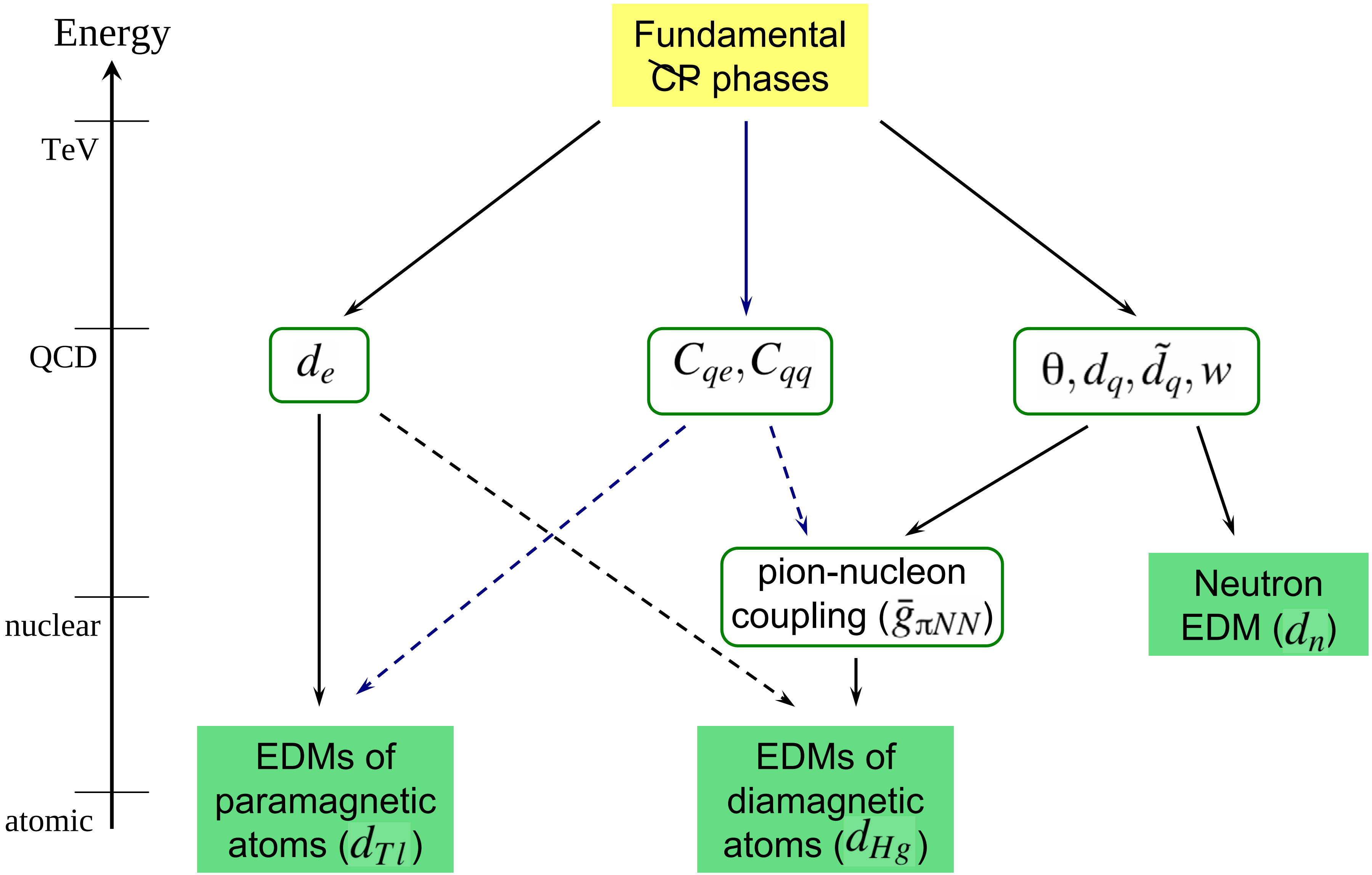
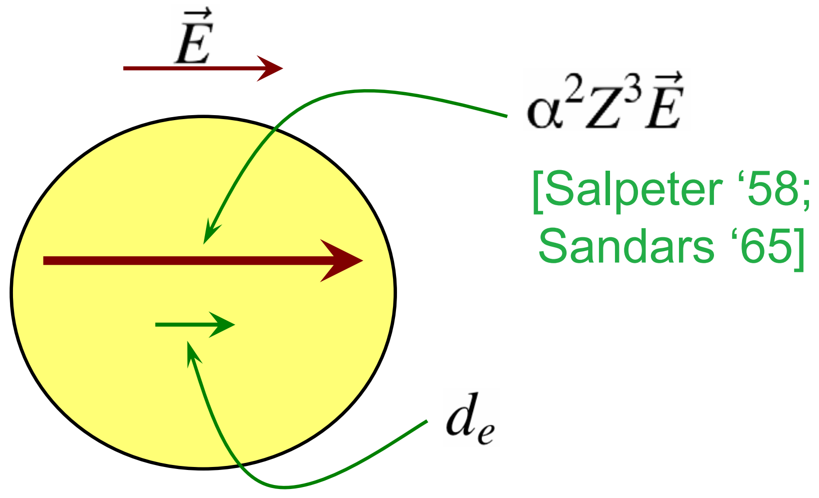
$$\to C_S \bar{N} N \bar{e} i\gamma_5 e$$

Origin of the EDMs



Calculating the EDMs - Tl

1. Tl EDM (paramagnetic)



$$d_{Tl} \sim -10\,\alpha^2 Z^3 d_e(1\ GeV) - e \sum_{q=d,s,b} C_{qe}(1\ GeV)\frac{2\ GeV^2}{m_q}$$

