

Title: Particle Physics 2

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Abstract:

# Probing new CP-odd thresholds with electric dipole moments

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University of Victoria



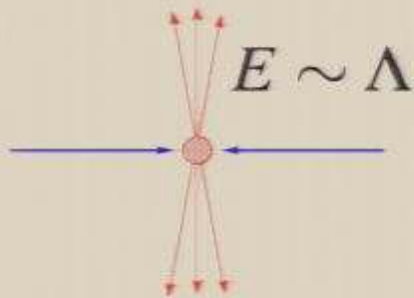
University  
of Victoria

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

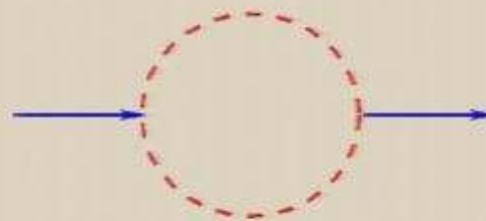
# Precision Tests as Probes for New Physics

Searches for new physics (at energy scale  $\Lambda$ ):

## 1. Colliders



## 2. Precision Tests



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

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:

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

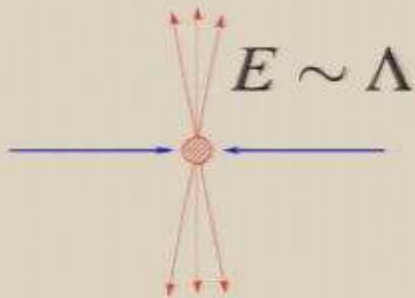
$$M_\nu = \frac{v^2}{\Lambda} Y$$

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

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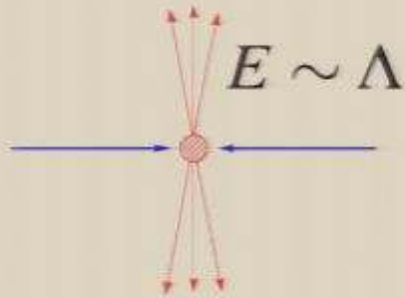
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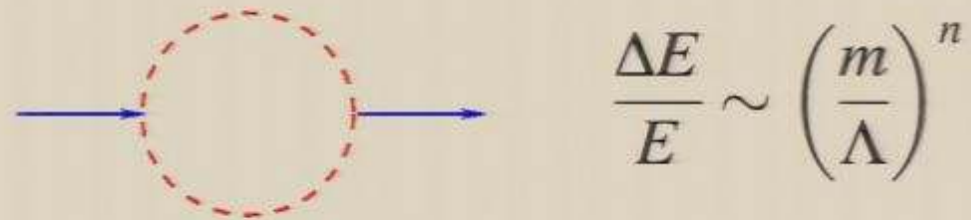
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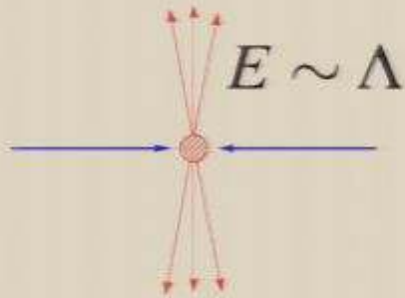
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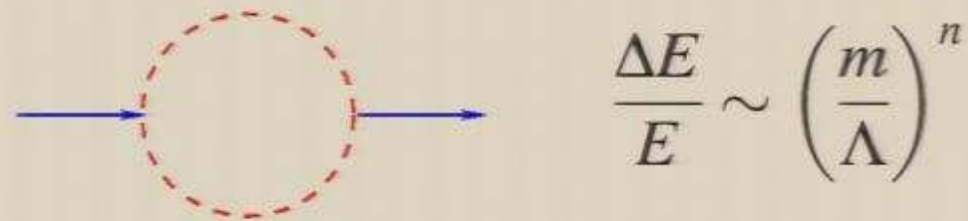
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# In this talk ...

