Title: Particle Physics 2

Date: Jun 08, 2006 09:30 AM

URL: http://pirsa.org/06060007

Abstract:

Probing new CP-odd thresholds with electric dipole moments

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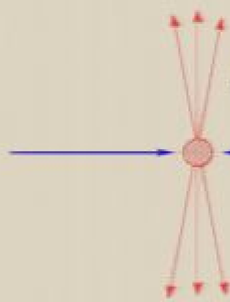
Based on work with:
M. Pospelov,
S. Huber & Y. Santoso

Precision Tests as Probes for New Physics

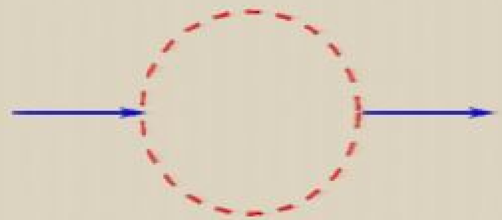
Searches for new physics (at energy scale Λ):

1. *Colliders*



$$E \sim \Lambda$$

2. *Precision Tests*



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

Especially powerful for tests of "*fundamental symmetr*
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} Ge

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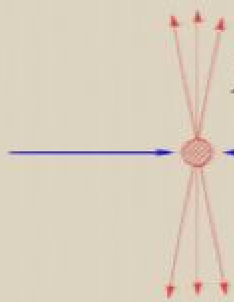

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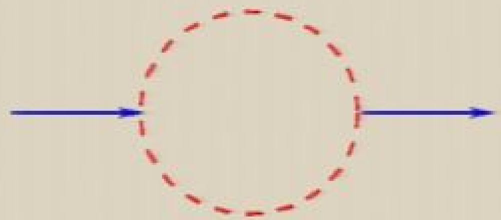

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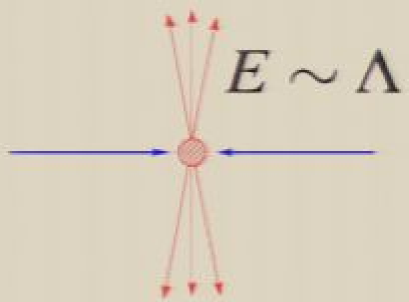

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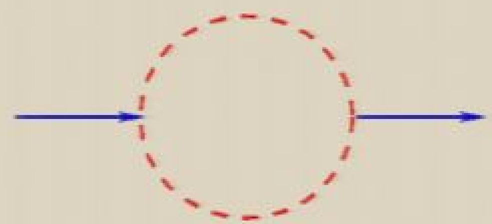

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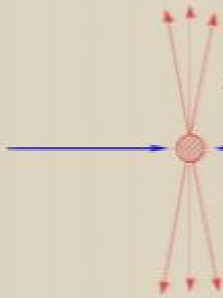

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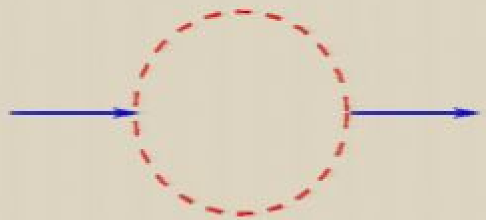

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In this talk ...

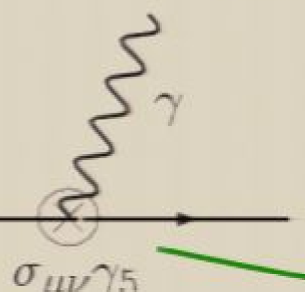
... we'll look at new CP-odd thresholds $\Leftarrow$
- baryogenesis
- generic phases in "UV completions" of SM

Assumption: non-CKM CP-violation is "*irrelevant*"

$$\mathcal{L} = \mathcal{L}_{SM}^{CKM} + \sum \frac{O_n^{CP}}{\Lambda^n}$$

motivated e.g. by success of CKM interpretation of CP-violation in K and B-meson mixing, and constraints on new soft-SUSY phases

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



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

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

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]

NB: *Small* SM background (via CKM phase)

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

[Khriplovich & Zhitnitsky '86]