$10\alpha^2 Z^3 \approx 585$ [Liu & Kelly '92]

relativistic violation of Schiff thm

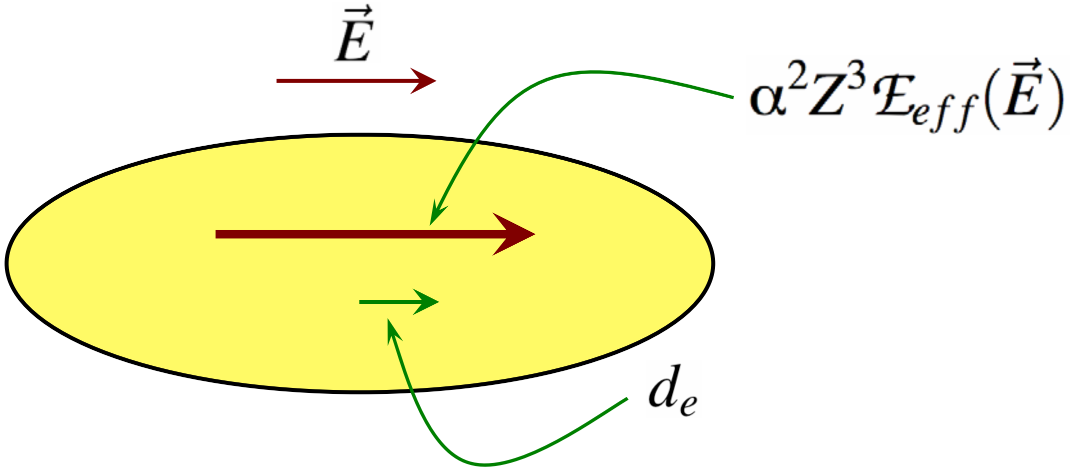
arises from $\bar{e}i\gamma_5 e\bar{N}N$

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

Future - e.g. paramagnetic molecules

YbF, PbO, …

[Hinds, DeMille, …]



$$\hbar \Delta \omega_L = \mathcal{E}_{eff} d_e + O(C_S)$$

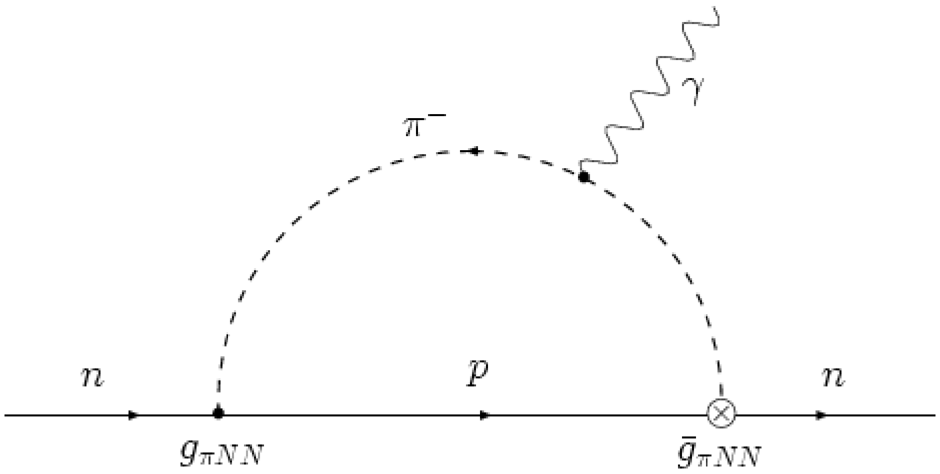
$O(10^5 E_{ext})$

[see talk by Kozlov]

Calculating the EDMs - n

2. 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 EDMs - n

2. neutron EDM

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

Calculating the EDMs - n

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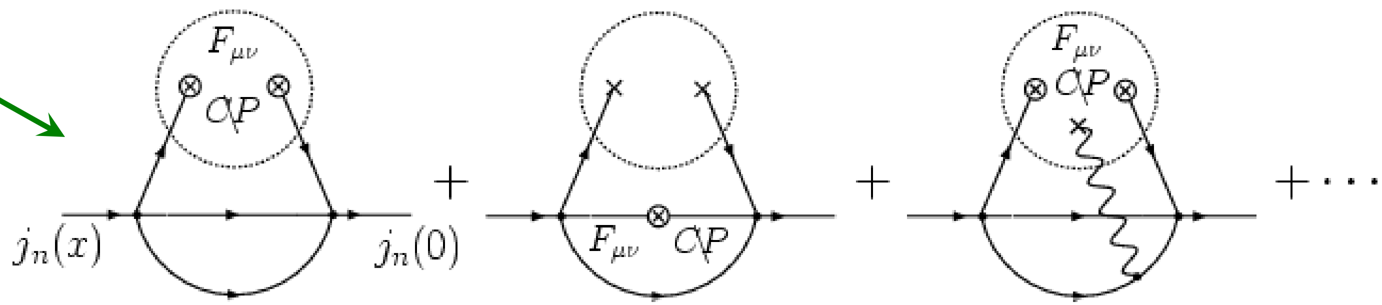
$$\Pi_1(p,\theta,d_q,\tilde{d}_q)\cdot F \sim \frac{d_n\lambda^2 m_n}{(p^2-m_n^2)^2}\{F\sigma\gamma_5,\not{p}\} + \cdots$$

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



Calculating the EDMs - n

2. neutron EDM

- QCD Sum Rules: Results
  - — Important condensates:

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

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

[Pospelov & AR '99,'00]