... we'll look at new CP-odd thresholds  $\Leftrightarrow$ 

- baryogenesis
- generic phases in “UV completions” of SM

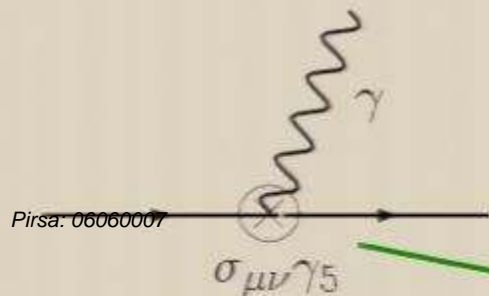
**Assumption:** non-CKM CP-violation is “*irrelevant*”

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

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

NB: Small SM background (via CKM phase)

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

[Khriplovich & Zhitnitsky '86]

# Future experimental progress

- Paramagnetic atoms & molecules

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

- Neutron

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

- Diamagnetic atoms

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

Deuteron	$d_D \sim 10^{-29} e \text{ cm}$	[SR EDM collab. (BNL)]
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+ 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:  $\bar{\theta} \alpha_s G \tilde{G}$

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

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

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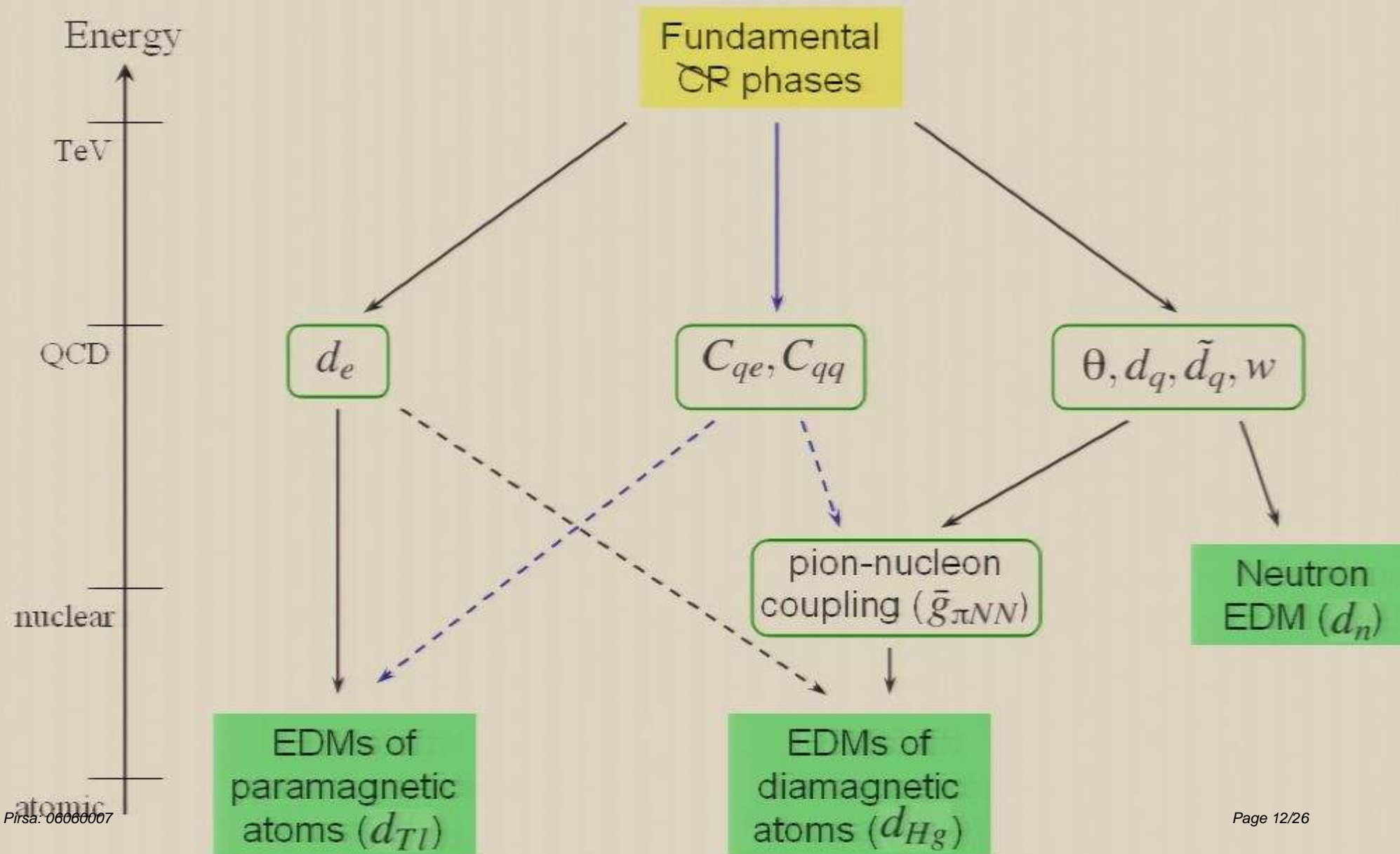
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# Origin of the EDMs



