Probing new CP-odd thresholds with EDMs

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Based on work with:

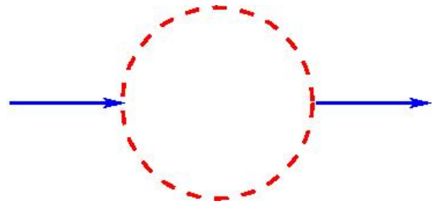
M. Pospelov,

S. Huber & Y. Santoso

[For a 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 "*symmetries*" of the SM:
e.g. Baryon no., Lepton no., Flavour, T (or CP), etc.

e.g: lepton number violation and neutrino mass

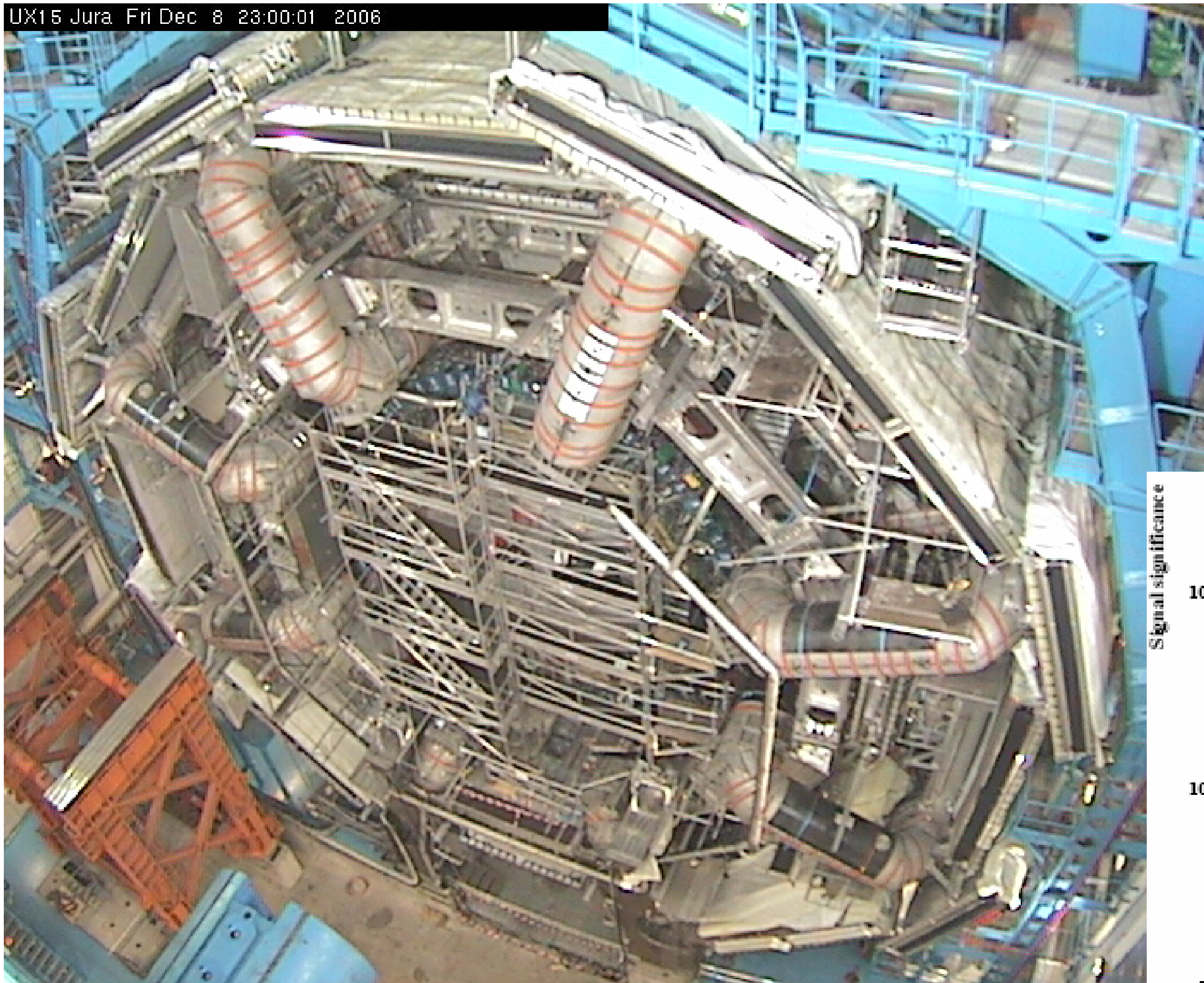
The Standard Model (above the EW scale) allows a *single* dimension five operator:

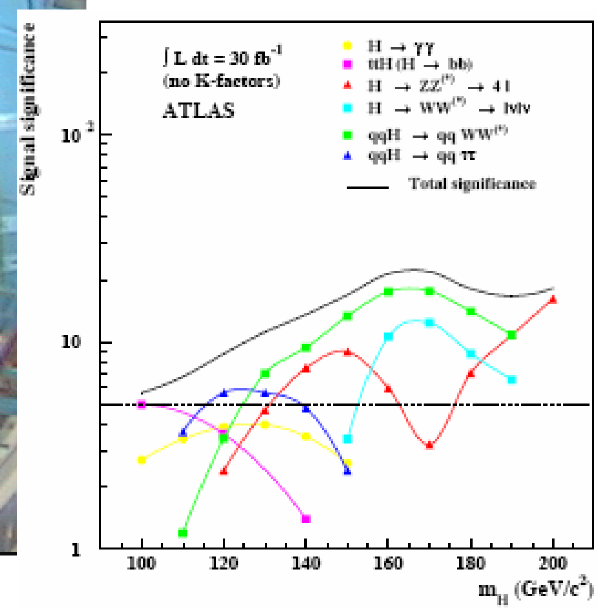
$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \frac{Y}{\Lambda}\bar{L}_L^c \tilde{H}\tilde{H}^T L_L + [dim \geq 6]}$$

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

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

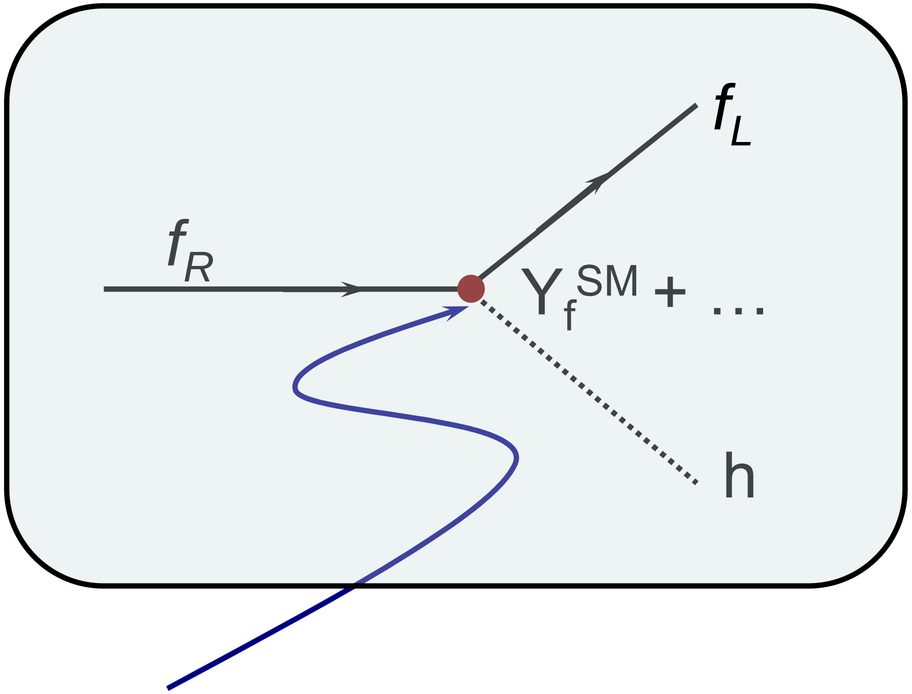
Probing the Higgs Sector





Higgs and CP-violation

In a complementary way, we can also use precision probes of the couplings



In particular, we can efficiently probe the CP structure of the (chirality changing) vertex

Higgs and CP-violation

With a convenient choice of basis we can associate all SM CP-violation with Yukawa couplings

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

[Jarlskog '85]

- Experimentally $\delta_{KM} \sim O(1)$, and consistently explains CP-violation in K and B meson mixing and decays

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

- Experimentally, $\theta < 10^{-9}$! (strong CP problem)

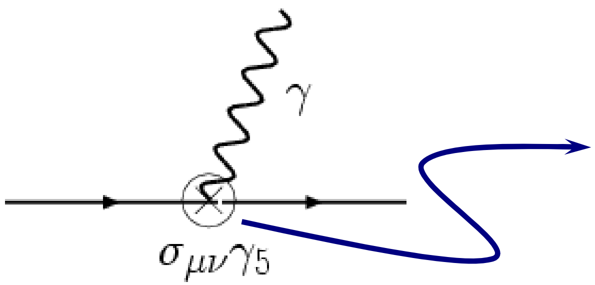
Do we anticipate other CP-odd sources ?

CP-violation and EDMs

YES

- Baryogenesis requires extra CP-violation
- Most "UV completions" of the SM (e.g. MSSM) provide additional sources of CP-violation

Within the SM, CP-violation is hidden behind the flavour structure $J_{CP} \sim 10^{-5} \sin(\delta_{KM})$ $\Rightarrow$ Look for CP-violation in flavour diagonal channels, with small SM bkgd



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

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

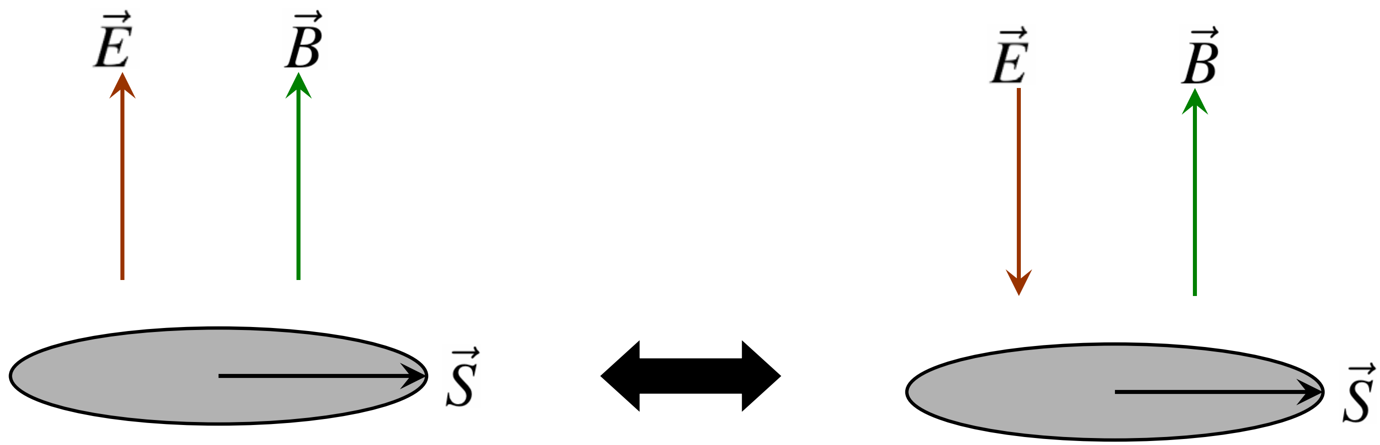
Currently, all experimental data $\Rightarrow$ EDMs vanish to very high precision thus leading to very strong constraints on new physics.