Sensitive only to ratios of light quark masses

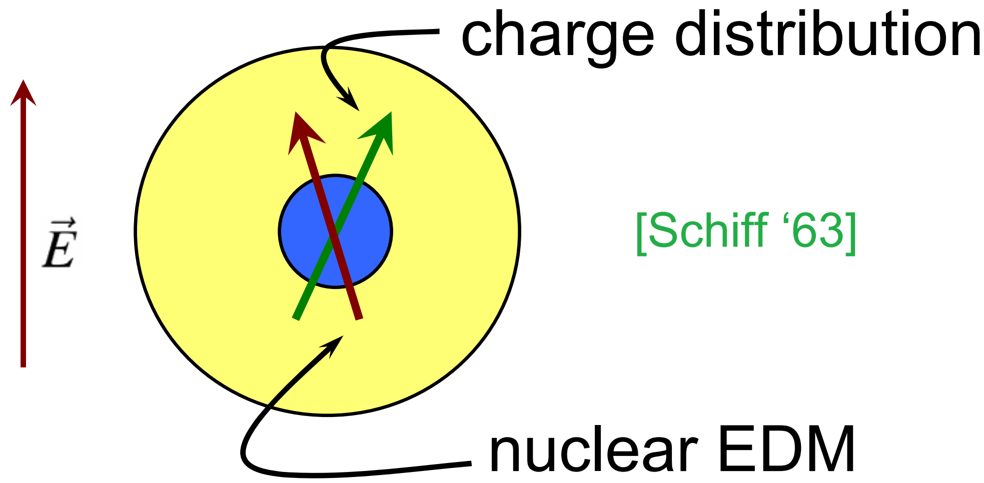
NB: PQ axion used to remove $\bar{\theta}$

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

Calculating the EDMs - Hg

3. Hg EDM (diamagnetic)

$$d_{Hg} \sim 10 Z^2 (R_N/R_A)^2 d_{nuc} \sim 10^{-3} d_{nuc}$$



[Schiff '63]

Calculating the EDMs - Hg

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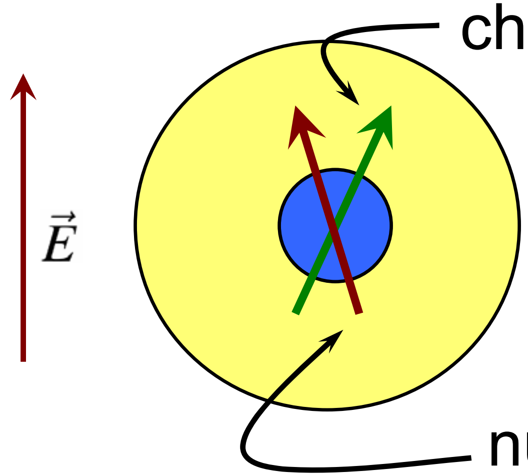


[Schiff '63]

- Misalignment of nuclear charge and dipole moment distribution

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

[Dzuba et al '02]

Schiff moment

$$S \sim -0.06 g_{\pi NN} \bar{g}^{(1)}_{\pi NN}\, e\, fm^3 + \cdots$$

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

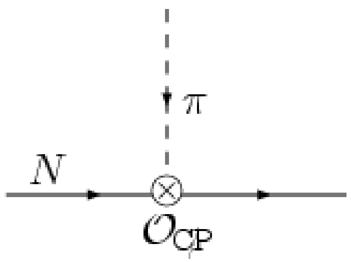
$\bar{g}^{(1)}_{\pi NN}(\tilde{d}_q)$

Calculating the EDMs - Hg

3. Hg EDM (diamagnetic)

- EDM (predominantly) due to CP-odd pion-nucleon coupling:

(a)



$$\bar{g}_{\pi NN}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2f_\pi} \left\langle N \left| \sum_{q=u,d} \bar{q} g_s G \sigma q \right| N \right\rangle + \cdots$$

Calculating the EDMs - Hg

3. <u>Hg EDM</u> (diamagnetic)

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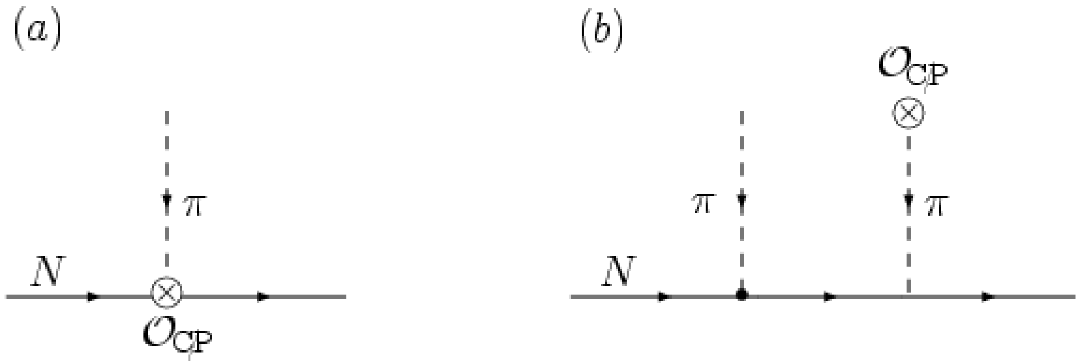

$$\bar{g}_{\pi NN}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2 f_\pi} \left\langle N \left| \sum_{q=u,d} \bar{q} g_s G \sigma q - m_0^2 \bar{q} q \right| N \right\rangle + \cdots$$

Calculating the EDMs - Hg

3. Hg EDM (diamagnetic)

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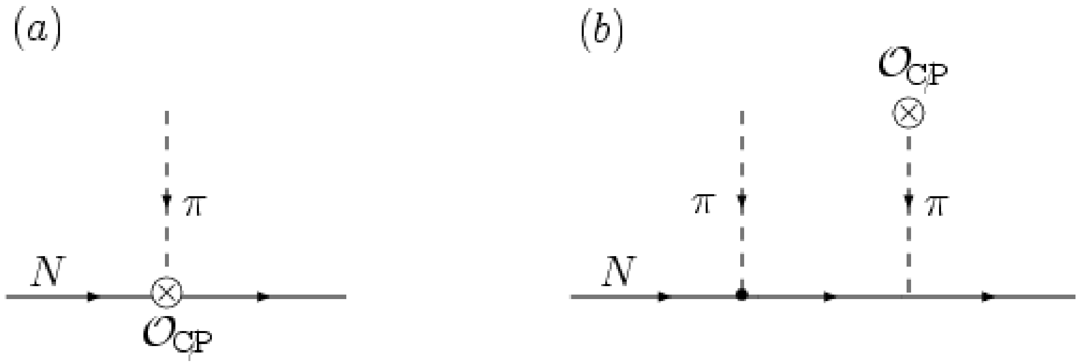

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Using QCD sum-rules: [Pospelov '01]

