EDMs in Supersymmetric Models

Maxim Pospelov

Perimeter Institute/University of Victoria

for a recent review, see *M. Pospelov and A. Ritz, Annals of Physics 2005*

Plan

1. Introduction. Current and future EDM measurements.
2. EDMs due to CP violation in the soft-breaking sector.
3. EDMs due to CP violation in the superpotential.
4. Baryon Asymmetry of the Universe and EDMs.
5. Conclusions.

Why bother with EDMs?

Is the accuracy sufficient to probe TeV scale and beyond?

Typical energy resoultion in modern EDM experiments

$$\Delta\text{Energy} \sim 10^{-6}\text{Hz} \sim 10^{-21}\text{eV}$$

translates to limits on EDMs

$$|d| < \frac{\Delta\text{Energy}}{\text{Electric field}} \sim 10^{-25}\text{e} \times \text{cm}$$

Comparing with theoretically inferred scaling,

$$d \sim 10^{-2} \times \frac{1\text{ MeV}}{\Lambda_{CP}^2},$$

we get **sensitivity to**

$$\Lambda_{CP} \sim 1\text{ TeV}$$

Comparable with the LHC reach!

Electric Dipole Moments

Purcell and Ramsey (1949) ("How do we know that strong interactions conserve parity?" $\longrightarrow |d_n| < 3 \times 10^{-18} e$cm.)

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

$d \neq 0$ means that both P and T are broken. If CPT holds then CP is broken as well.

CPT is based on locality, Lorentz invariance and spin-statistics = very safe assumption.

search for EDM = search for CP violation, if CPT holds

Relativistic generalization

$$H_{\rm T,P-odd} = -d\mathbf{E} \cdot \frac{\mathbf{S}}{S} \rightarrow \mathcal{L}_{\rm CP-odd} = -d\frac{i}{2}\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu},$$

corresponds to dimension five effective operator and naively suggests $1/M_{\rm new\ physics}$ scaling. Due to $SU(2) \times U(1)$ invariance, however, it scales as m_f/M^2.

Current Experimental Limits

"paramagnetic EDM", Berkeley experiment

$$|d_{\rm Tl}| < 9 \times 10^{-25} e\,{\rm cm}$$

"diamagnetic EDM", U of Washington experiment

$$|d_{\rm Hg}| < 2 \times 10^{-28} e\,{\rm cm}$$

neutron EDM, ILL-based experiment

$$|d_n| < 3 \times 10^{-26} e\,{\rm cm}$$

Despite widely different numebrs, the interplay of atomic and nuclear physics leads to the approximately the same level of sensitivity to constitutents, $d_q \sim O(10^{-26})e$cm.

(In addition, there are valuable but less sensitive results from Michigan (Xe), Leningrad (n), Amherst College (Cs), ...)

Expansion of experimental EDM program

Paramagnetic EDMs (electron EDM):
PbO, Yale; $d_e \sim 10^{-30} e\text{cm}$
YbF, IC UL; $d_e \sim 10^{-29} e\text{cm}$
Solid State experiments, LANL, $d_e \sim 10^{-31} e\text{cm}$
Rb and Cs in optical lattices....

Diamagnetic EDMs:
Hg, U of Washington; $d_{\text{Hg}} \sim 10^{-29} e\text{cm}$
Rn, TRIUMF et al., $d_{\text{Rn}} \sim 10^{-27} e\text{cm}$
Ra, Argonne, $d_{\text{Ra}} \sim 10^{-27} e\text{cm}$
Liquid Xe idea, Princeton...

nuclear EDMs:
neutron, ILL-based and PSI-based; $d_{\text{n}} \sim 10^{-27} e\text{cm}$
neutron, LANL-Oak Ridge; $d_{\text{n}} \sim 10^{-28} e\text{cm}$
New BNL project with D in storage ring, $d_{\text{D}} \sim 10^{-28} e\text{cm}$.

Muon EDM down to $10^{-24} e\text{cm}$.

CP violation via in CKM matrix

There are two possible sources of CP violation at a renormalizable level: δ_{KM} and θ_{QCD}.

δ_{KM} is the form of CP violation that appears only in the charged current interactions of quarks.

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{U}_L \not{W}^+ V D_L \, + \, (\text{H.c.}) \right).$$

CP violation is closely related to flavour changing interactions.