Outline of the Talk

- Current status of the 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

Measurement

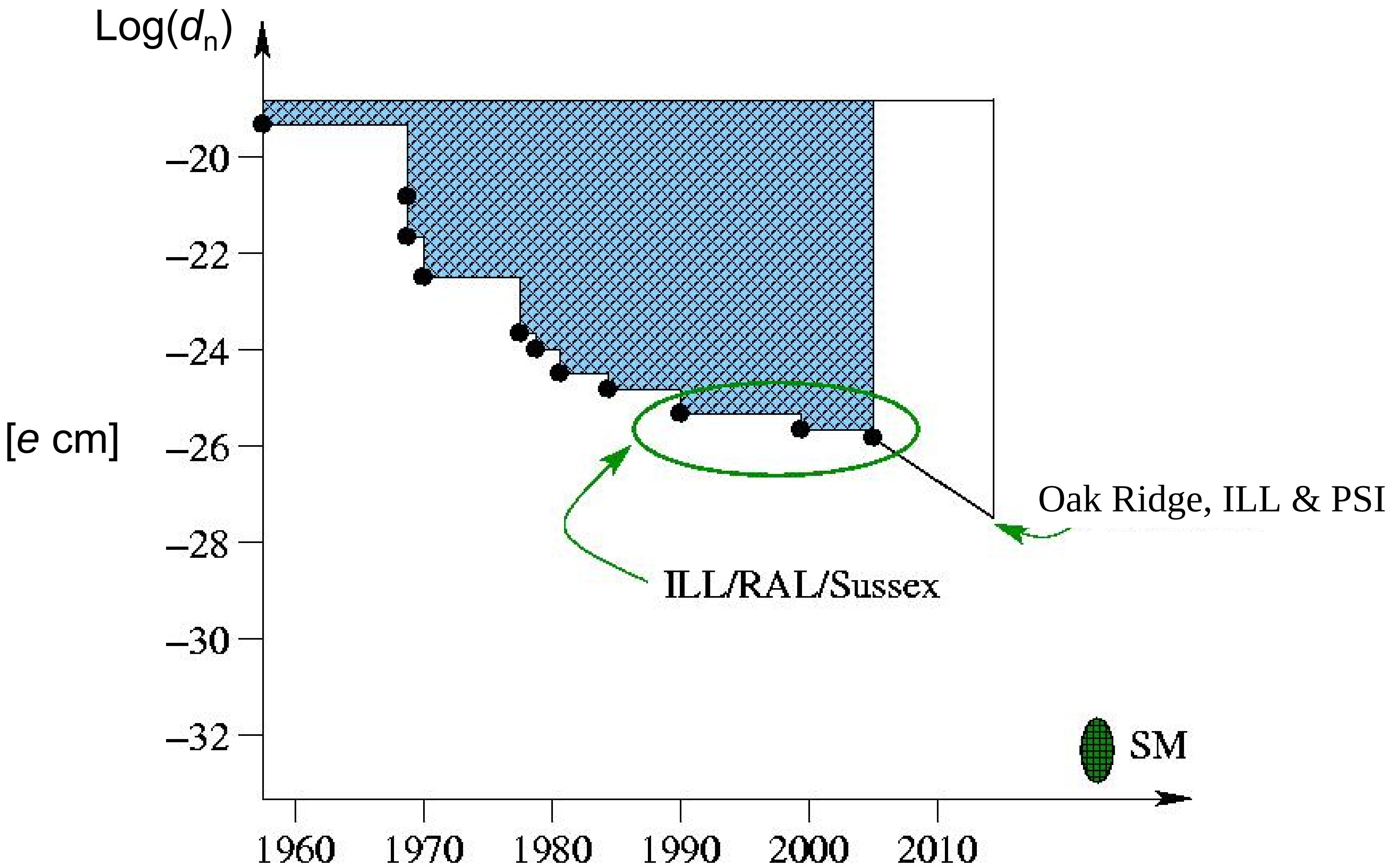
- Measure Larmor precession frequency in (anti-)aligned E and B fields



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

$$d = \frac{\hbar}{4E}(\omega_L^1 - \omega_L^2), \qquad \sigma_d \sim \frac{\hbar S}{ET\sqrt{N}}$$

Experimental Bounds on the neutron EDM



Experimental Status

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

There are ~10 new experiments
(either operating or in development)

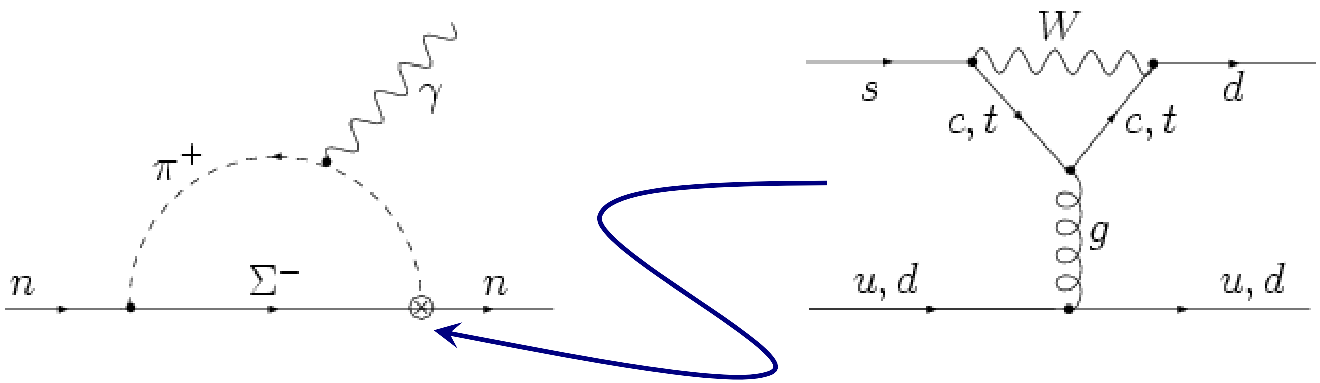
(optimistically) $\Rightarrow \boxed{\mathcal{O}(10^{-2} - 10^{-3})}$

gain in sensitivity for each channel

Experimental Status

Small 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: $\bar{\theta}\alpha_s G\tilde{G}$

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

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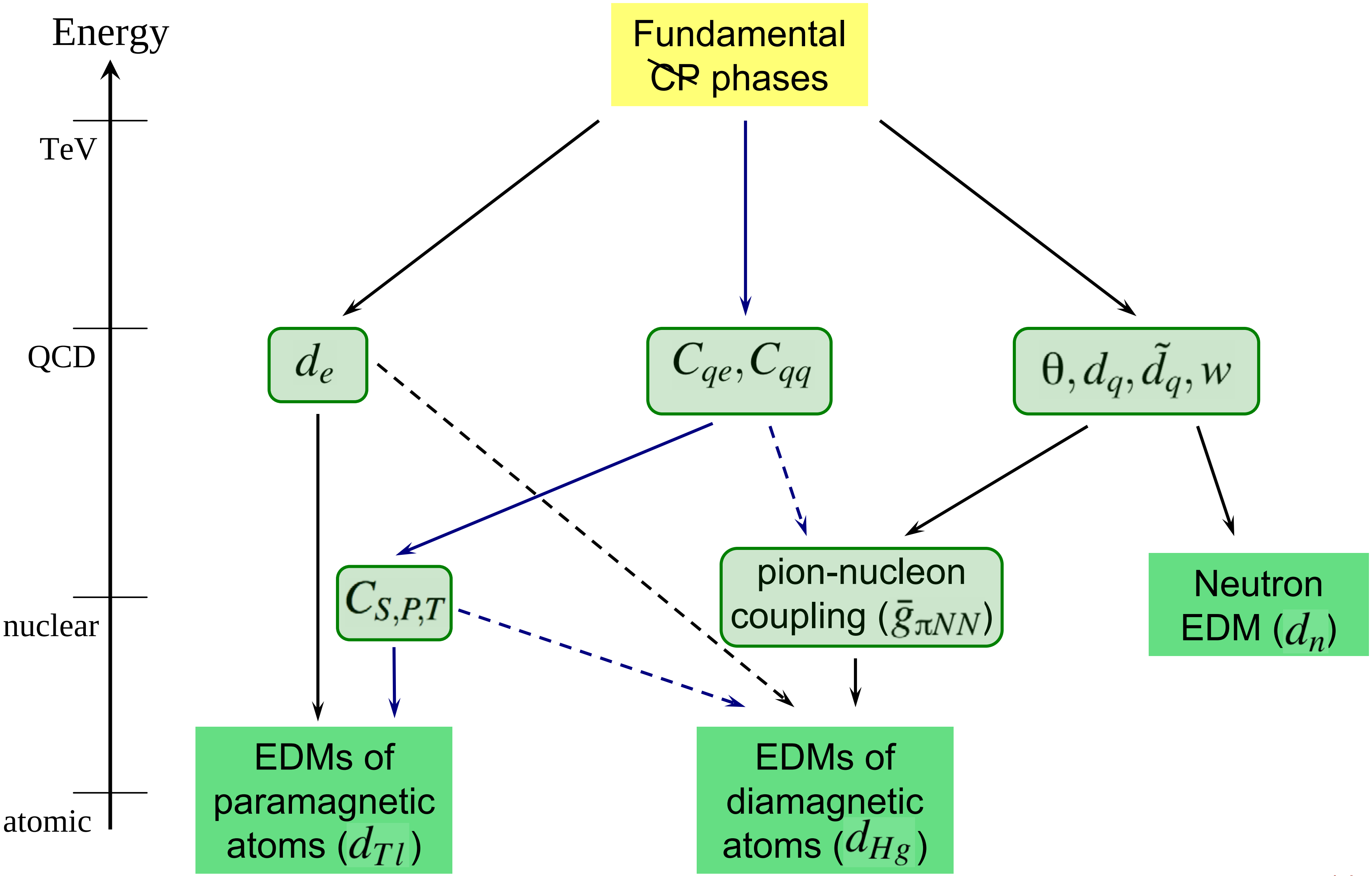
Dimension "8": $\sum_{q=u,d,s} \boxed{C_{qq}}\bar q q \bar q i\gamma_5 q + \boxed{C_{qe}}\bar q q \bar e i\gamma_5 e + \cdots$