[or, using LETs: Falk et al '99; Hisano & Shimizu '04]

$$\bar{g}_{\pi NN}(\tilde{d}_q) = (1-6)\frac{|\langle \bar{q}q\rangle|}{(225MeV)^3}(\tilde{d}_u - \tilde{d}_d) + O(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w)$$

NB: large errors due to cancelations

Future - charged nuclei

Deuteron EDM   [SREDM Collab]

$$d_D \sim (d_n + d_p) + d_D^{\pi NN}$$

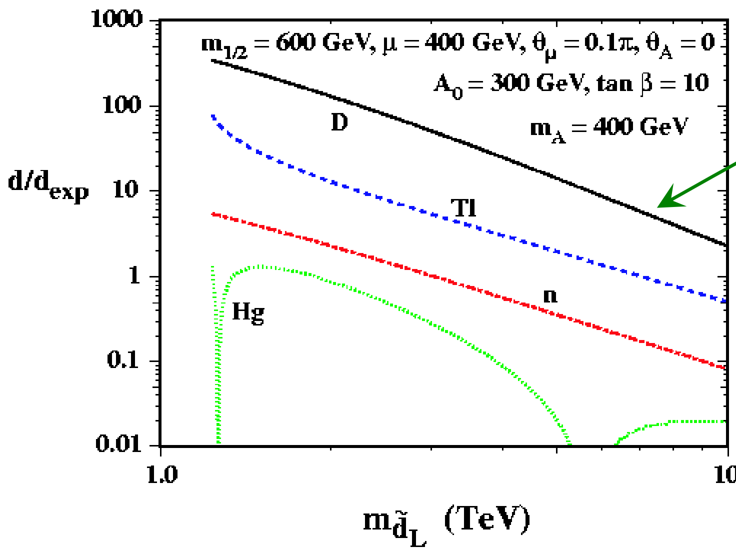
[Lebedev, Olive, Pospelov, AR '04]

$$d_D^{\pi NN} \sim -2 \times 10^{-14} \bar{g}_{\pi NN}^{(1)} e\, cm$$

[Khriplovich & Korkin '00]

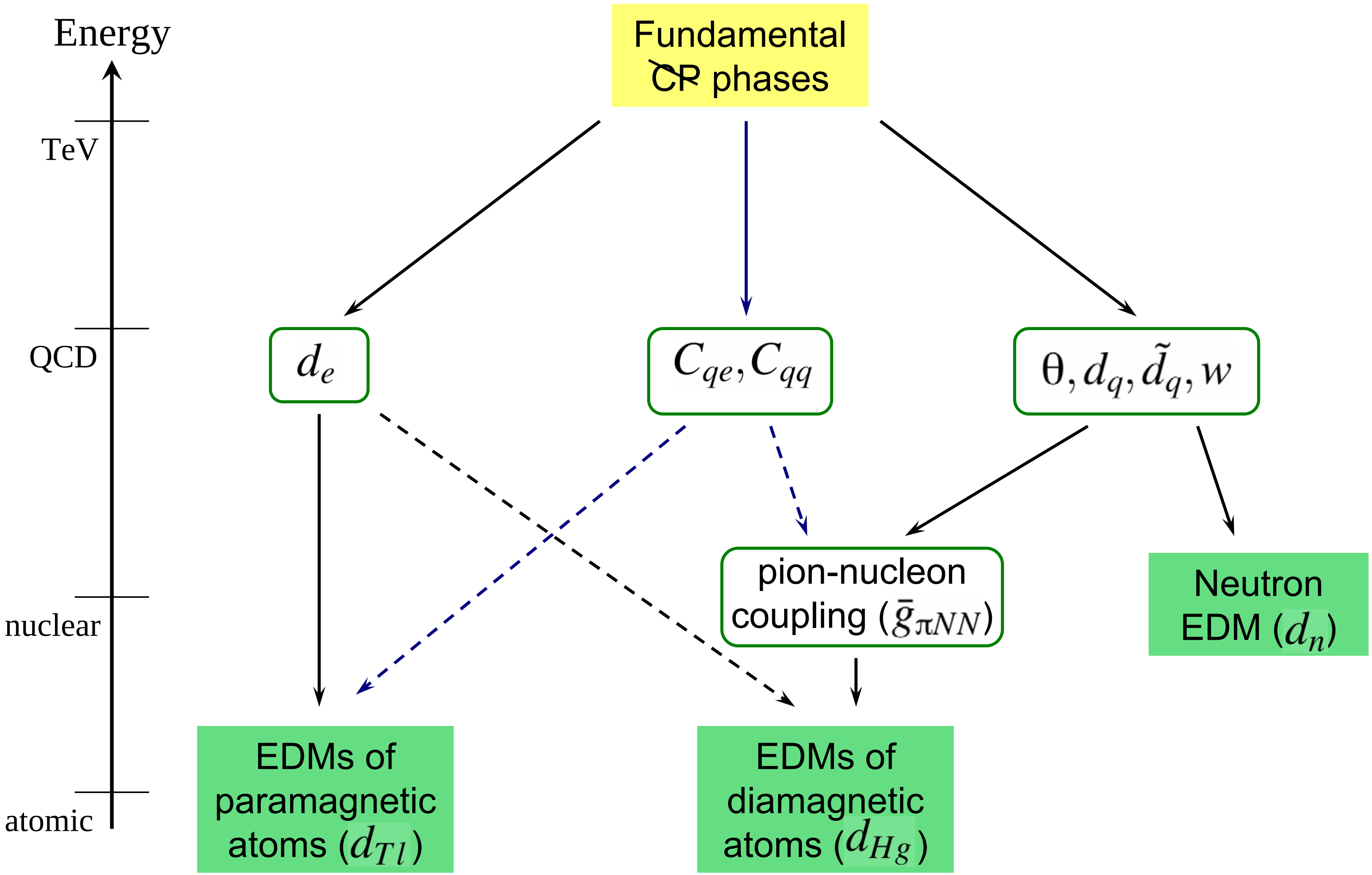
- Same (leading) dependence as Hg (but without Schiff suppression)

$$\theta_\mu = \frac{\pi}{10}$$



$$d_D \sim 10^{-27} e\, cm$$

Origin of the EDMs



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 (+200%)	$e\|\tilde{d}_d - \tilde{d}_u + O(d_e, \tilde{d}_s, C_{qq}, C_{qe})\| < 2 \times 10^{-26} e\ cm$