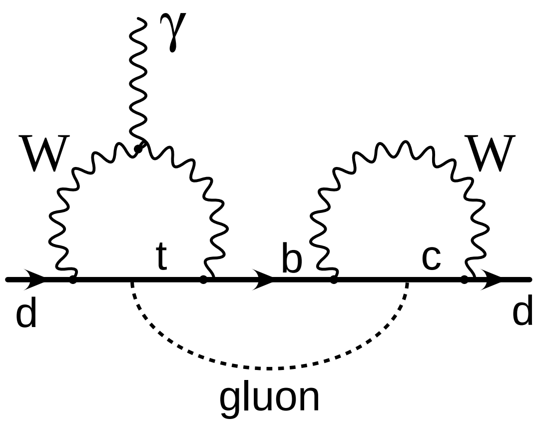
$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

CKM model of CP violation is independenly checked using nutral K and B systems. *No other sources of CP are needed to describe observables!*

CP violation disappear if any pair of the same charge quarks is degenerate or some mxing angles vanish.

$$J_{CP} = \text{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*)\times$$
$$(y_t^2 - y_c^2)(y_t^2 - y_u^2)(y_c^2 - y_u^2)(y_b^2 - y_s^2)(y_b^2 - y_d^2)(y_s^2 - y_d^2)$$
$$< 10^{-15}$$

Why EDMs are important



CKM phase generates tiny EDMs:

$$d_d \sim \mathrm{Im}(V_{tb}V_{td}^*V_{cd}V_{cb}^*)\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$

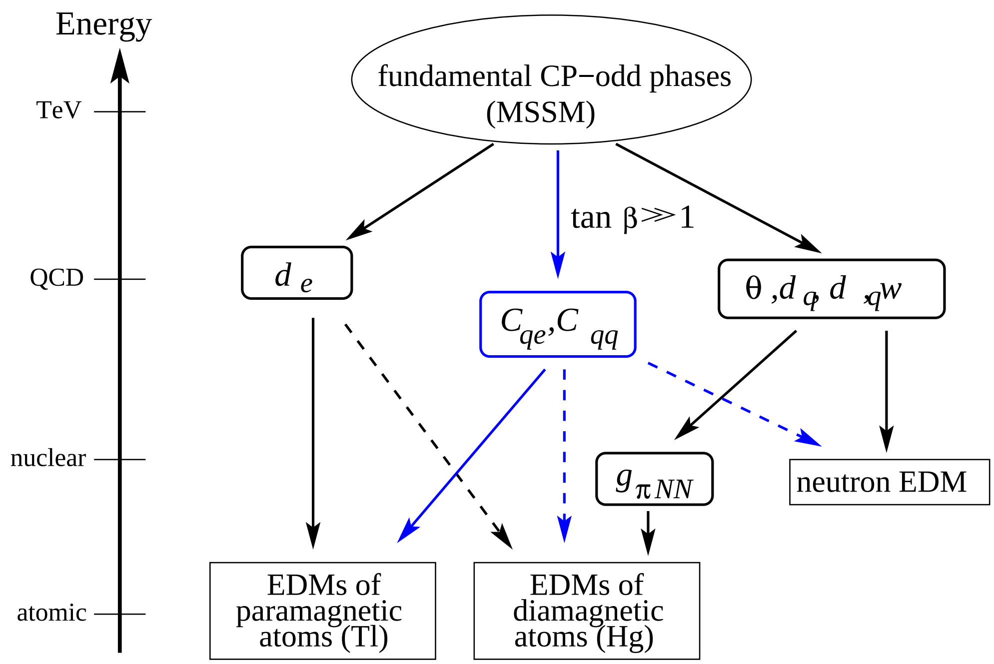
$$< 10^{-33} e\text{cm}$$

EDMs do not have δ_{KM}-induced background. On a flip-side, δ_{CKM} cannot source baryogenesis.

EDMs test

1. Extra amount of CP violation in many models beyond SM
2. Some theories of baryogenesis
3. Mostly *scalar-fermion* interactions in the theory
4. EDMs are one of the very few low-energy probes that are sensitive to energy scale of new physics beyond 1 TeV

From SUSY to an atomic/nuclear EDM



Hadronic scale, 1 GeV, is the normalization point where perturbative calculations stop.

Effective CP-odd Lagrangian at 1 GeV

Khriplovich et al., Weinberg,... Appying EFT, one can classify *all CP-odd operators of dimension 4,5,6,...* at $\mu = 1$ GeV.

$$\mathcal{L}_{eff}^{1\text{GeV}} = \frac{g_s^2}{32\pi^2}\,\theta_{QCD} G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a}$$
$$-\frac{i}{2}\sum_{i=e,u,d,s} d_i\,\overline{\psi}_i(F\sigma)\gamma_5\psi_i - \frac{i}{2}\sum_{i=u,d,s}\widetilde{d}_i\,\overline{\psi}_i g_s(G\sigma)\gamma_5\psi_i$$
$$+\frac{1}{3}w\; f^{abc}G^a_{\mu\nu}\widetilde{G}^{\nu\beta,b}G_\beta{}^{\mu,c} + \sum_{i,j=e,d,s,b} C_{ij}\,(\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j) + \cdots$$

If the model of new physics is specified, for example, a specific paparameter space point in the SUSY model, Wilson coefficients $d_i, \tilde{d}_i$, etc. can be calculated.