# Computations

## 1. TI EDM (paramagnetic) (atomic)

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

$$\alpha^2 Z^3$$

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

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

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

[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]

$$\bar{g}_{\pi NN}(\tilde{d}_q) \sim (1 - 6)(\tilde{d}_u - \tilde{d}_d) + O(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w) \quad [\text{Pospelov '01}]$$

# Constraints on TeV-Scale models

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

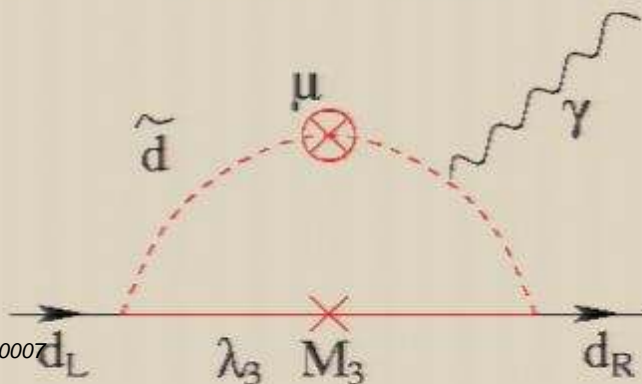
$$\Delta\mathcal{L} \sim -\mu \tilde{H}_1 \tilde{H}_2 + B\mu H_1 H_2 + h.c. \quad \text{Complex} \Rightarrow \text{CP-odd phases}$$

$$-\frac{1}{2} \left( M_3 \tilde{\lambda}_3 \lambda_3 + M_2 \tilde{\lambda}_2 \lambda_2 + M_1 \tilde{\lambda}_1 \lambda_1 \right) + h.c.$$

$$-A_{ij}^d H_1 \tilde{q}_{Li} \tilde{q}_{Rj} + h.c. + \dots$$

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

- EG: 1-loop EDM contribution:



[Ellis, Ferrara & Nanopoulos '82]

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

$M \sim$  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:

$$\mathcal{W} = \mathcal{W}_{MSSM} + \frac{y_h}{\Lambda} (H_u H_d)^2 + \frac{Y^{qe}}{\Lambda} Q U L E + \frac{Y^{qq}}{\Lambda} Q U Q D + \textit{seesaw} + \textit{baryon}$$

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

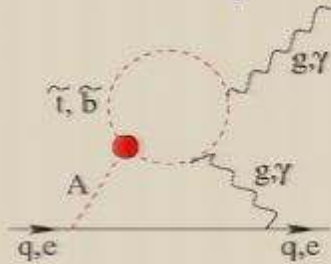
$$d_f \sim \frac{m_{f'}}{m_{soft} \Lambda}$$

- Sensitivity depends on flavor structure of  $Y^{ff}$ 
  - we will assume  $Y^{ff'} \neq Y_f Y_{f'} \sim 1$

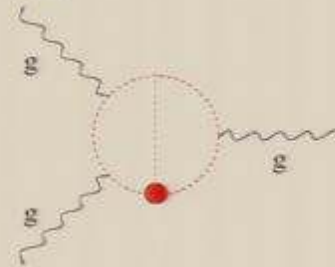
# SUSY CP Constraints

Decoupling 1st/2nd generation

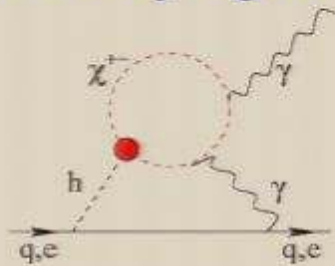
[Chang, Keung & Pilaftsis '98]



[Weinberg '89; Dai et al. 90]