Sensitivity: $d_f \sim e\frac{m_f}{M_{CP}^2} \Rightarrow$ $M_{CP} \geq \mathcal{O}(10 - 50)\, TeV$

Constraints on TeV-Scale models

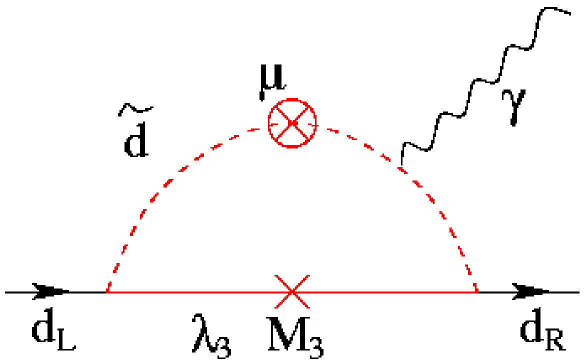
- E.G. MSSM: In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

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 new physical CP-odd phases $\{\theta_\mu, \theta_A\}$

- EG:1-loop EDM contribution:

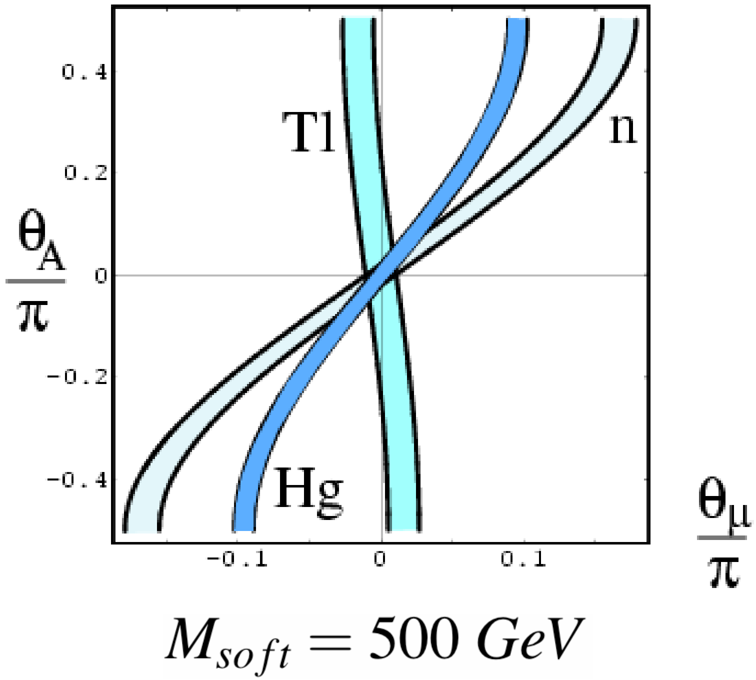


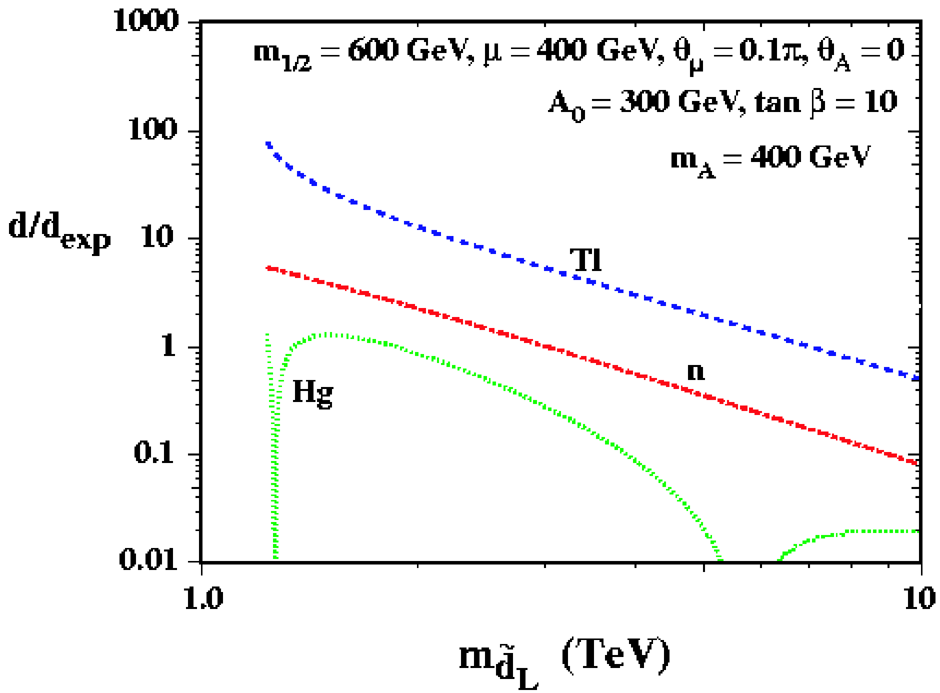
[Ellis, Ferrara & Nanopoulos '82]

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

M ~ sfermion mass

SUSY CP Problem





Generic Implications $\Rightarrow$ Soft CP-odd phases $O(10^{-2} - 10^{-3})$

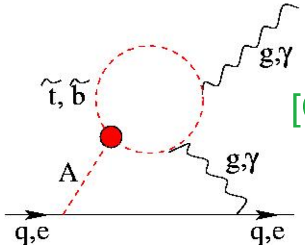
[Olive, Pospelov, AR, Santoso '05]

[Also: Barger et al. '01, Abel et al. '01, Pilaftsis '02]