To get beyond simple estimates, one needs $d_{n,\ atom}$ as a function of $\theta, d_i, \tilde{d}_i, w, C_{ij}$, which requires non-perturbative calculations.

Strong CP problem

Energy of QCD vacuum depends on θ-angle:

$$E(\bar{\theta}) = -\frac{1}{2}\bar{\theta}^2 m_* \langle \bar{q}q \rangle + \mathcal{O}(\bar{\theta}^4, m_*^2)$$

where $\langle \bar{q}q \rangle$ is the quark vacuum condensate and m_* is the reduced quark mass, $m_* = \frac{m_u m_d}{m_u + m_d}$. In CP-odd channel,

$$d_n \sim e \frac{\bar{\theta} m_*}{\Lambda_{\rm had}^2} \sim \bar{\theta} \cdot (6 \times 10^{-17})\, e\,{\rm cm}$$

Strong CP problem = naturalness problem = Why $|\bar{\theta}| < 10^{-9}$ when it could have been $\bar{\theta} \sim O(1)$? $\bar{\theta}$ can keep "memory" of CP violation at Planck scale and beyond. Suggested solutions

- Minimal solution $m_u = 0 \leftarrow$ apparently can be ruled out by the chiral theory analysis of other hadronic (CP-even) observables.
- $\bar{\theta} = 0$ by construction, requiring either exact P or CP at high energies + their spontaneous breaking. Tightly constrained scenario.
- Axion, $\bar{\theta} \equiv a(x)/f_a$, relaxes to $E = 0$, eliminating theta term. $a(x)$ is a very light field. Not found so far.

Does SUSY add anything conceptually new to the story of Strong CP problem?

Models that have $\bar{\theta} = 0$ built-in by construction (exact parity and/or exact CP, spontanepously broken at the scale Λ_{CP}) are sensitive to radiative corrections to $\bar{\theta}$. There are more possibilities for creating a substantially non-zero $\bar{\theta}_{rad}$ through the soft-breaking phases. Yet in the models where s.b. phases are nil, and $\Lambda_{SUSY\ breaking} \ll \Lambda_{CP}$, corrections to $\bar{\theta}$ are suppressed due to non-renormalization theorems.

Synopsis of EDM formulae

Thallium EDM:
The Schiff (EDM screening) theorem is violated by relativistic (magnetic) effects. Atomic physics to 10 − 20% accuracy gives

$$d_{\rm Tl} = -585 d_e - e\ 43\ {\rm GeV} C_S^{(0)}$$

where C_S is the coefficient in front of $\bar{N}Ni\bar{e}\gamma_5 e$. Parametric growth of atomic EDM is $d_e \times \alpha^2 Z^3 \log Z$.

neutron EDM:
∼50-100% level accuracy QCD sum rule evaluation of d_n is available. Ioffe-like approach gives

$$d_n = -\frac{e m_* \bar\theta}{2\pi^2 f_\pi^2};\ d_n = \frac{4}{3}d_d - \frac{1}{3}d_u - e\left(\frac{m_n}{2\pi f_\pi}\right)^2\left(\frac{2}{3}\tilde d_d + \frac{1}{3}\tilde d_u\right)$$

(Reproduces naive quark model and comes close to chiral-log estimates)

Mercury EDM: Screening theorem is avoided by the finite size of the nucleus

$$d_{\rm Hg} = d_{\rm Hg}\left(S(\bar g_{\pi NN}[\tilde d_i, C_{q_1q_2}]),\, C_S[C_{qe}],\, C_P[C_{eq}],\, d_e\right).$$

For most models $\bar g_{\pi NN}$ is the most important source. The result is dominated by $\tilde d_u - \tilde d_d$ but the uncertainty is large:

$$d_{\rm Hg} = 7\times 10^{-3}\, e\,(\tilde d_u - \tilde d_d) + ...$$

Better accuracy for diamagnetic EDMs can only be achieved via a more precise value for

$$\langle 0|\bar{q}q|0\rangle\langle N|\bar{q}(G\sigma)q|N\rangle - \langle N|\bar{q}q|N\rangle\langle 0|\bar{q}(G\sigma)q|0\rangle$$

CP violation from the soft-breaking

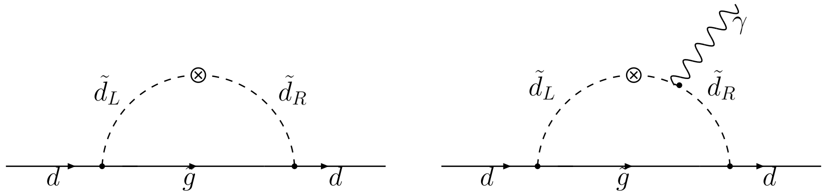
Generic MSSM contains many soft-breaking parameters, including $O(40)$ (?) complex phases.