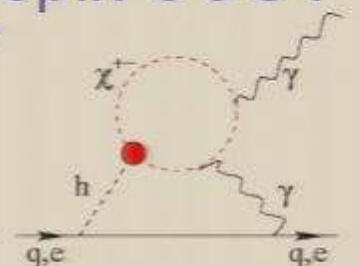
EW baryogenesis



MSSM parameter space

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

split SUSY



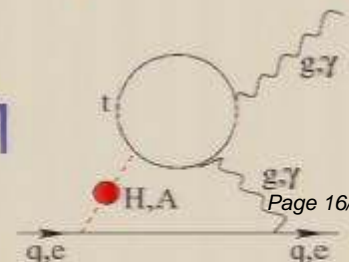
[Barr, Zee '92]

[Barr '92; Lebedev & Pospelov '02]



large  $\tan\beta$

2 HDM



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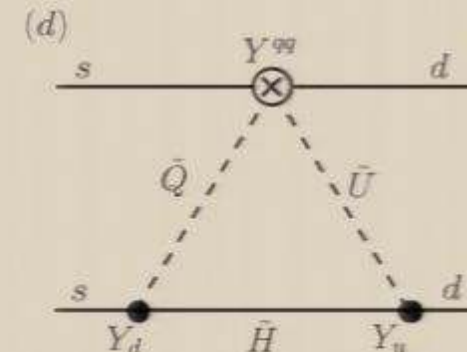
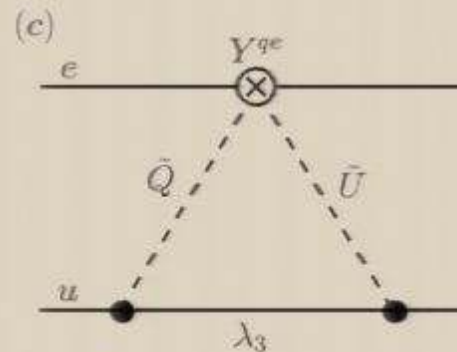
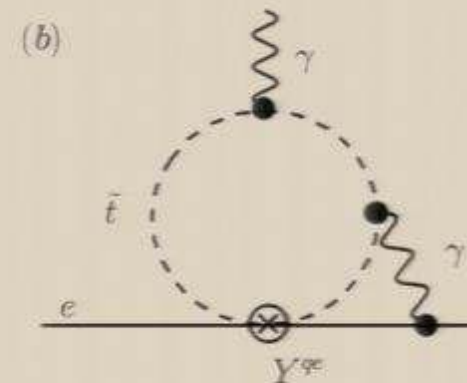
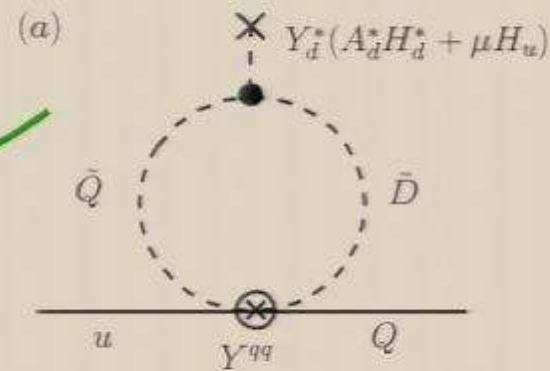
$$d_f \sim \frac{m_{f'}}{m_{soft} \Lambda}$$

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# SUSY threshold sensitivity