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

Origin of the EDMs



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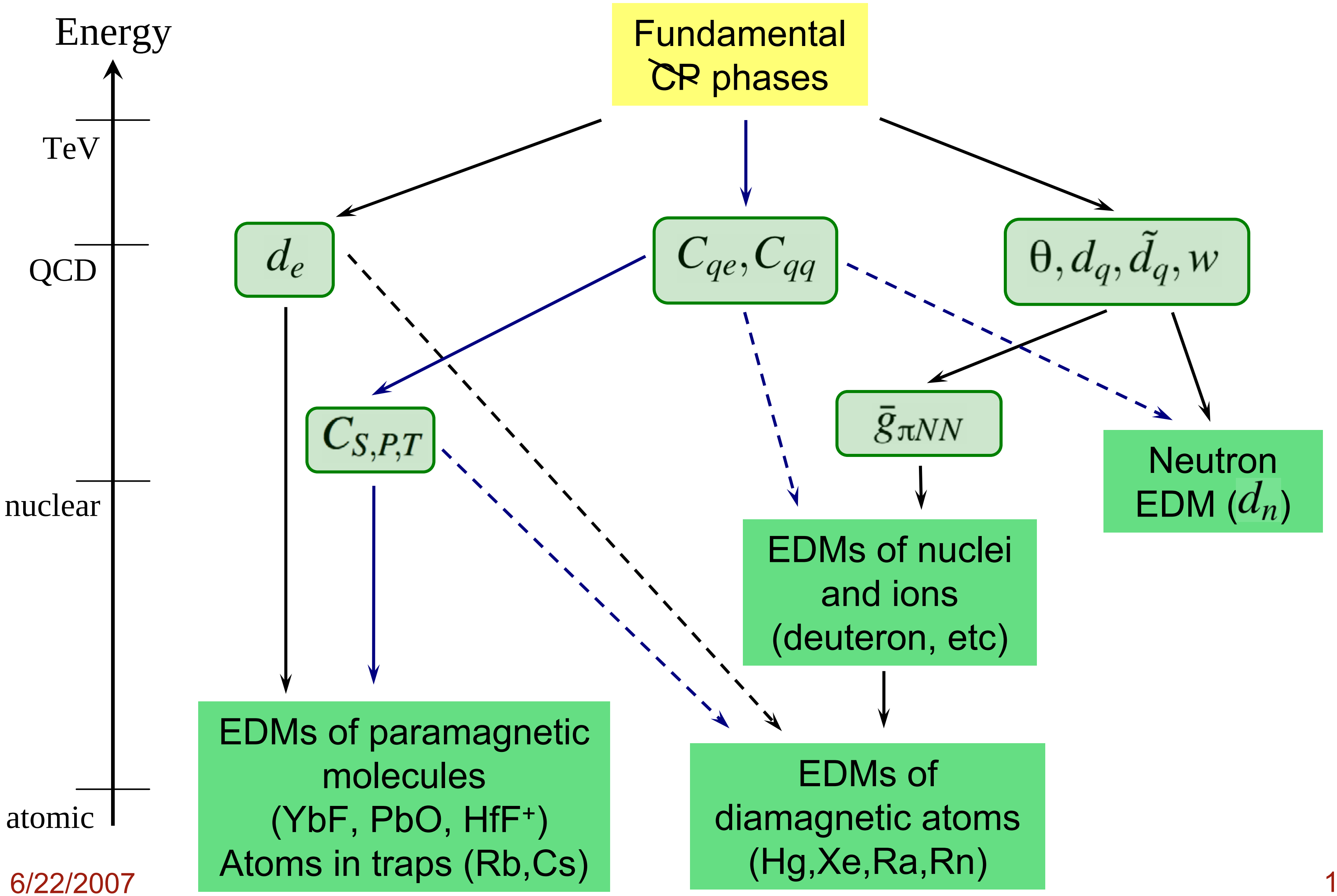
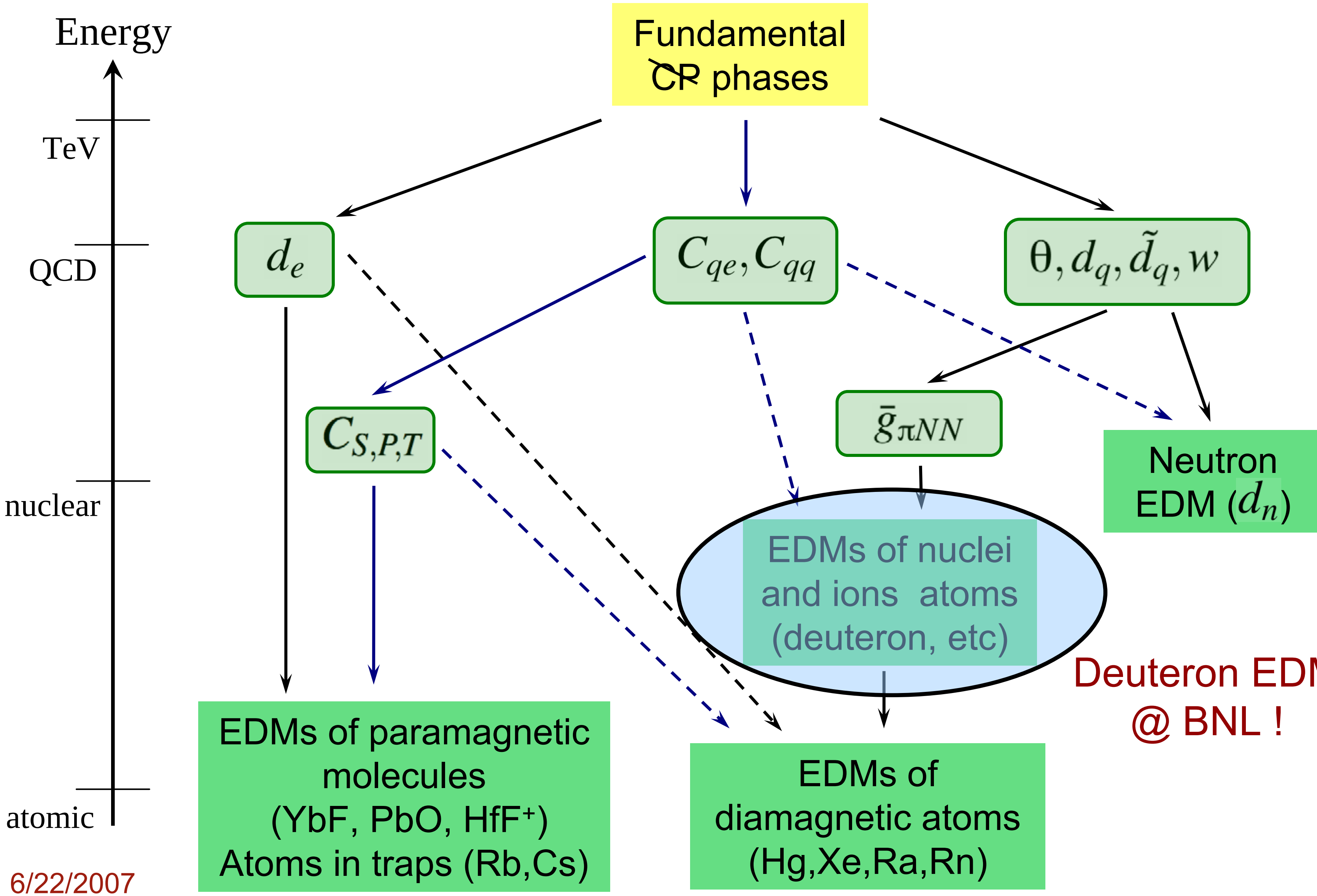
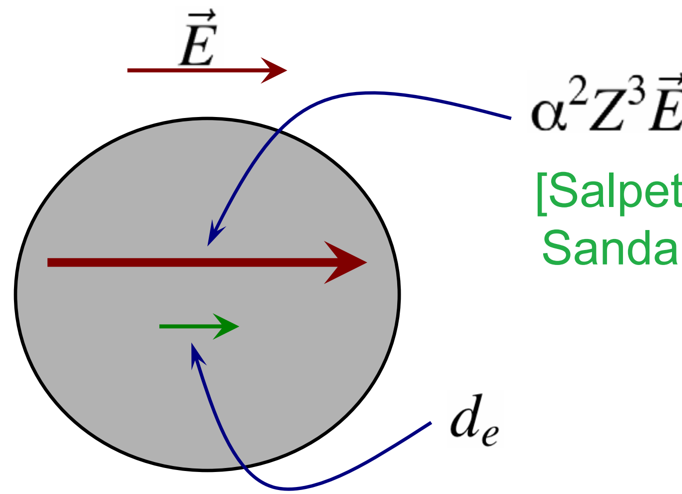


Next-generation Experiments



Deuteron EDM
@ BNL !

1. Tl EDM (paramagnetic)



[Salpeter '58; Sandars '65]

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

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

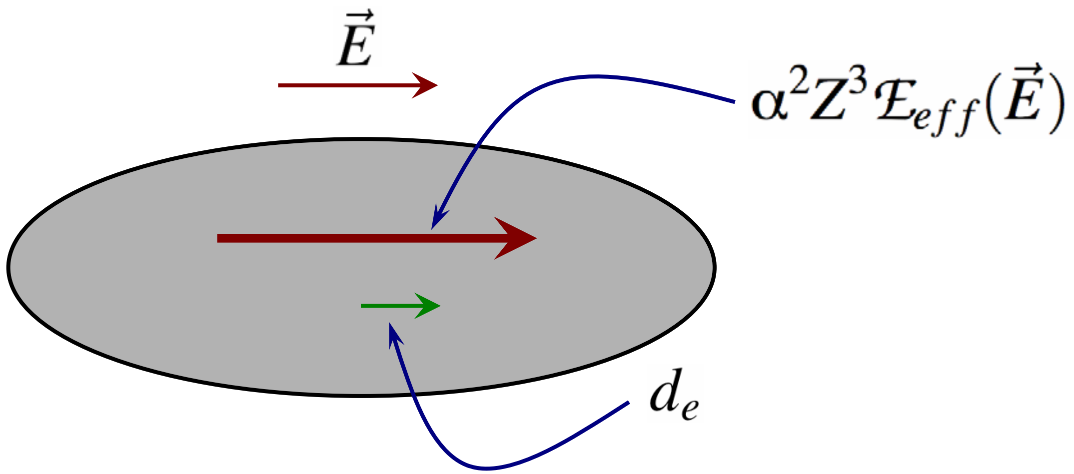
relativistic violation of Schiff thm

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

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

e.g. YbF, PbO

[Hinds; DeMille]



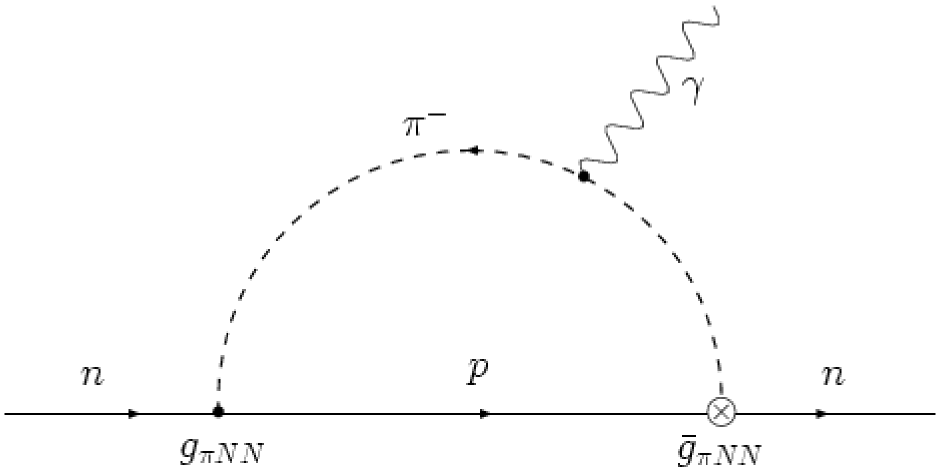
$$\boxed{\hbar \Delta\omega_L = \mathcal{E}_{eff} d_e + O(C_S)}$$

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

[Kozlov et al.]