$$\mathcal{L} = -\mu\bar{\tilde{H}}_d\tilde{H}_u + B\mu H_d H_u + (h.c.)$$
$$-\frac{1}{2}\left(M_3\bar{\lambda}_3\lambda_3 + M_2\bar{\lambda}_2\lambda_2 + M_1\bar{\lambda}_1\lambda_1\right) + (h.c.)$$
$$-A^d H_d\tilde{Q}\tilde{d} + (h.c.) + ...$$

With the flavour and gaugino mass universality assumption, the number of free phases reduces to 2, $\{\theta_\mu,\ \theta_A\}$.

Anatomy of SUSY EDMs

All one-loop and most important ($\tan\beta$-enhanced) two-loop diagrams have been computed.



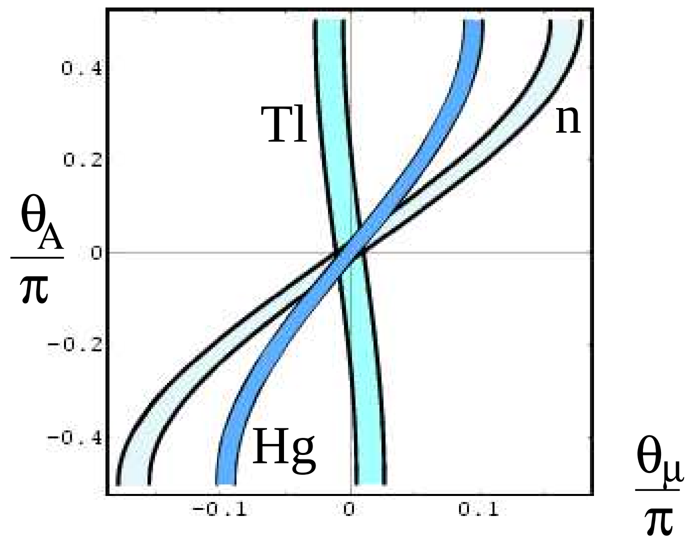
$$\frac{d_e}{e\kappa_e} = \frac{g_1^2}{12}\sin\theta_A + \left(\frac{5g_2^2}{24}+\frac{g_1^2}{24}\right)\sin\theta_\mu \tan\beta,$$
$$\frac{d_q}{e_q\kappa_q} = \frac{2g_3^2}{9}(\sin\theta_\mu[\tan\beta]^{\pm1} - \sin\theta_A) + O(g_2^2, g_1^2), \quad (1)$$
$$\frac{\tilde{d}_q}{\kappa_q} = \frac{5g_3^2}{18}(\sin\theta_\mu[\tan\beta]^{\pm1} - \sin\theta_A) + O(g_2^2, g_1^2).$$

The notation $[\tan\beta]^{\pm1}$ implies that one uses the plus(minus) sign for $d(u)$ quarks, g_i are the gauge couplings, and $e_u = 2e/3$, $e_d = -e/3$. All these contributions to d_i are proportional to κ_i,

$$\kappa_i = \frac{m_i}{16\pi^2 M_{\rm SUSY}^2} = 1.3\times10^{-25}{\rm cm}\times\frac{m_i}{1{\rm MeV}}\left(\frac{1{\rm TeV}}{M_{\rm SUSY}}\right)^2.$$

Combining constraints together

In the model where at the weak scale all superpartners have one and the same mass, $M_{\rm SUSY}$, both CP-odd phases of the MSSM are tightly constrained



The combination of the three most sensitive EDM constraints, d_n, $d_{\rm Tl}$ and $d_{\rm Hg}$, for $M_{\rm SUSY} = 500$ GeV, and $\tan\beta = 3$. The region allowed by EDM constraints is at the intersection of all three bands around $\theta_A = \theta_\mu = 0$.

"SUSY CP Problem"

"Overproduction" of EDMs in SUSY models imply that

$$\sin(\delta_{\rm CP}) \times \left(\frac{1\ \rm TeV}{M_{\rm SUSY}}\right)^2 < 1,$$

and been dubbed the SUSY CP problem.