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

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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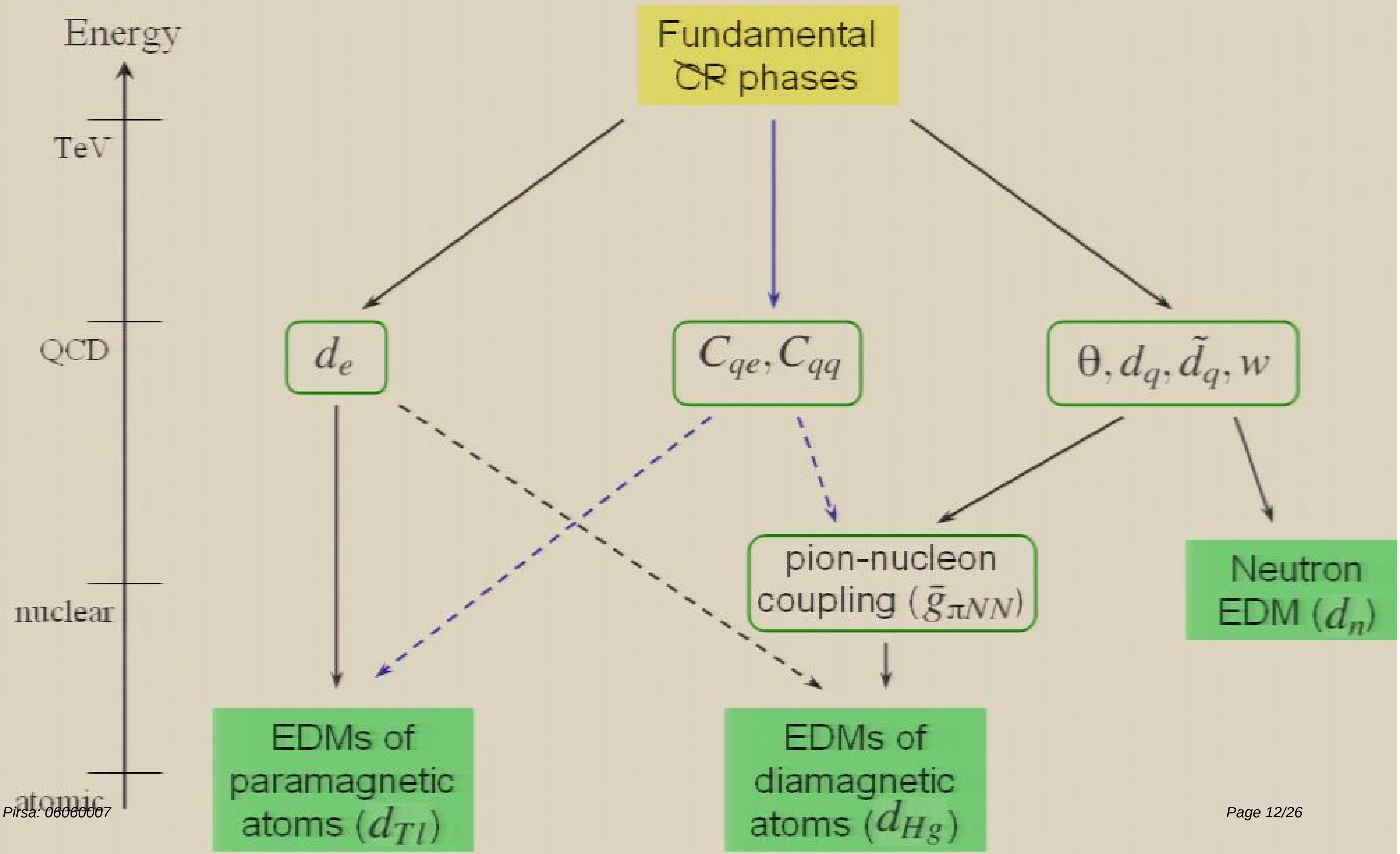
Origin of the EDMs



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 e
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]