2. neutron EDM

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



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

[also Baluni '79]

Calculating the EDMs - n

2. neutron EDM

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

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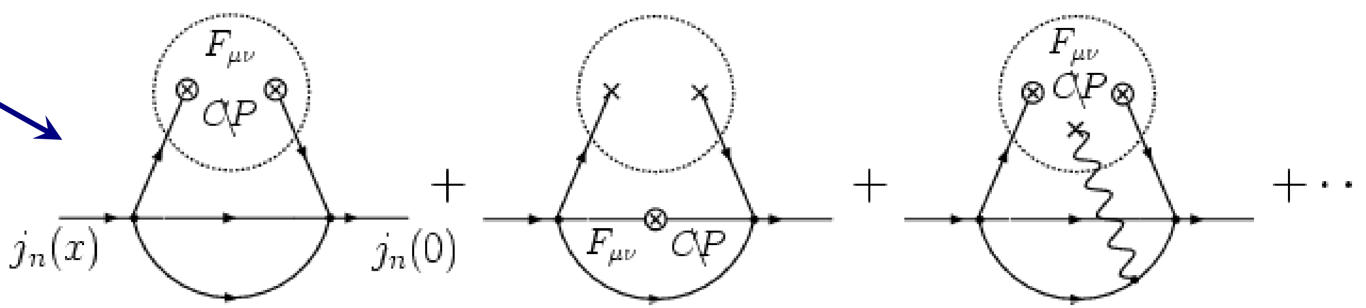
$$\Pi_1(p,\theta,d_q,\tilde{d}_q)\cdot F \sim \frac{d_n\lambda^2 m_n}{(p^2-m_n^2)^2}\{F\sigma\gamma_5,\not{p}\} + \cdots$$

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



Calculating the EDMs - n

2. neutron EDM

- QCD Sum Rules: Results
  - — Important condensates:

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

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

Sensitive only to ratios of light quark masses

[Pospelov & AR '99,'00]

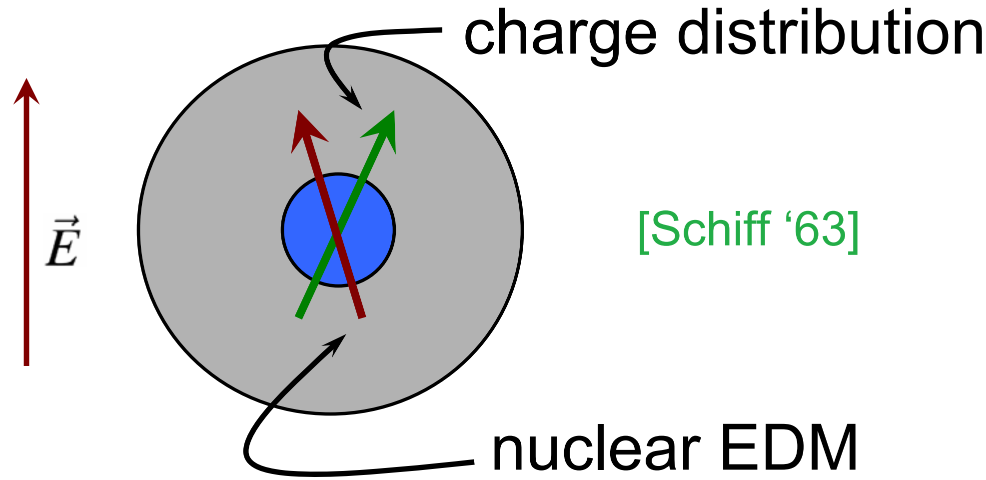
NB: PQ axion used to remove $\bar{\theta}$ $\quad \boxed{\theta_{ind} = \frac{1}{2}m_0^2 \sum_{q=u,d,s} \frac{\tilde{d}_q}{m_q}}$

Future developments: $d_n(\vartheta)$ in LQCD [Berruto et al; Shintani et al.]

Calculating the EDMs - Hg

3. Hg EDM (diamagnetic)

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



[Schiff '63]

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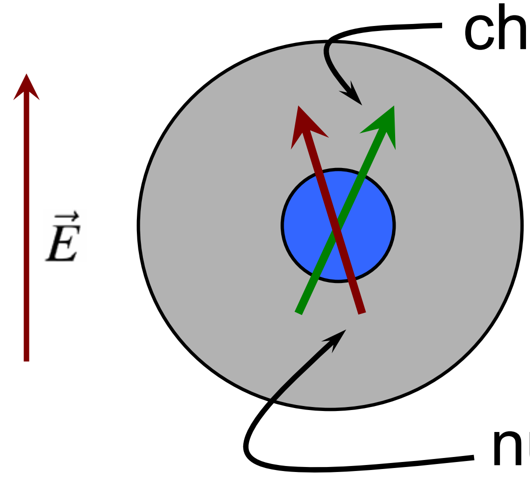


[Schiff '63]

- 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]

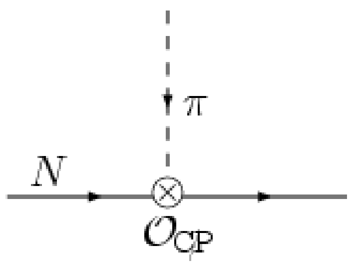
$$\bar{g}^{(1)}_{\pi NN}(\tilde{d}_q)$$

Calculating the EDMs - Hg

3. Hg EDM (diamagnetic)

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

(a)



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

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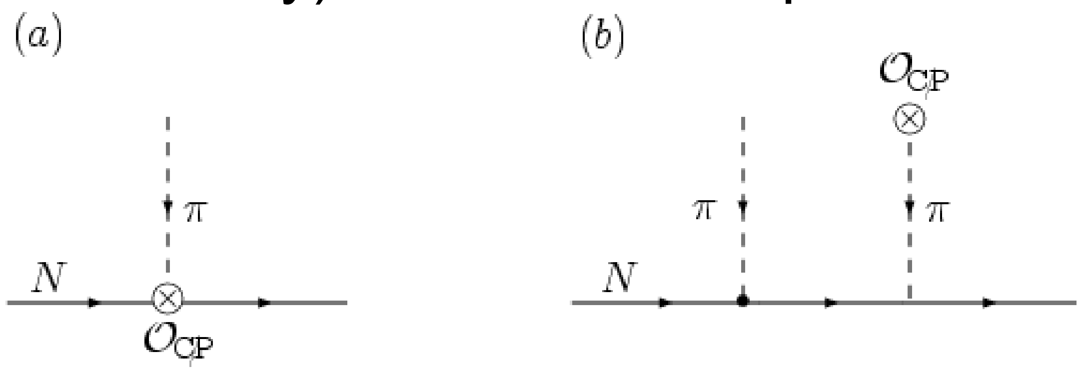

$$\bar{g}_{\pi NN}(\tilde{d}_q) = \frac{\tilde{d}_u - \tilde{d}_d}{2 f_\pi} \left\langle N \middle| \sum_{q=u,d} \bar{q} g_s G \sigma q - m_0^2 \bar{q} q \middle| N \right\rangle + \cdots$$

Calculating the EDMs - Hg

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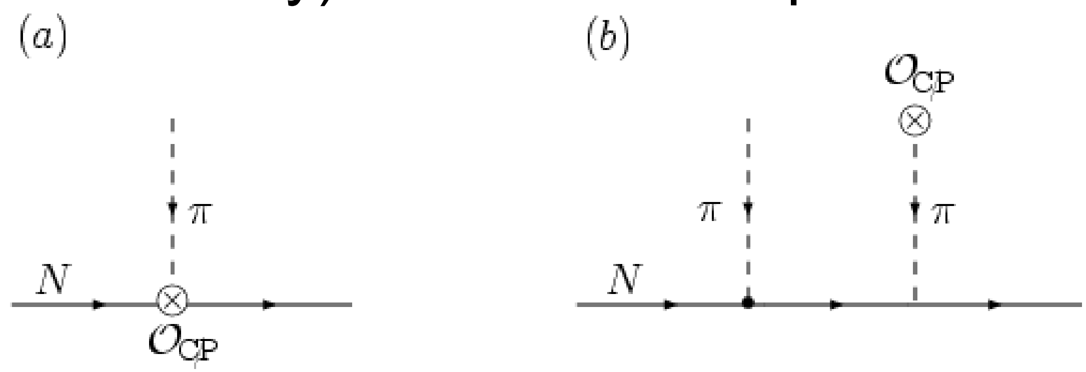
- EDM (predominantly) due to CP-odd pion-nucleon coupling:



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

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 & octupoles

Deuteron EDM @ BNL [SREDM Collab.]