Possible solutions:

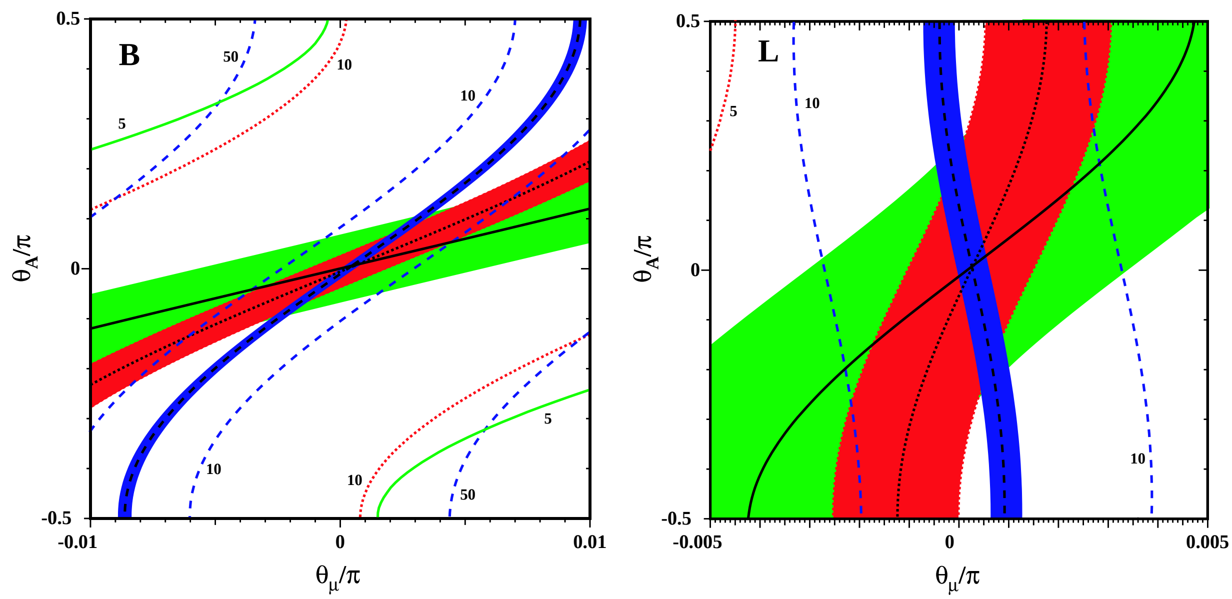
1. *No SUSY around the weak scale.*
2. *Phases are small.* Models of SUSY breaking are arranged in such a way that $\delta_{\rm CP} \simeq 0$.
3. *Superpartner masses are very heavy* - in a multi-TeV range.
4. *Accidental cancellations.* Unlikely in all three observables.

Turning numerical with CMSSM

CMSSM (or mSUGRA) = constrained (compassionate?) minimal supersymmetric standard model.

$$108 \text{ parameters} \longrightarrow (\tan\beta,\ m_0,\ m_{1/2},\ |A_0|,\ \theta_A,\ \theta_\mu).$$

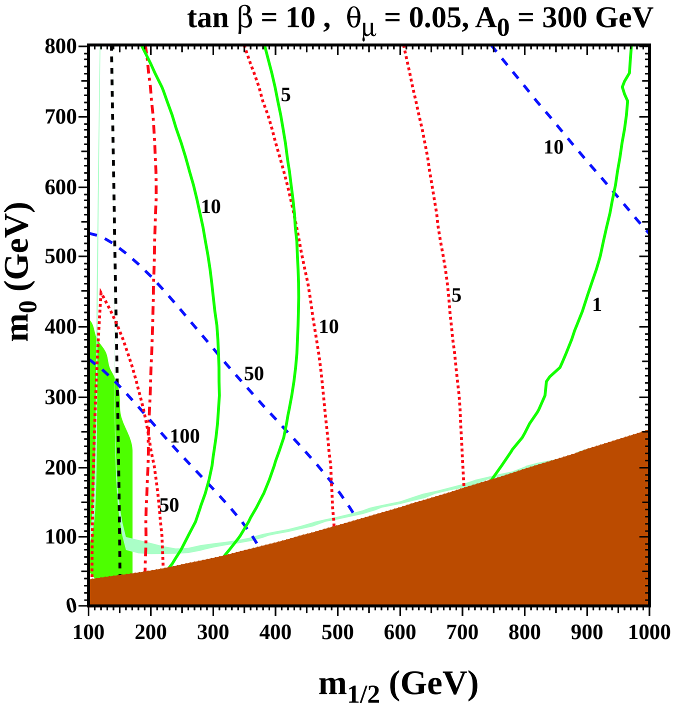
Benchamrk point B: $\tan\beta$=10, $m_{1/2} = 250$ GeV, $m_0 = 65$ GeV
Benchmark point L: $\tan\beta$=50, $m_{1/2} = 450$ GeV, $m_0 = 310$GeV.