Constraints on TeV-Scale models

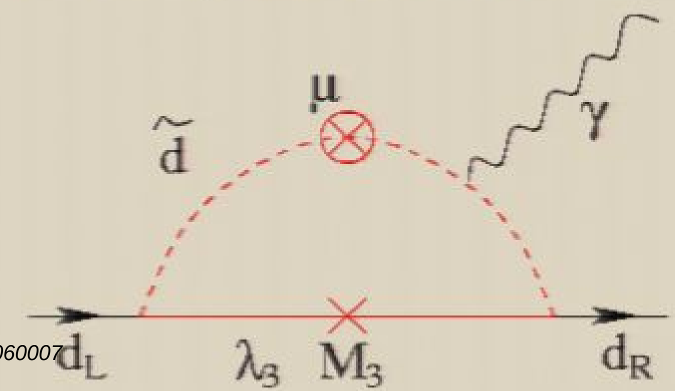
- E.G. MSSM: In general, the MSSM contains many new parameters, including multiple new CP-violating phases, e.g.

Complex $\Rightarrow$ CP-odd phas

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

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 threshold sensitivity

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

[Pospelov, AR, Santoso '05]

Dim 5:

$$\mathcal{W} = \mathcal{W}_{MSSM} + \frac{y_h}{\Lambda}(H_u H_d)^2 + \frac{Y^{qe}}{\Lambda} QULE + \frac{Y^{qq}}{\Lambda} QUQD + seesaw + \not{baryon}$$

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

$$d_f \sim \frac{m_{f'}}{m_{soft}\Lambda}$$

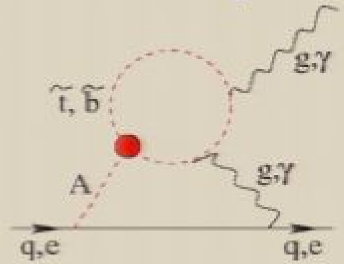
- Sensitivity depends on flavor structure of Y^{ff}

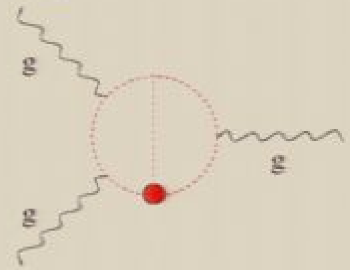
— we will assume $Y^{ff'} \neq Y_f Y_{f'} \sim 1$

SUSY CP Constraints

Decoupling 1st/2nd generation

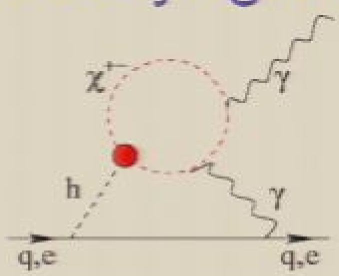
[Chang, Keung & Pilaftsis '98]





[Weinberg '89; Dai et al. 90]

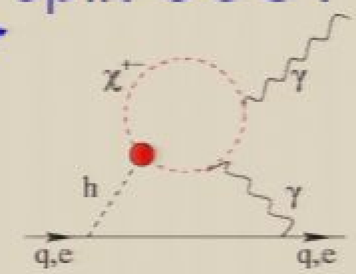
EW baryogenesis



MSSM
parameter space

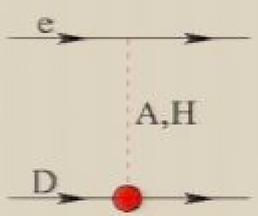
$phases < O(10^{-3} - 1)$

split SUSY



[Barr, Zee '92]

[Barr '92; Lebedev & Pospelov '02]