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

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

[Lebedev, Olive, Pospelov, AR '04]

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

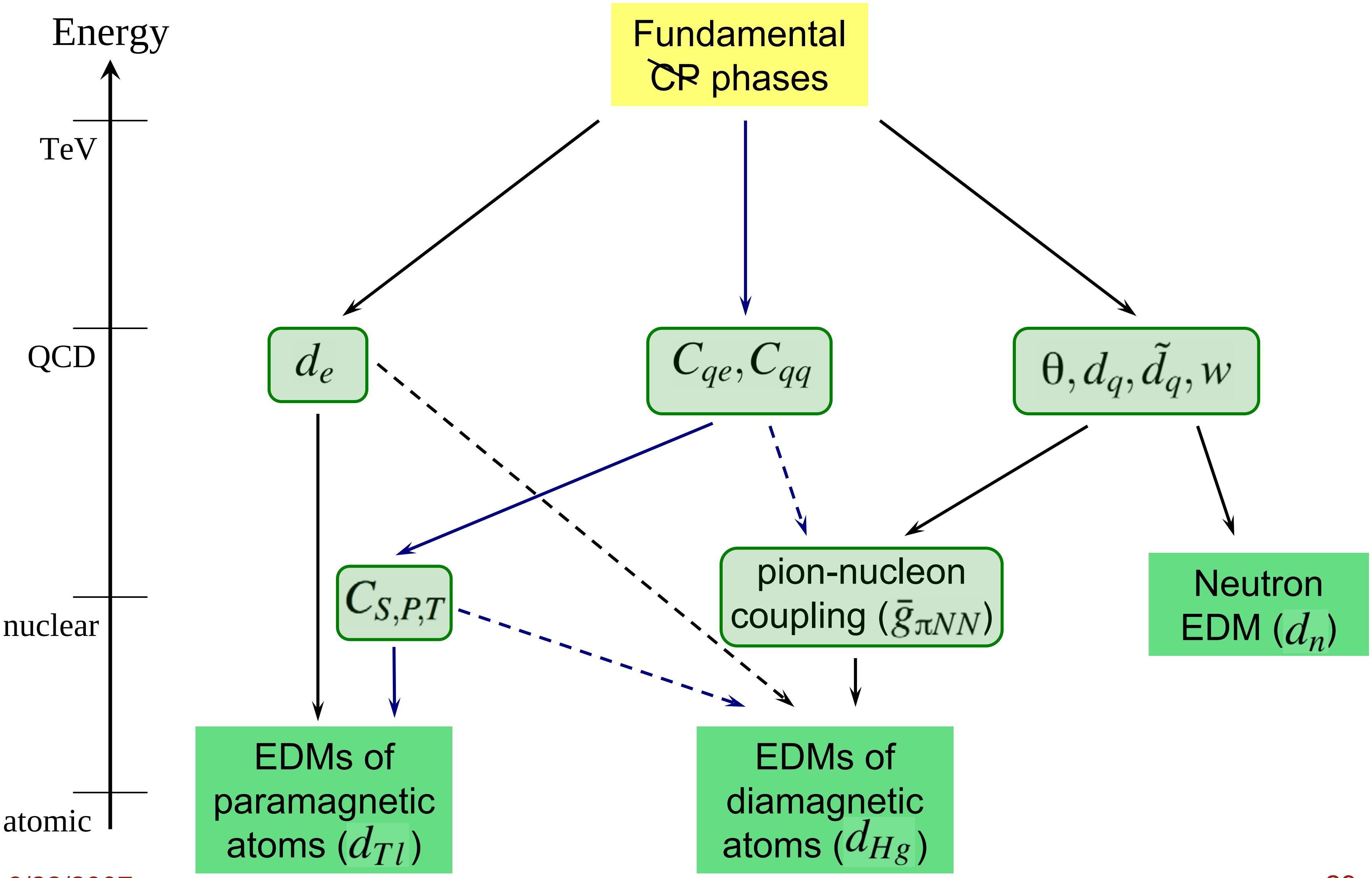
[Khriplovich & Korkin '00; Liu & Timmermans '04]

Sensitivity: $\boxed{d_D \sim 10^{-29}\,\mathrm{cm}} \Leftrightarrow \boxed{d_{Hg} \sim 3 \times 10^{-17} \bar{g}^{(1)}_{\pi NN} \sim 10^{-32}\,\mathrm{cm}}$

Ra, Rn EDM [Holt et al, Chupp et al]

- Nuclear octupole deformations enhance the Schiff moment, by O(100-1000) relative to Hg [Flambaum et al.]

Origin of the EDMs



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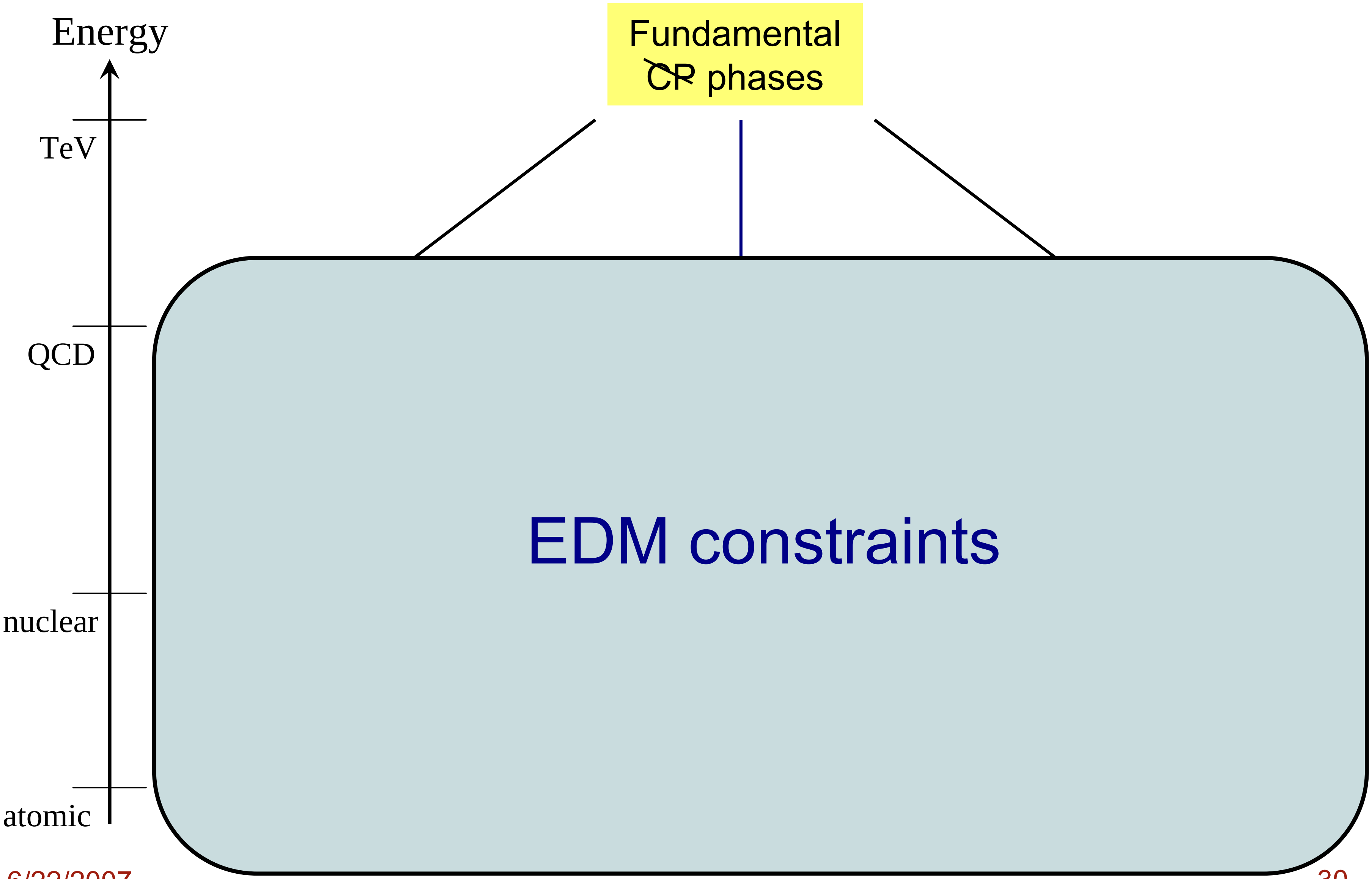


Resulting Bounds on fermion EDMs & CEDMs

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

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

Constraints on TeV-Scale models

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

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

Constraints on TeV-Scale models

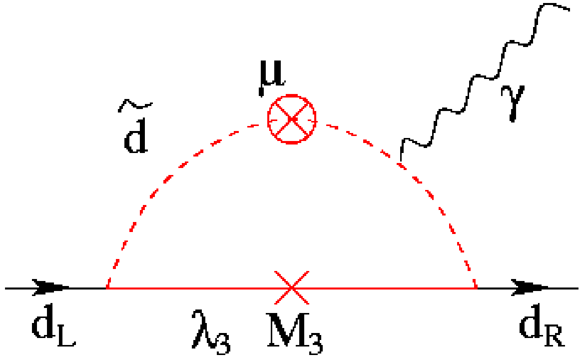
- E.G. MSSM: In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

Complex $\Rightarrow$ 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:

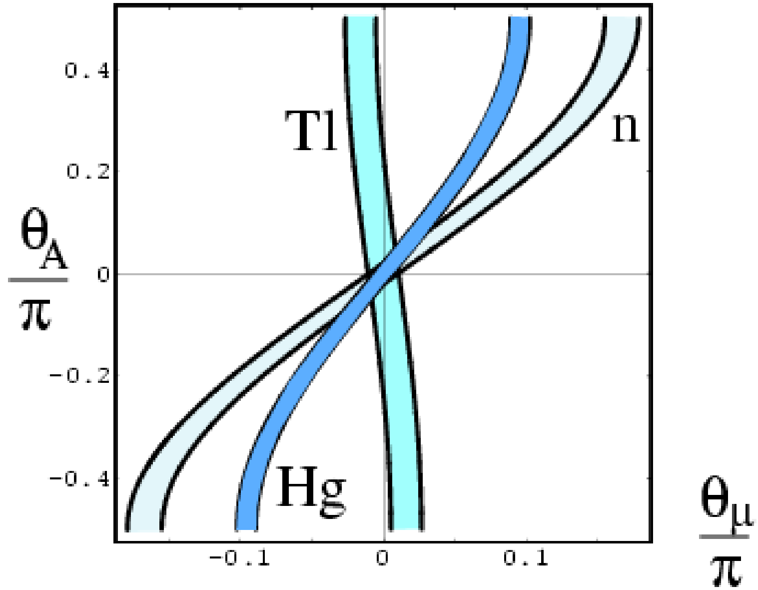


[Ellis, Ferrara & Nanopoulos '82]

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

M ~ sfermion mass

SUSY CP Problem



$M_{soft} = 500\ GeV$

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

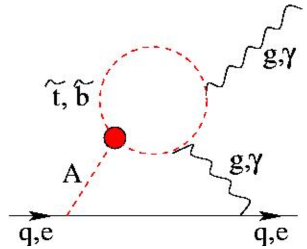
[Olive, Pospelov, AR, Santoso ‘05]

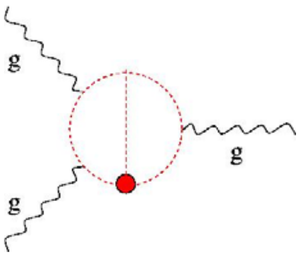
[Also: Barger et al. ‘01, Abel et al. ‘01, Pilaftsis ‘02]