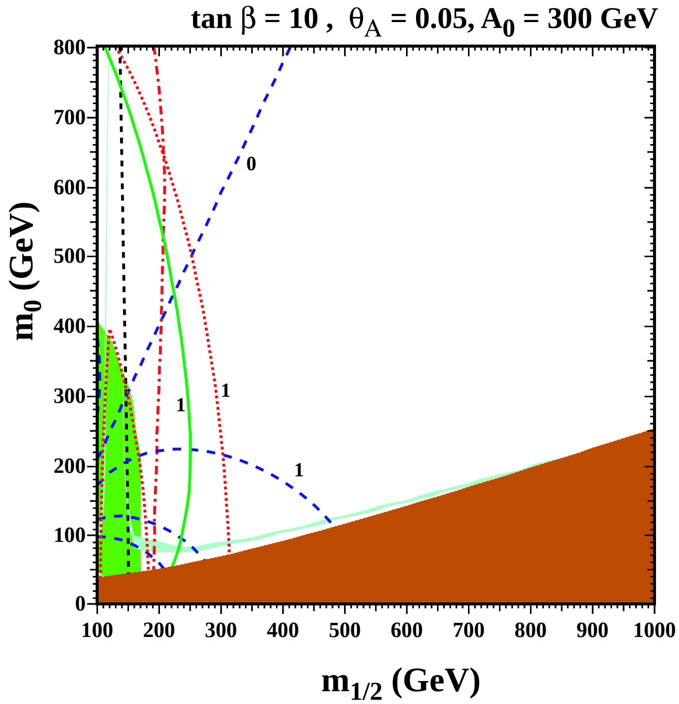


Electron (or Tl) EDM is more constraining because
$m^2_{\text{squark}} \simeq m_0^2 + (2.5 m_{1/2})^2$,
$m^2_{\text{selectron}} \simeq m_0^2 + (0.4 m_{1/2})^2$,
and usually sleptons are several times *lighter* than squarks.
Phase of μ is significantly more constrained.

Scan of m_0 and $m_{1/2}$ in 1 TeV $\times$ 1 TeV

Contours of ratios $d_i/|d_i^{\mathrm{exp\ limit}}|$.





Contours of d_i in extended plots (not shown) in some cases (large $\tan\beta$, large θ_μ remain > 1 beyond 10 TeV.

Favorite spots in the parameter space

First and Second generation squarks are decoupled. Two-loop diagrams involving stops and sbottoms are operative (Weinberg; Barr, Zee; Dai et al.; Chang, Keung, Pilaftsis...) Enhancement by $\tan\beta$

All squarks and extra Higgses are decoupled (split-susy). Two-loop diagrams with chargino are operative (Chang, Chang, Keung; Giudice, Romanino...). Close to current experimental bound.

All superpartners are decoupled, MSSM $\rightarrow$ 2HDM. A, H Higgs exchange becomes important source of CP violation, and grows as $\tan^3\beta$ (Barr; Pospelov and Lebedev; Babu and Kolda...)

...

Interplay of flavour and CP physics in the soft-breaking. New flavour structures due to i.e. Yukawa Unification, RH neutrinos, Left-Right symmetry, etc. leave an imprint on the squark and slepton mass matrices via RG evolution, which feed back to EDMs and FCNCs at the superpartner threshold.

Dimension 5 operators in superpotential

MSSM is an effective theory. Even if the soft-breaking sector tuned/constructed to have no CP-violation, higher-dimensional effective operators can generate EDMs. Some of these operators, $QQQL$, $DDUE$, LH_uLH_u, have been studied extensively in connection with proton decay and neutrino masses.

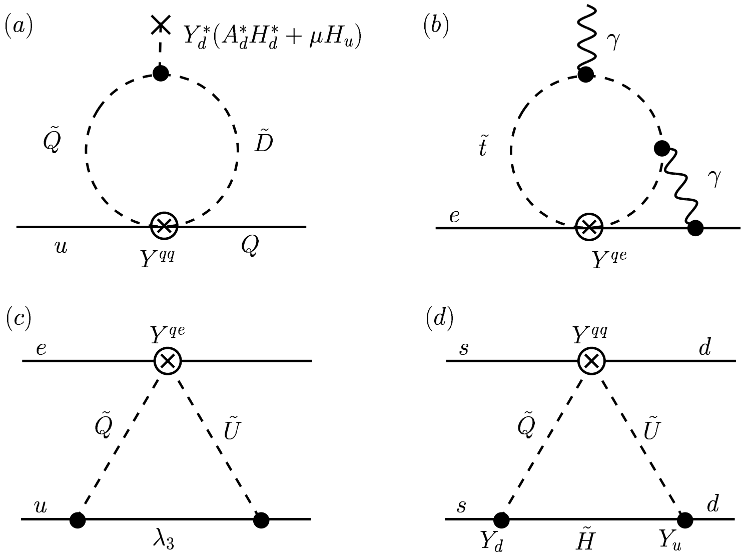
Extra dim=5 operators capable of inducing EDMs:

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + \frac{y_h}{\Lambda_h} H_d H_u H_d H_u + \frac{Y^{qe}}{\Lambda_{qe}} (UQ)EL$$

$$\frac{Y^{qq}}{\Lambda_{qq}} (UQ)(DQ) + \frac{\tilde{Y}^{qq}}{\Lambda_{qq}} (Ut^A Q)(Dt^A Q)$$

Decoupling properties of the observables: $\sim v_{EW}/(m_{soft}\Lambda_{(5)})$.