large tanβ

2 HDM

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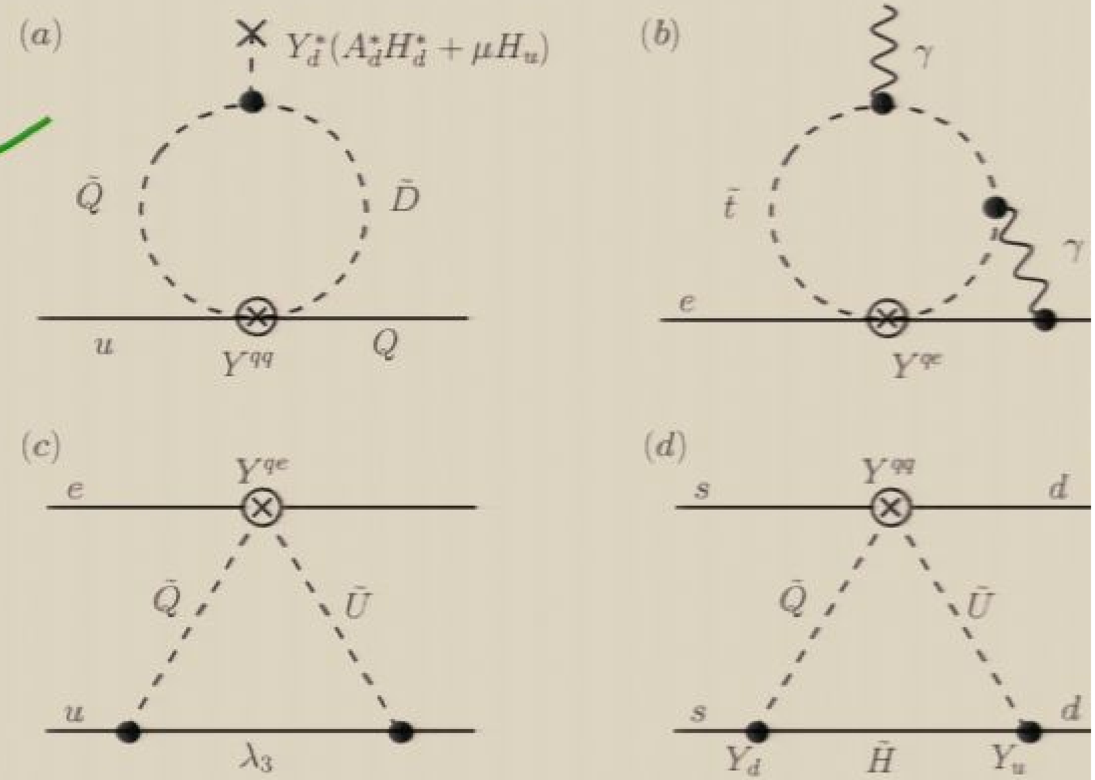
SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

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



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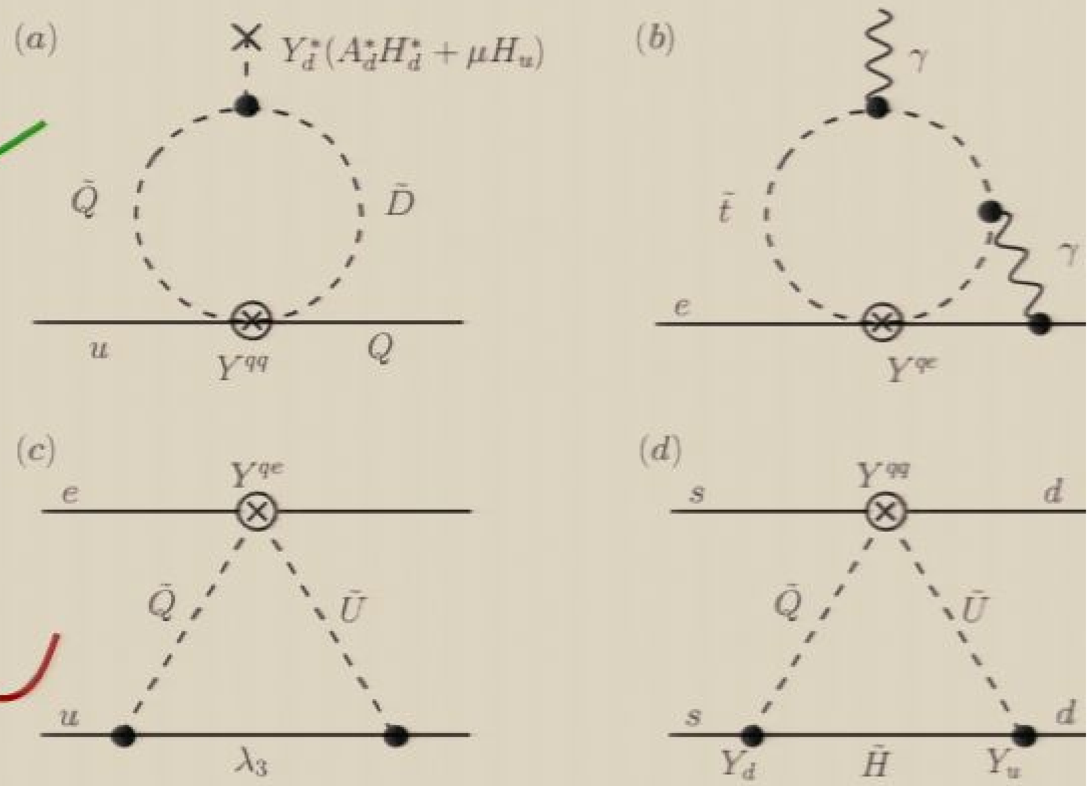