SUSY CP Constraints

Decoupling 1st/2nd generation

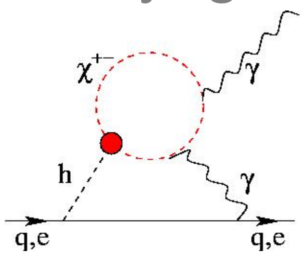
[Chang, Keung & Pilaftsis '98]





[Weinberg '89; Dai et al. 90]

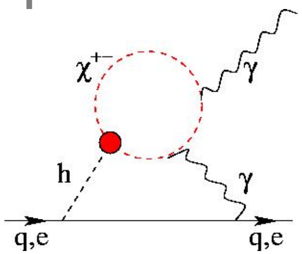
EW baryogenesis



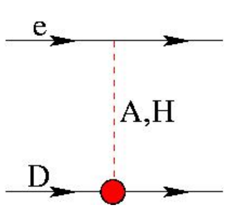
MSSM
parameter space

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

split SUSY



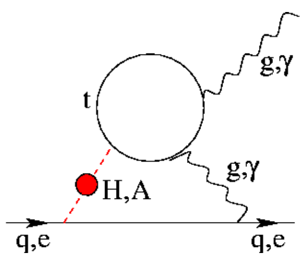
[Barr '92; Lebedev & Pospelov '02]



large tanβ

2 HDM

[Barr, Zee '92]



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"

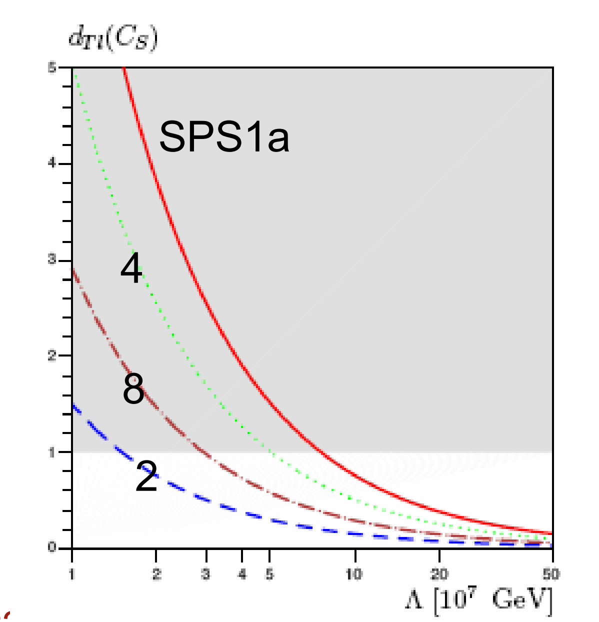
$$d_f \sim \frac{v_{EW}}{m_{soft}\Lambda}$$

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

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

SUSY threshold sensitivity

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]

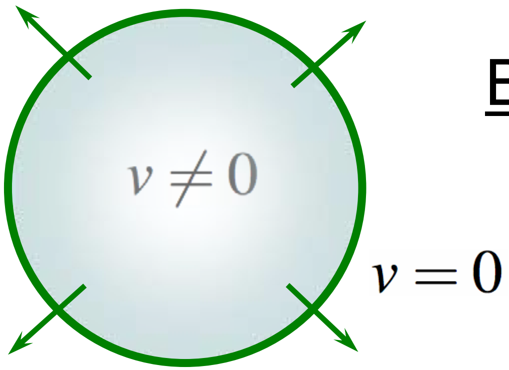
Models: e.g. MSSM + extended Higgs sector

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

(Electroweak) Baryogenesis

$$\boxed{\eta_b = (8.8 \pm 0.3) \times 10^{-11}}$$ [WMAP3 + BBN]

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



BUT

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

Alternatives:

- 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

⇒ What is the minimal SM modification required for viable EWBG ? (*)

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

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

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

⇒ makes predictions for the top-Higgs coupling, cf. LHC

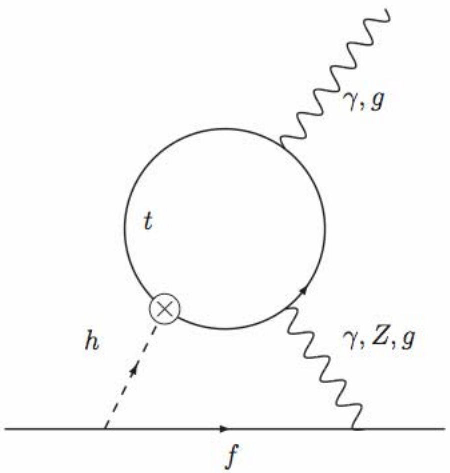
Questions:

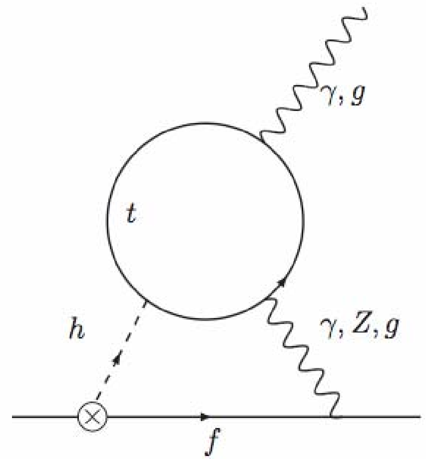
Tuning of other operators at such low thresholds ?

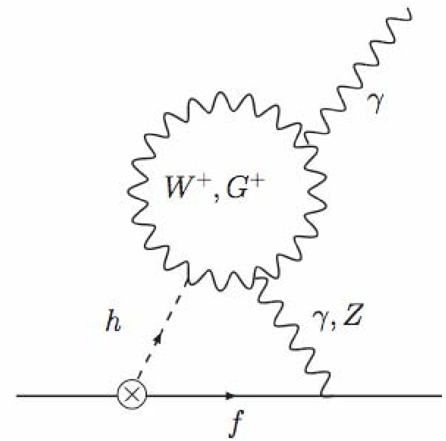
Do EDM bounds really allow such a scenario ?

* NB: Can also flip sign of quartic Higgs coupling

Barr-Zee diagrams



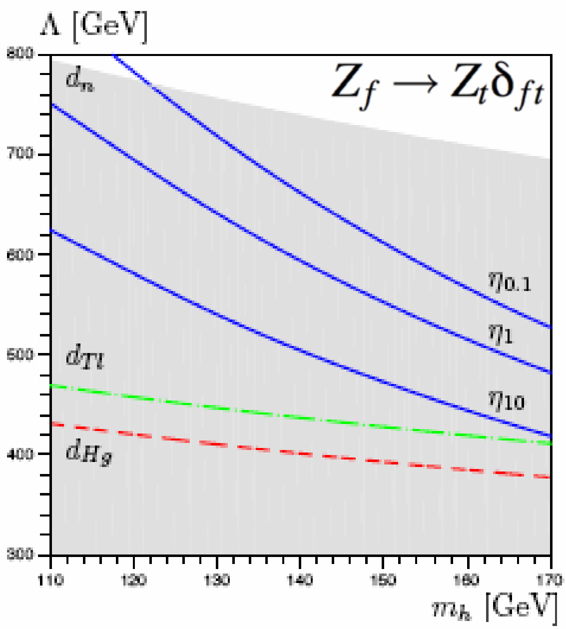


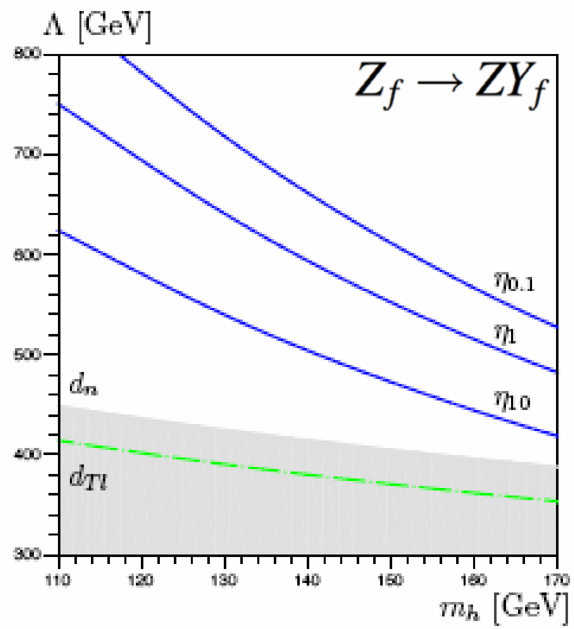


CP-odd top-Higgs coupling

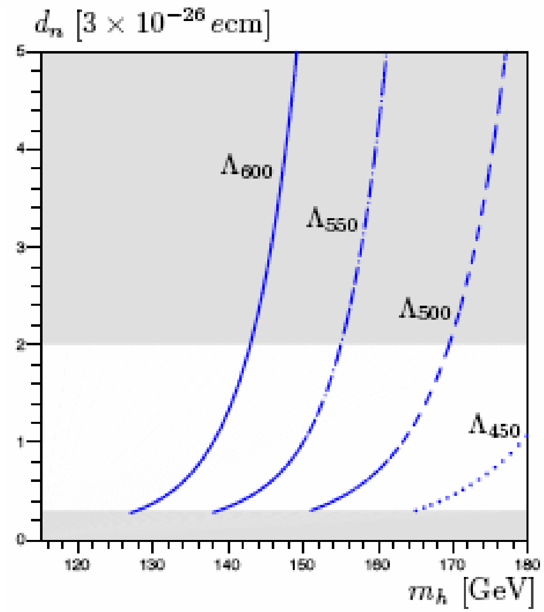
Assuming MFV structure

Constraints





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



[Huber, Pospelov, AR '06]

Next-generation EDM sensitivity:

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

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.