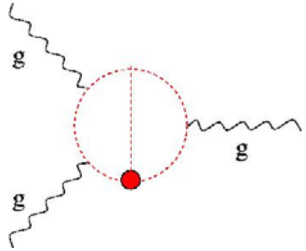
SUSY CP Constraints

MSSM parameter space: $phases < O(10^{-3} - 1)$

Decoupling 1st/2nd generation

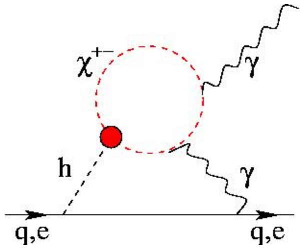


[Chang, Keung & Pilaftsis '98]



[Weinberg '89; Dai et al. 90]

Decoupling scalars (split SUSY, EW baryogenesis)

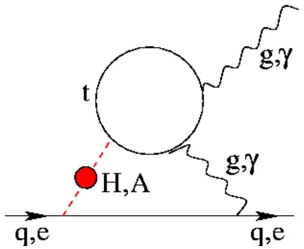


[Arkani-Hamed et al. '04]

Decoupling fermions

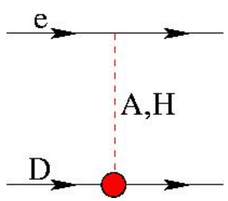
2 HDM

[Barr, Zee '92]



large tanβ

[Barr '92; Lebedev & Pospelov '02]



Naturalness and new CP-odd thresholds

Success of CKM CP-violation (with natural O(1) phase) in K and B-meson mixing, and e.g. constraints on soft-SUSY phases

Assumption: non-CKM CP-violation is <u>*irrelevant*</u> (to leading order) at the weak scale

$$\mathcal{L}_{new}^{CP-odd} = \sum \frac{O_n^{CP-odd}}{\Lambda^n}$$

Q:

- can it resolve the problems which motivate new CP-odd sources? (e.g. baryogenesis)
- what is the threshold sensitivity?

SUSY threshold sensitivity

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

[Pospelov, AR, Santoso '05]

<u>Dim 5:</u>

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

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

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

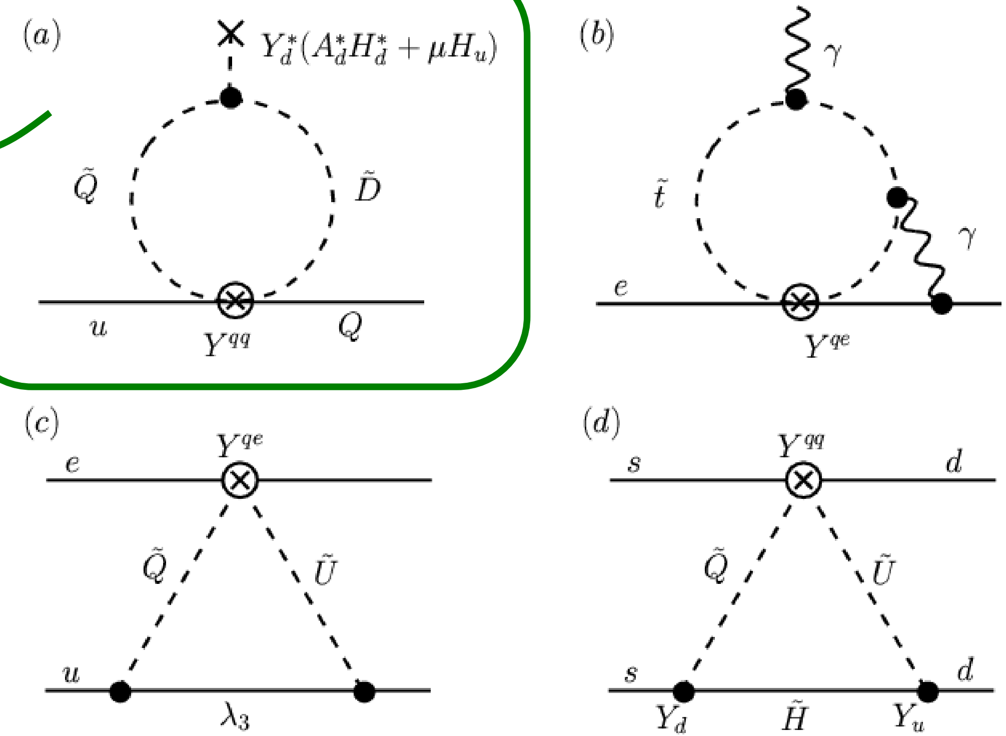
- Sensitivity depends on flavor structure of Y^{ff}