Dim 5 of MSSM → Dim 6 of SM



$$\mathcal{L}_{CP} = -\frac{\alpha_s \mathrm{Im} Y^{qe}_{1111}}{6\pi \Lambda_{qe} m_{\rm susy}} \left[(\bar{u}u)\bar{e}i\gamma_5 e + (\bar{u}i\gamma_5 u)\bar{e}e\right]$$

Assumption of Im$Y \sim O(1)$ gives

$\Lambda^{qe} > 3 \times 10^8$ GeV	from Tl EDM
$\Lambda^{qe} > 1.5 \times 10^8$ GeV	from Hg EDM
$\Lambda^{qq} > 3 \times 10^7$ GeV	from Hg EDM

Sensitivity to New Threshold

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

In terms of sensitivity to $\Lambda_{(5)}$, EDMs are the third most sensitive observable, after proton decay and neutrino masses

"Effective" EW Baryogenesis

Suppose that the SM degrees of freedom are *the only* degrees of freedom with $m \sim 100$ GeV, and other particles are heavy, > 500 GeV.

$$\mathcal{L}_{\rm effective} = \mathcal{L}_{SM} + \sum_{CP-even} \frac{O^{(6)}}{M^2} + \sum_{CP-odd} \frac{O^{(6)}}{M'^2},$$

Can one "fix" the problems of the SM EWB this way? Are "model-independent" predictions for η_B and EDMs possible?

Yes. Servant, Wells; Bödeker et al. 2004.

$$V(\phi) = -m^2(H^\dagger H) + \lambda(H^\dagger H)^2 + \frac{1}{M^2}(H^\dagger H)^3$$

can make strong enough first order phase transition for 300 GeV $< M <$ 800 GeV.

CP violation comes from

$$\mathcal{L}_{CP} = y_t Q t_R H + \frac{1}{M^2} y_t' Q t_R H (H^\dagger H),$$

when y and y' have relative complex phase. Only the top operator is important for η_B. ${\rm Im} y_t'/M^{-2} \equiv (M')^{-2}$.

$$\mu_{B_L} \text{ would scale as } y_t v_{EW}^3/(M')^2$$

Natural level of EDMs predicted by η_B

$\eta_B(M'; M, m_h)$ vs $EDMs(M'; m_h)$

Correlated CP-even and CP-odd thresholds, $M = M'$
A: The phase is *only* in the top-Higgs sector.