Dimension-3,6 operators generated at the soft threshold

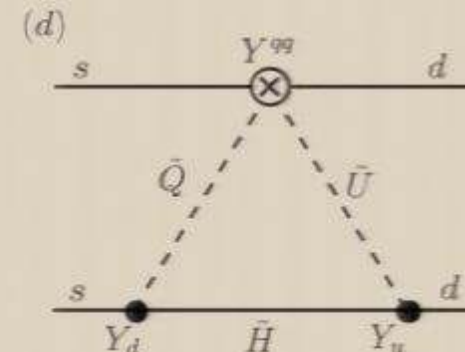
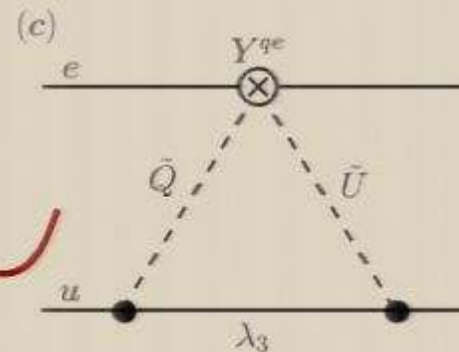
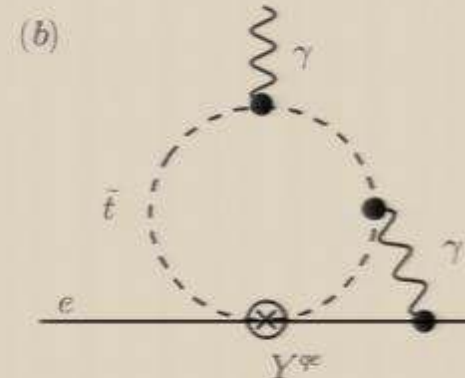
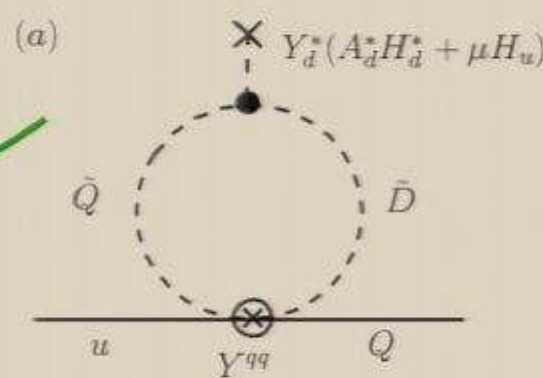
$$\Delta m_e \sim m_e \Rightarrow \Lambda > 10^6 \text{ GeV}$$



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$$d_{Tl}(C_S), d_{Hg}(C_S), \mu \rightarrow e$$


$$\Rightarrow \Lambda > 10^8 \text{ GeV}$$

# SUSY threshold sensitivity

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

[Pospelov, AR, Santos '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

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

[Archambault, Czarnecki & Pospelov '04]

# Minimal EW Baryogenesis

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

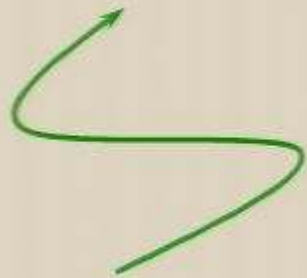
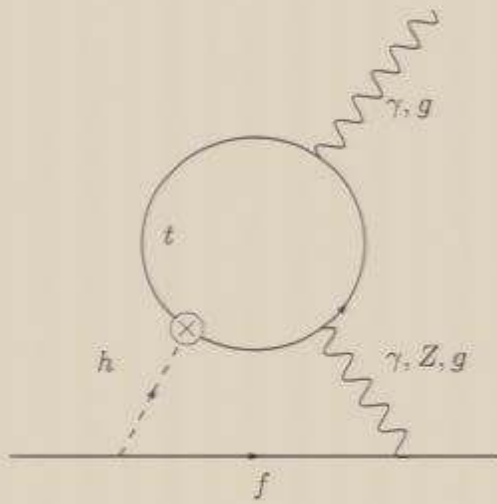
⇒ makes predictions for the top-Higgs coupling, cf. LHC

## Questions:

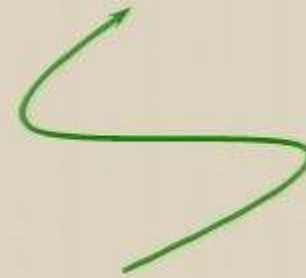
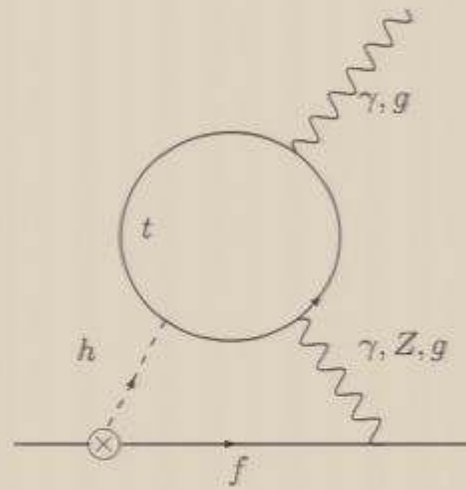
Tuning of other operators at such low thresholds ?