$$d_{Tl}(C_S), d_{Hg}(C_S), \mu \to e$$
$$\Rightarrow \Lambda > 10^8 GeV$$

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}	$10^7 - 10^8$	$\mu \rightarrow e$ 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]

Models: e.g. MSSM + extended Higgs sector

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

Minimal EW Baryogenesis

$$\eta_b = 8.9 \times 10^{-11}$$

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 ? (*)

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

[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

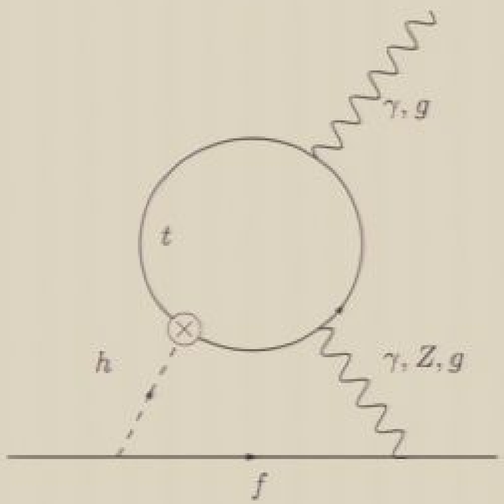
Questions:

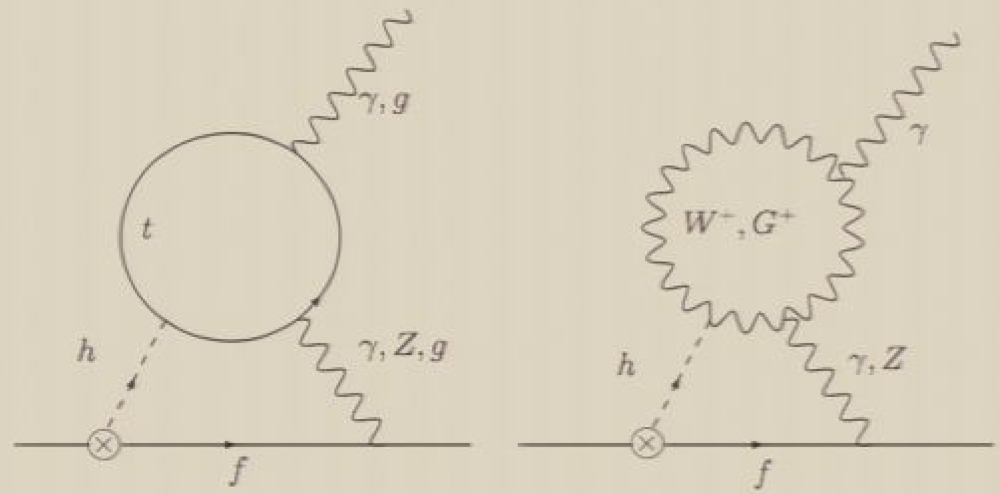
Tuning of other operators at such low thresholds ?

Do EDM bounds really allow such a scenario ?