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

SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

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

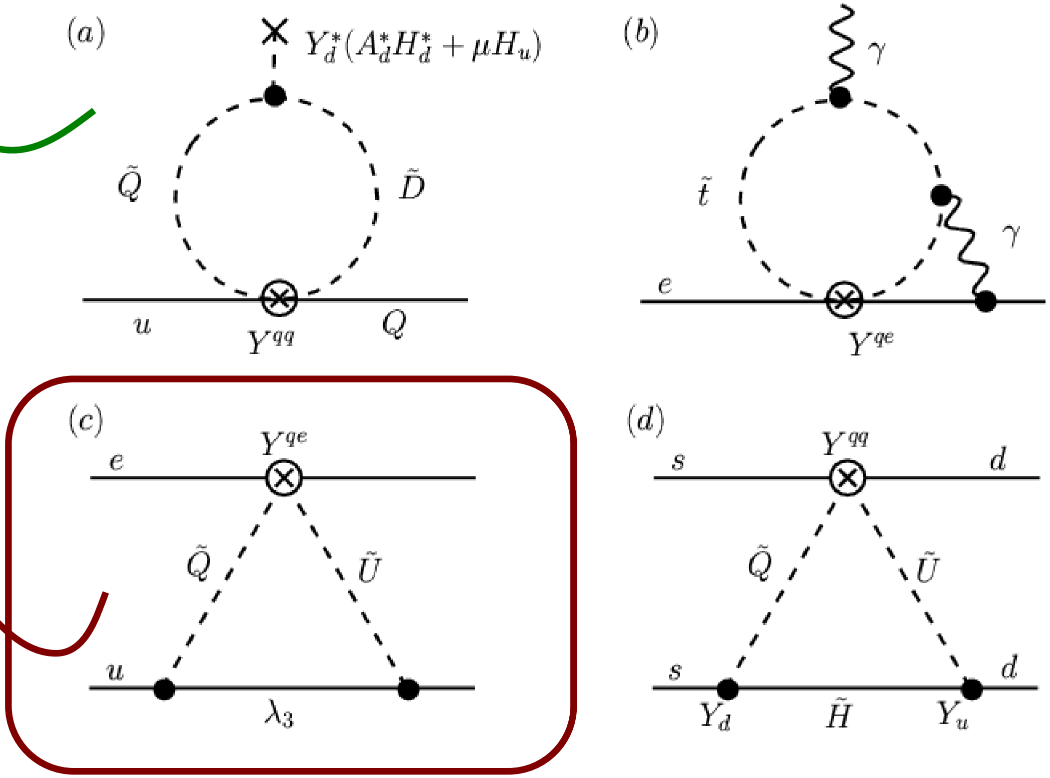


SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

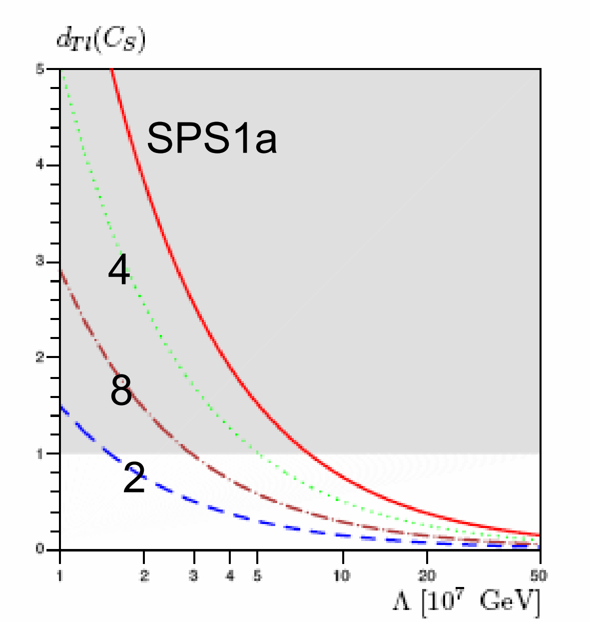
$$\Delta m_e \sim m_e \Rightarrow \Lambda > 10^6 GeV$$

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



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

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

Minimal EW Baryogenesis

$$\eta_b = (8.8 \pm 0.3) \times 10^{-11}$$

[WMAP3 + BBN]

The SM satisfies, in principle, all 3 Sakharov criteria for baryogenesis

<u>BUT</u>

- m_h too large for a strong 1st order PT [Kajantie et al. '96]
- insufficient CP-violation [Gavela et al. '94]

<u>Alternatives:</u>

- EWBG still possible in the MSSM —needs one light stop, a large M1-phase, and a rather tuned spectrum
- Leptogenesis —decoupled from EW scale, difficult to test

$$d_e(\eta) \sim m_e m_\nu^2 G_F^2 \sim 10^{-43}\, e\ cm$$

[Archambault, Czarnecki & Pospelov '04]

Minimal EW Baryogenesis

$\Rightarrow$ What is the minimal SM modification required for viable EWBG ? (*)

$$\delta\mathcal{L} = \frac{1}{\Lambda^2}(H^\dagger H)^3 + \frac{Z_t}{\Lambda_{CP}^2}(H^\dagger H)t^c H Q_3$$

[Grojean et al. '04; Huber et al '05]

require $\Lambda \sim \Lambda_{CP} \sim 400 - 800\ GeV$

$\Rightarrow$ makes predictions for the top-Higgs coupling, cf. LHC

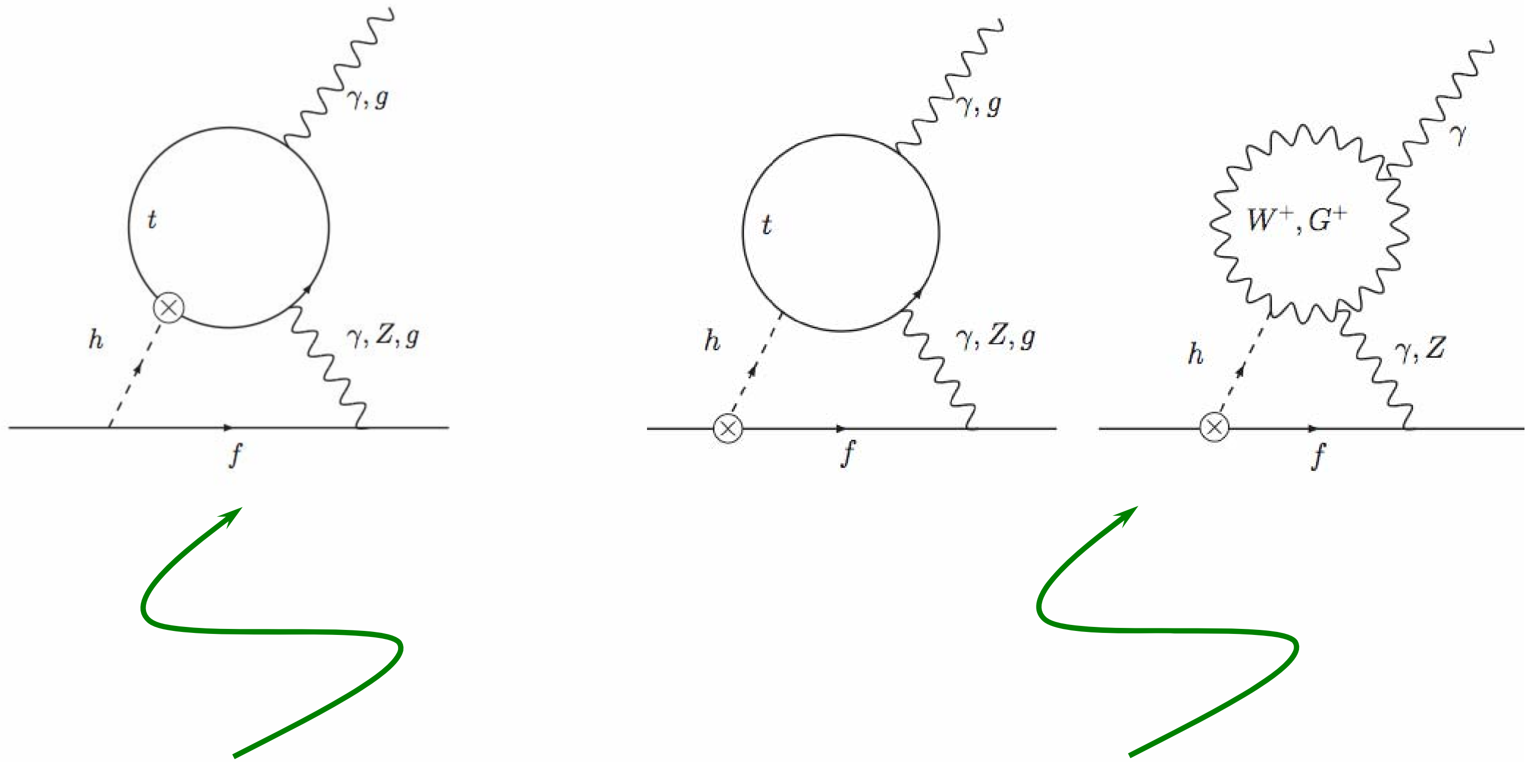
Questions:

Tuning of other operators at such low thresholds ?

Do EDM bounds really allow such a scenario ?

* NB: Can also flip sign of quartic Higgs coupling

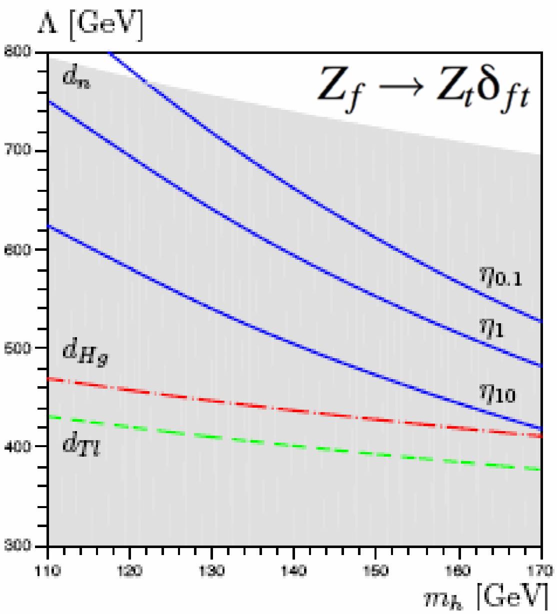
Barr-Zee diagrams

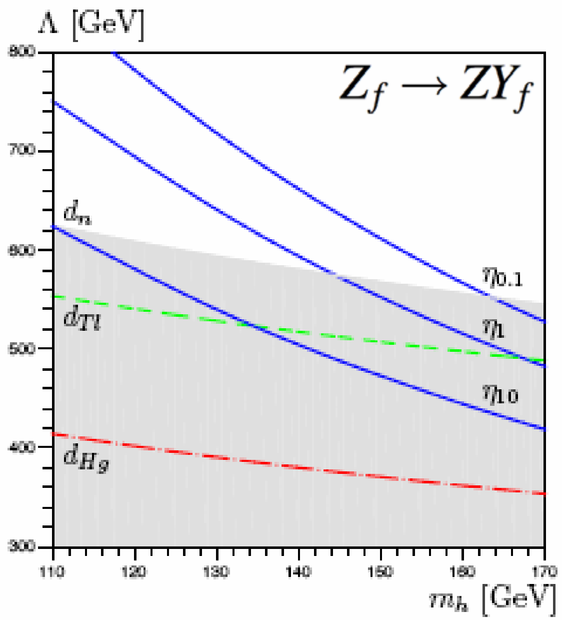


CP-odd top-Higgs coupling

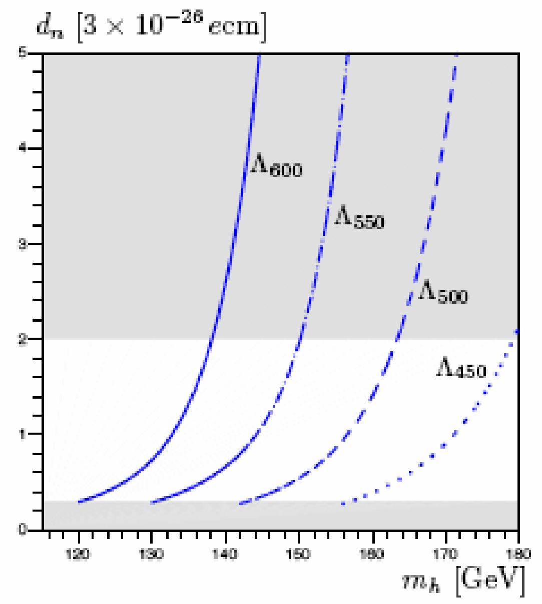
Assuming MFV structure

Constraints





$\Lambda = \Lambda_{CP} = M$



[Huber, Pospelov, AR '06]

Next-generation EDM sensitivity:

$$\Lambda_{CP} \sim 3\ TeV$$

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 the soft-breaking sector of the MSSM.

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- 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 the soft-breaking sector of the MSSM.
- If the soft sector is real, EDMs and other precision flavor physics provide impressive sensitivity to new SUSY thresholds.

next generation tests will push the scale close to that of RH neutrinos, etc.

- Current EDM bounds still allow for electroweak baryogenesis in a minimal dim=6 extension of the SM.

next-generation expts will provide a conclusive test.

Appendices