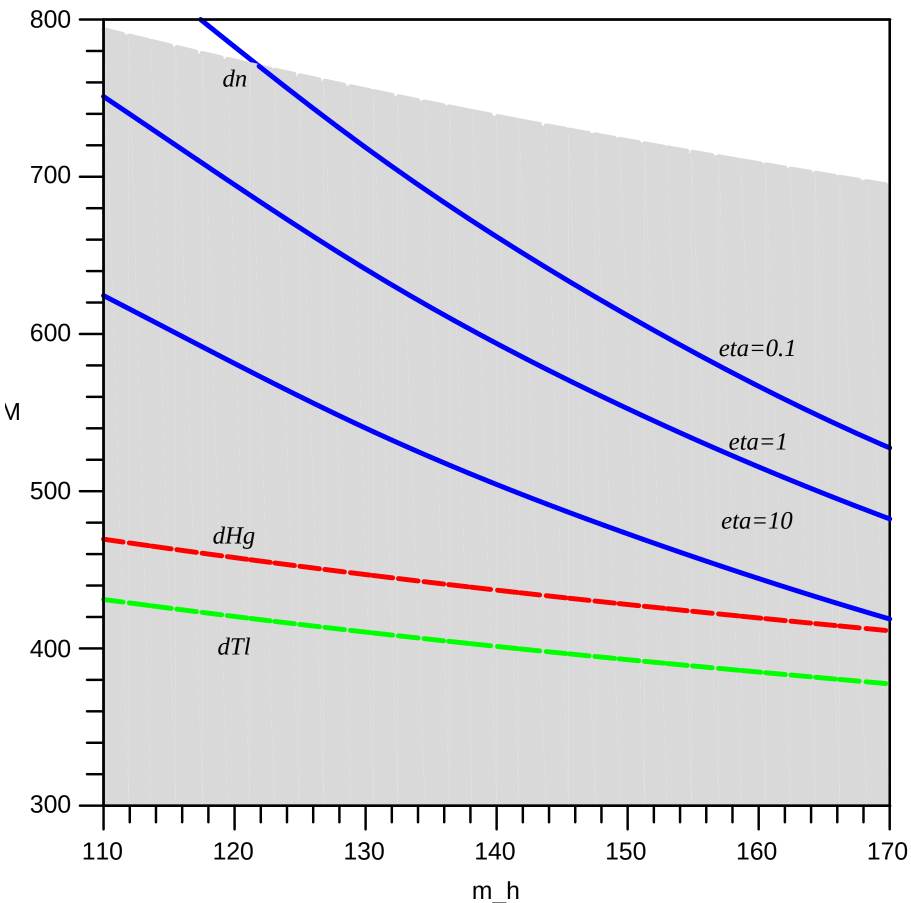
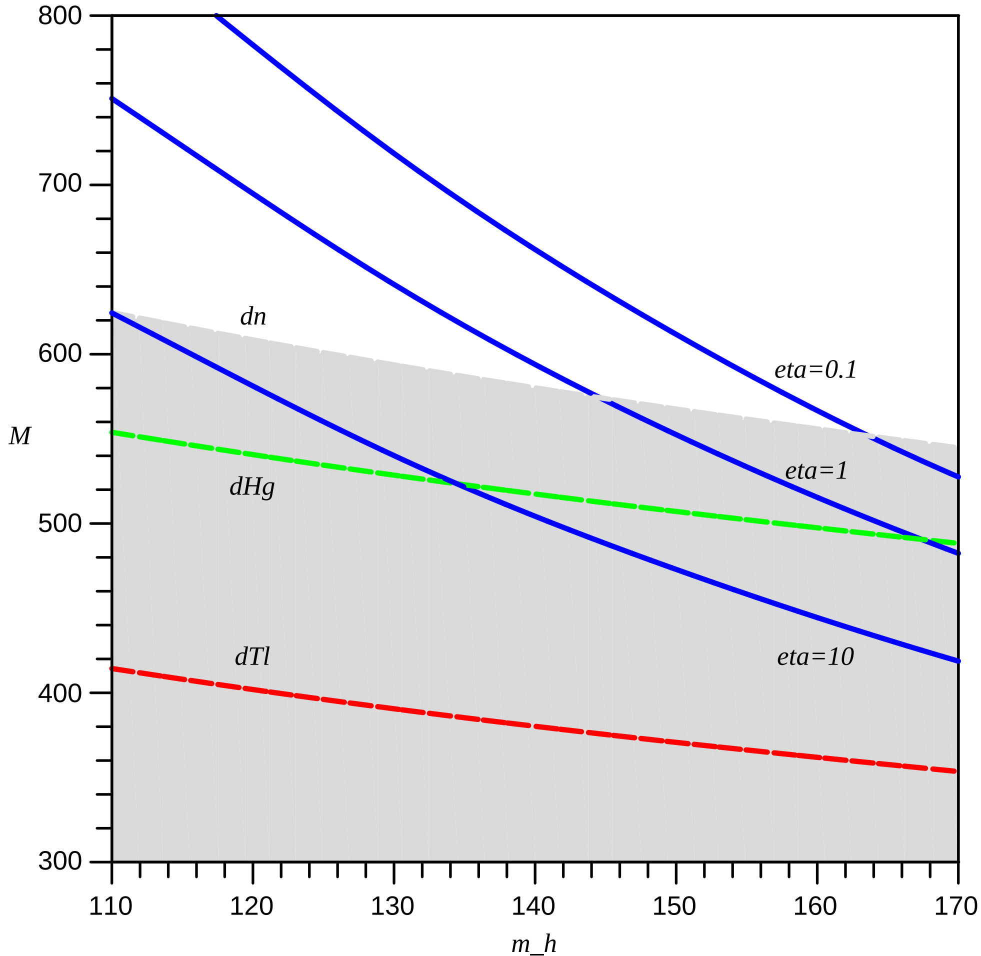


Figure 1: Contours of η_B and the EDMs over the Λ vs m_h plane, with correlated thresholds, $\Lambda_{\rm CP} = \Lambda$. On the left, we retain only a single CP-odd phase in the top-Higgs vertex, while on the right the full set imposed by assuming the Standard Model flavor structure is allowed, which allows the d_n bound to be weakened.

Correlated CP-even and CP-odd thresholds, $M = M'$
B: There is a *universal* phase in the up-Higgs sector
(Huber, Pospelov, Ritz, in preparation)



Conclusions

- **Electroweak scale SUSY can create EDMs at one loop level, well above the current experimental EDM sensitivity**
- **New generation of experiments will be able to cover even those corners of parameter space where one-loop sources are suppressed**
- **EDM probe the scale of new physics in the superpotential up to scales of 10^9 GeV**
- **Electroweak baryogenesis scenario (SUSY or not) still has some breathing space, which might be taken away by coming experimental results**