Do EDM bounds really allow such a scenario ?

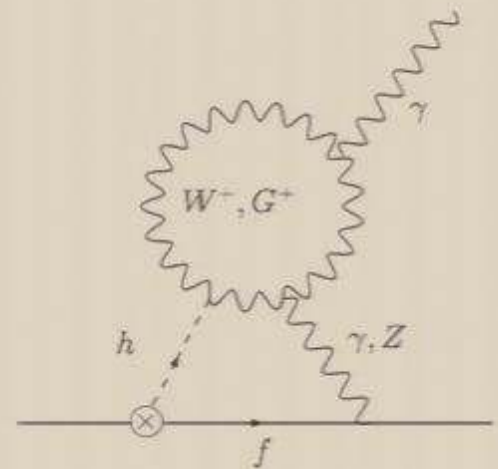
# Barr-Zee diagrams



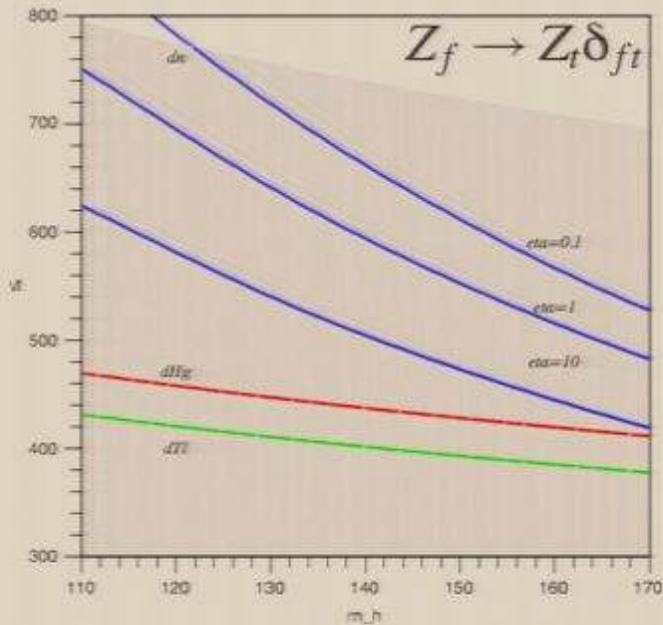
CP-odd top-Higgs coupling



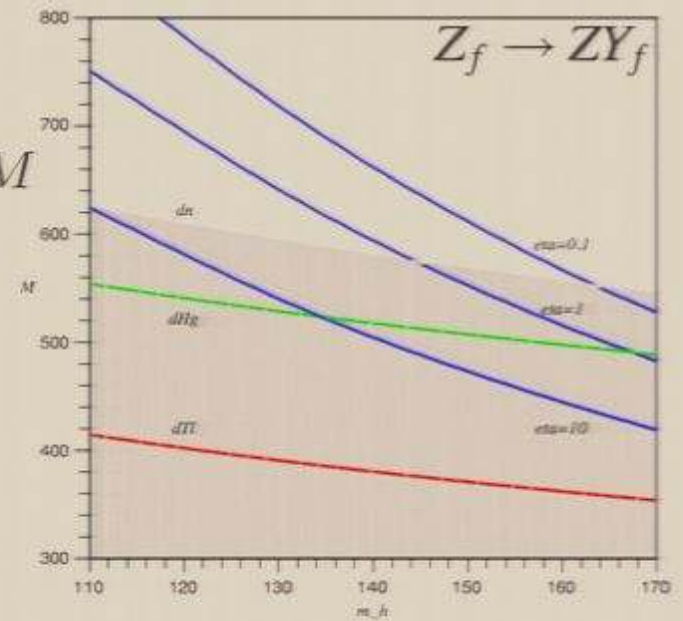
Assuming MFV structure



# Constraints



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



[Huber, Pospelov, AR, to appear]

Next-generation EDM sensitivity:

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

## Concluding Remarks

- Precision tests can play a crucial role in probing fundamental symmetries at scales well beyond the reach of colliders.
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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  $\text{dim}=6$  extension of the SM.

next-generation expts will provide a conclusive test.