Concluding Remarks

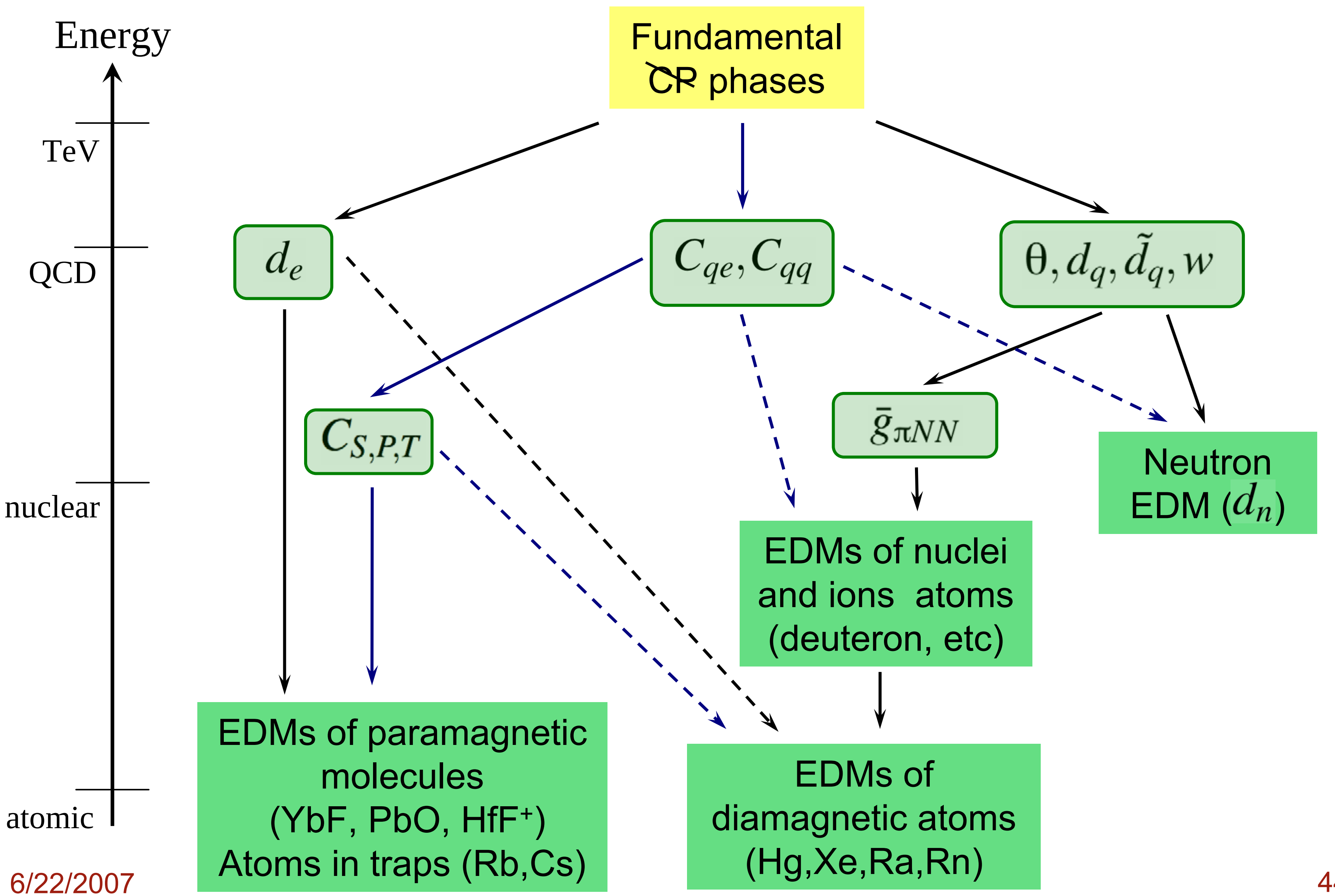
- Precision tests can play a crucial role in probing fundamental symmetries at scales well beyond the reach of colliders.
- EDMs currently provide stringent constraints on CP-phases in the soft-breaking sector of the MSSM.
- If the soft sector is real, EDMs and other precision flavor physics provide impressive sensitivity to new SUSY thresholds.

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

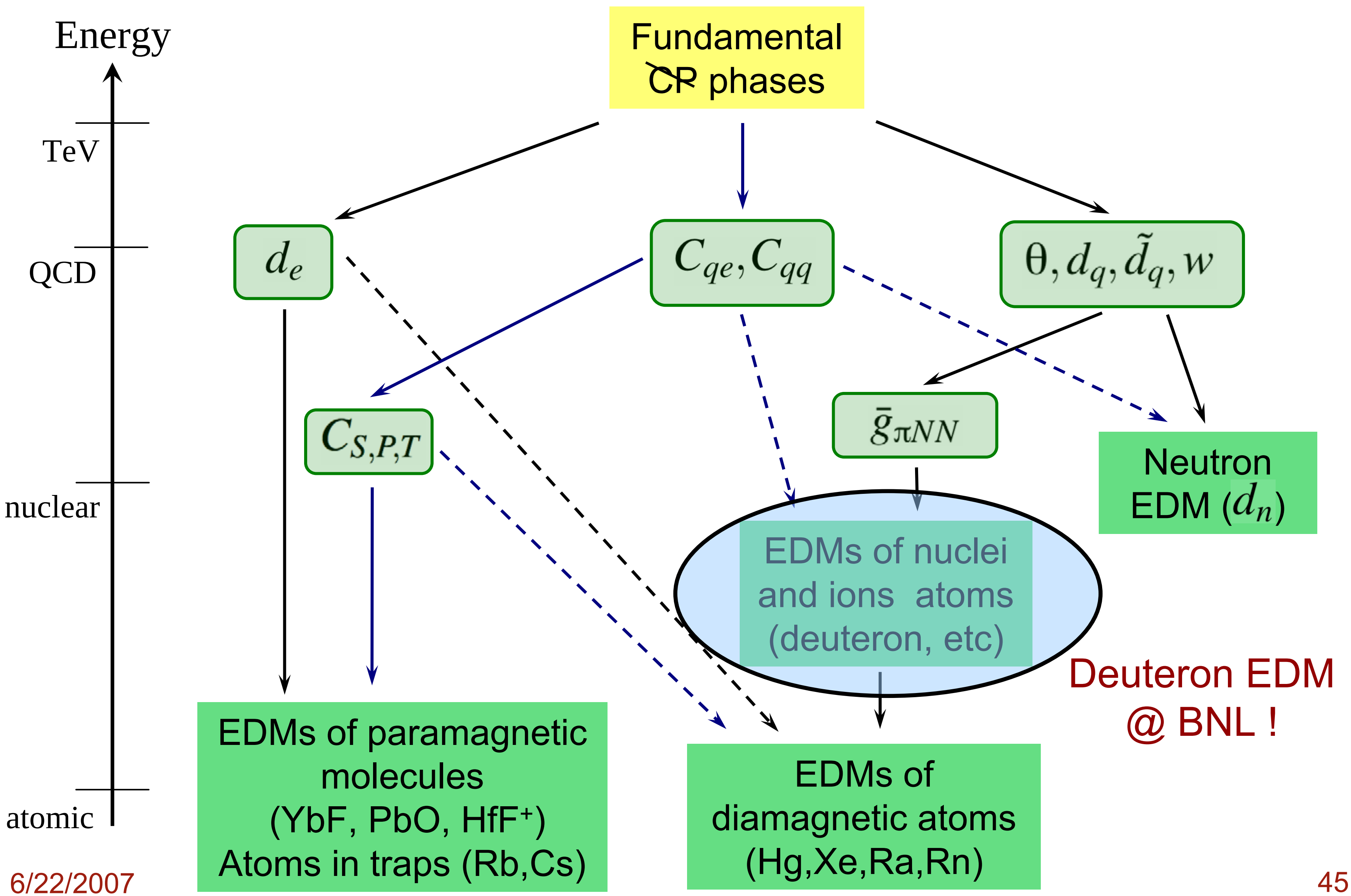
- Current EDM bounds still allow for electroweak baryogenesis in a minimal dim=6 extension of the SM.

next-generation expts will provide a conclusive test.

Next-generation Experiments



Next-generation Experiments



Appendices

Future experimental progress

- Paramagnetic atoms & molecules

PbO	$d_e \sim 10^{-30}\, e\ cm$	[DeMille et al. (Yale '06/07)]
YbF	$d_e \sim 10^{-29}\, e\ cm$	[Hinds et al. (Imperial '06/07)]
solid state (garnet)	$d_e \sim 10^{-31}\, e\ cm$	[LANSCE '06/07]

- Neutron

UCN bottle (Hg comag)	$d_n \sim 1 \times 10^{-27} e\ cm$	[PSI '07/09]
UCN in liquid He4 (He3 comag)	$d_n \sim 1 \times 10^{-28} e\ cm$	[LANSCE '07/10; Sussex et al. '07/10]

- Diamagnetic atoms

Hg	$d_{Hg} \sim 5 \times 10^{-29} e\, cm$	[Fortson, (Washington)]
Liquid Xe	$d_{Xe} \sim 10^{-31}\, e\ cm$	[Romalis, (Princeton)]

Deuteron	$d_D \sim 10^{-29} e\ cm$	[SR EDM collab. (BNL)]

+ many others ….

CP-violation and EDMs

YES

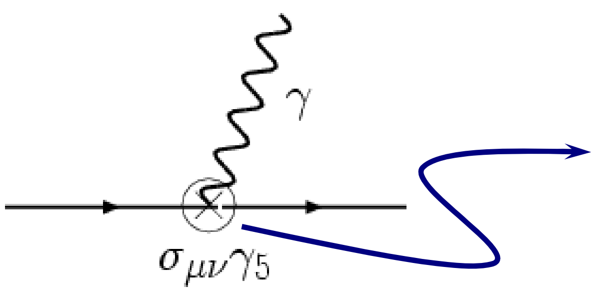
- Baryogenesis requires extra CP-violation
- Most "UV completions" of the SM (e.g. MSSM) provide additional sources of CP-violation

Within the SM, CP-violation is hidden behind the flavour structure

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

Are CP and flavour intrinsically linked ?

$\Rightarrow$ Look for CP-violation in flavour diagonal channels



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

– 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 <u>high precision</u> thus leading to very strong constraints on new physics.

Computations

1. Tl EDM (paramagnetic) (atomic)

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

$\alpha^2 Z^3$

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

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

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

[Pospelov & AR '99,'00]

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

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

[Dzuba et al. '02; Flambaum et al. '86; Dmitriev & Senkov '03]

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

[Pospelov '01]

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 (?)

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

Lattice ?