* NB: Can also flip sign of quartic Higgs coupling

Barr-Zee diagrams

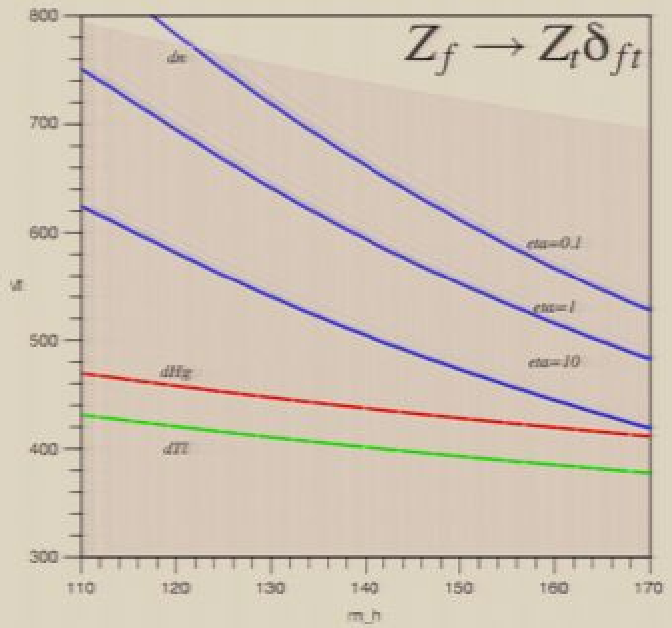




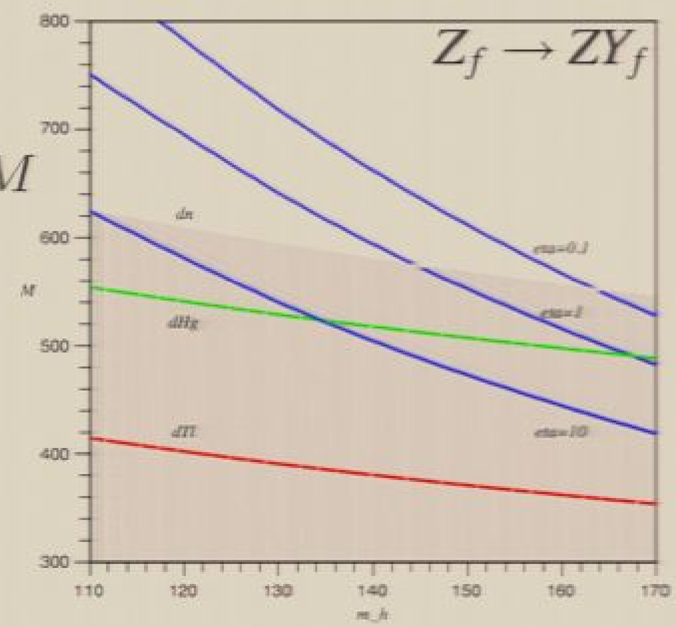
CP-odd top-Higgs coupling

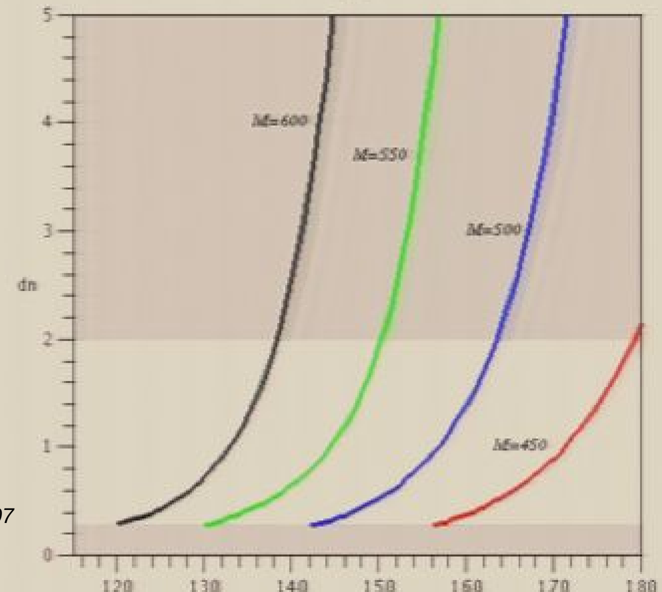
Assuming MFV structure

Constraints



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





[Huber, Pospelov, AR, to appear]

Next-generation EDM sensitivity:

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

Concluding Remarks

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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.