Future - charged nuclei

Deuteron EDM

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

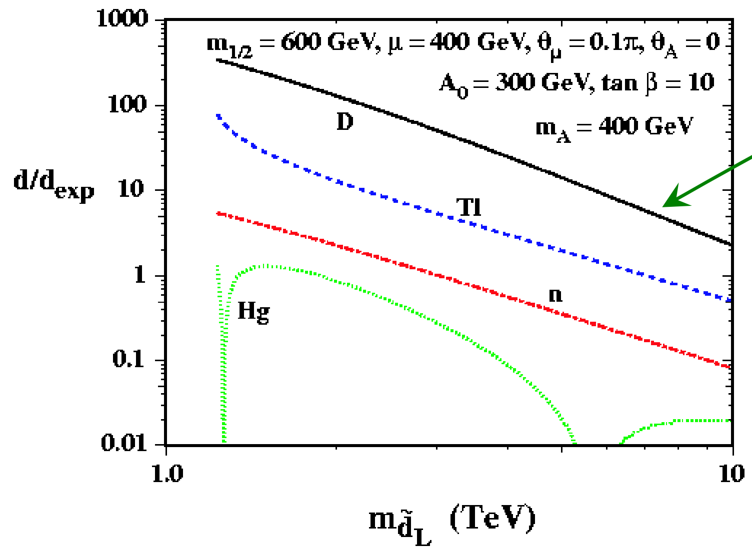
[Lebedev, Olive, Pospelov, AR '04]

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

[Khriplovich & Korkin '00]

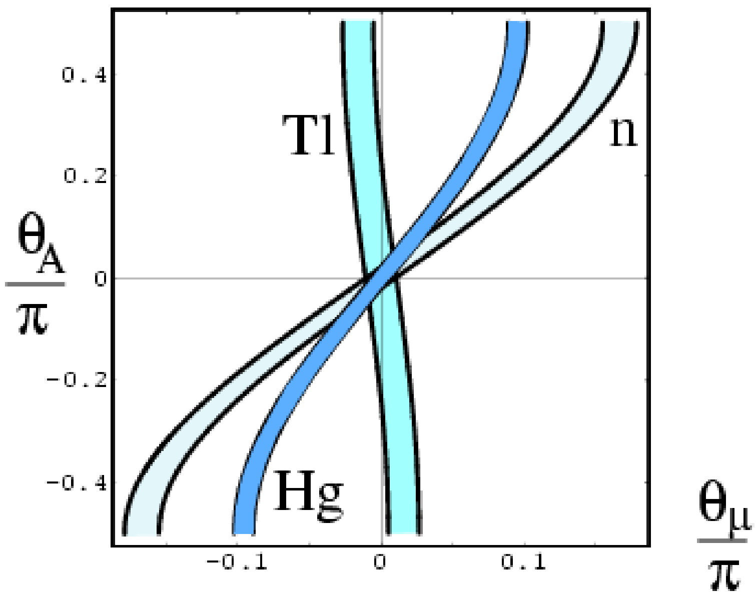
- Same (leading) dependence as Hg (but without Schiff suppression)

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

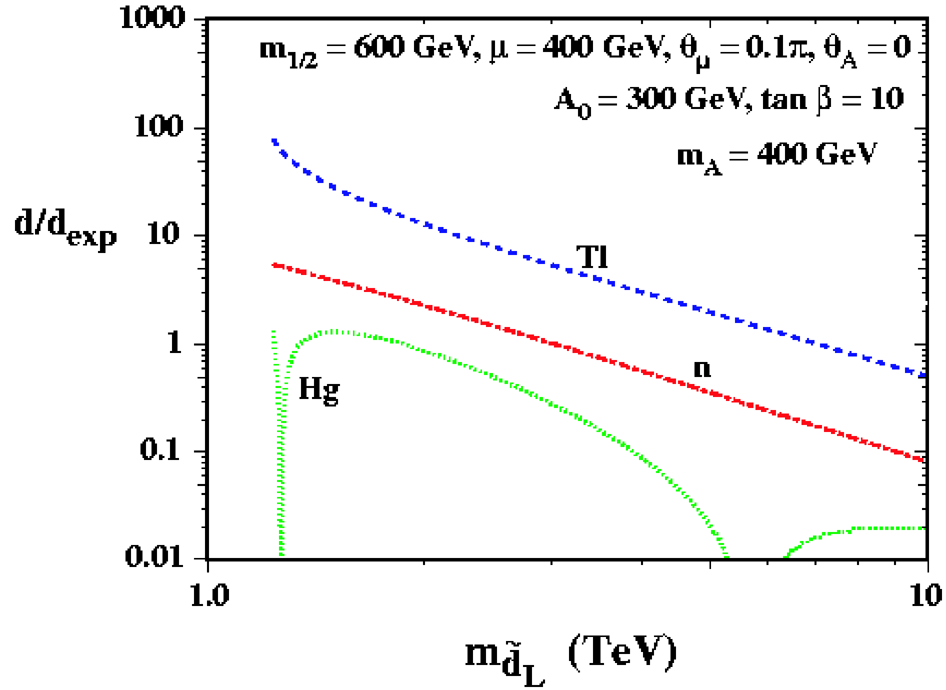


$$d_D \sim 10^{-27} e\, cm$$

SUSY CP Problem



$M_{soft} = 500\ GeV$



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

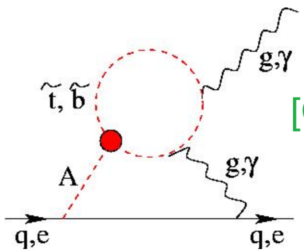
[Olive, Pospelov, AR, Santoso '05]

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

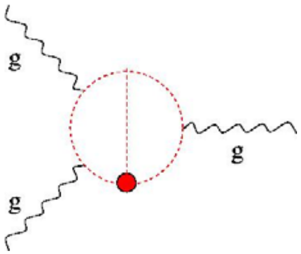
SUSY CP Constraints

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

Decoupling 1st/2nd generation

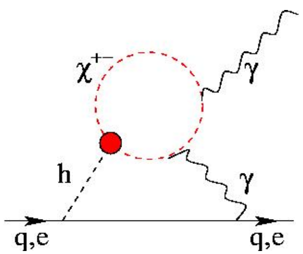


[Chang, Keung & Pilaftsis '98]



[Weinberg '89; Dai et al. 90]

Decoupling scalars (split SUSY, EW baryogenesis)

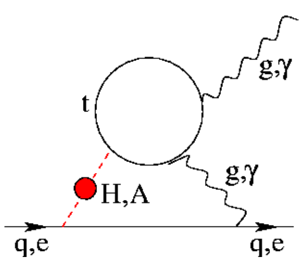


[Arkani-Hamed et al. '04]

Decoupling fermions

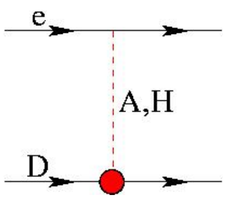
2 HDM

[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

$\Longrightarrow$ Assumption: non-CKM CP-violation is "*irrelevant*" (to leading order) at the weak scale

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

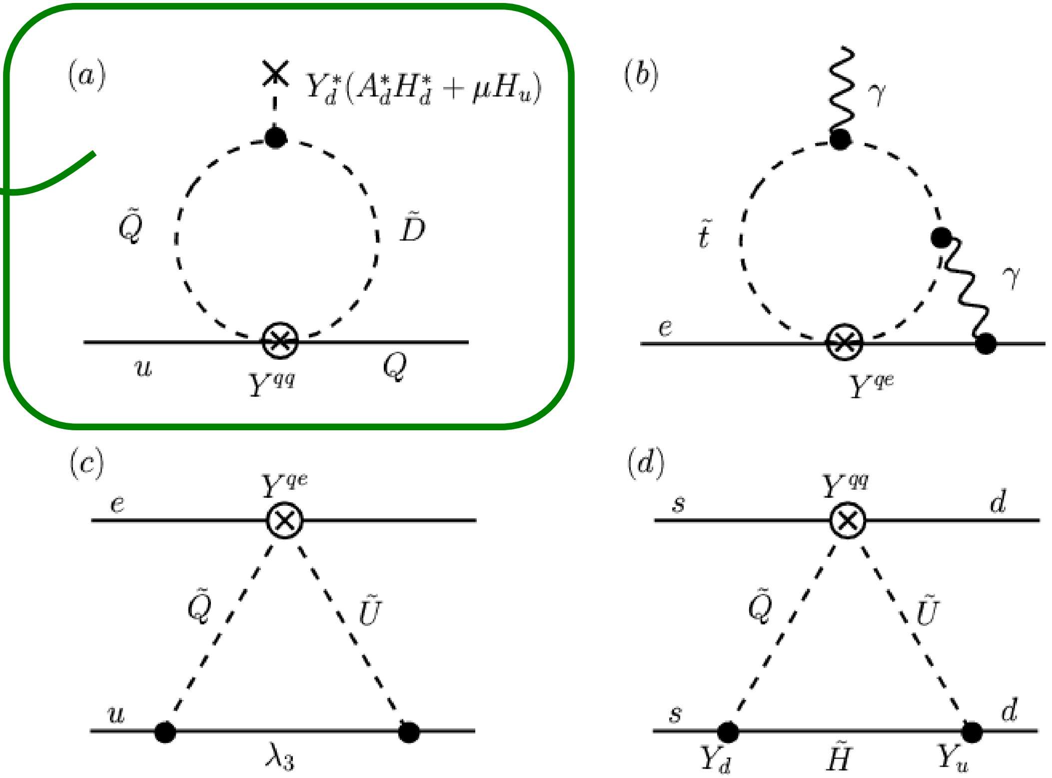
Questions:

- Can this scenario provide a viable baryogenesis mechanism ?
- What is the threshold sensitivity?

SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

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



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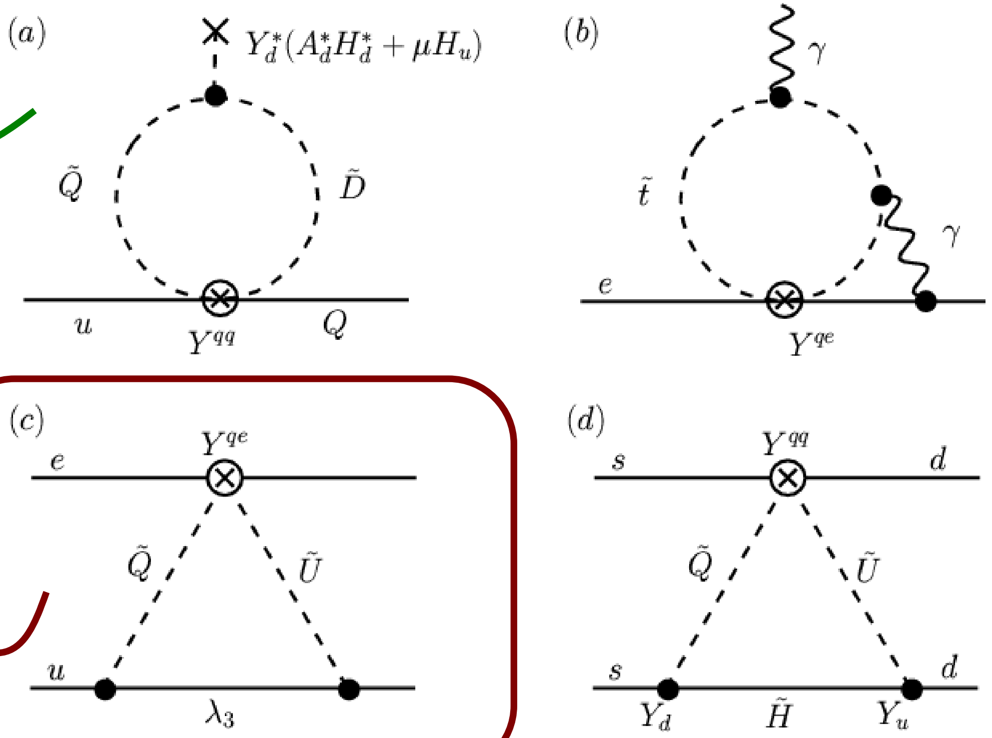

$$d_{Tl}(C_S), d_{Hg}(C_S), \mu \rightarrow e$$
$$\Rightarrow \Lambda > 10^8 GeV$$