Electric Dipole Moments and New Physics

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

Plan

1. Introduction. Current EDM constraints and future directions.
2. EDMs and cosmology.
3. Effective CP-odd Lagrangian at 1GeV and EDMs. Synopsis of some EDM formulae.
4. EDMs in SUSY models. CP violation in the soft-breaking sector.
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! EDMs are one of the very few low-energy measurements sensitive to the fundamental particle physics.

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

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

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 constituents, $d_q \sim O(10^{-26})e$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; $d_e \sim 10^{-30} e\mathrm{cm}$
YbF, IC UL; $d_e \sim 10^{-29} e\mathrm{cm}$
Solid State experiments, LANL, Indiana, $d_e \sim 10^{-31} e\mathrm{cm}$
Rb and Cs in optical lattices....

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

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

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

CP violation via in CKM matrix

There are two possible sources of CP violation at the 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.

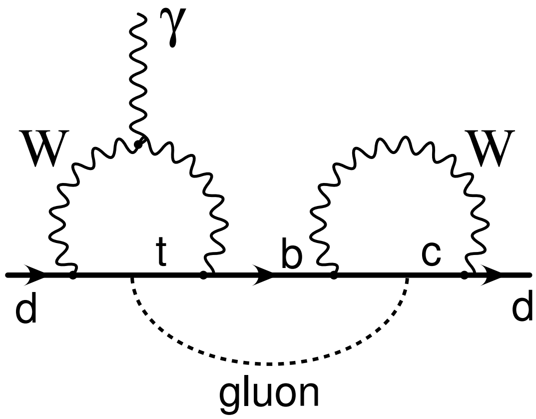
$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

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 (but not all!) 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

Baryon asymmetry of the Universe

Basic facts that are known about observable Universe:
1. $n_B \gg n_{\bar{B}}$
2. $\eta_B \equiv n_B/n_\gamma = 6.1 \pm 0.3 \times 10^{-10}$ (Any baryogenesis scenario would have mostly *theoretical* uncertainties.)
3. Fluctuations in the CMB spectrum give a strong support to an inflationary paradigm. The *initial* state of the Universe according to inflation was vacuum-like, and therefore B-$\bar{B}$ symmetric. Baryogenesis is needed!

Baryogenesis $\equiv$ a process that transfers intial baryo-symmetric state of the universe to a state with $n_B - n_{\bar{B}} > 0$.

Baryons can be generated dynamically ! (Sakharov, 1967)
Three Sakharov's conditions for baryogensis
1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

First three conditions are *in principle* satisfied within Standard Model at $T \sim 100$ GeV.

Could SM generate observed η_B?

No.

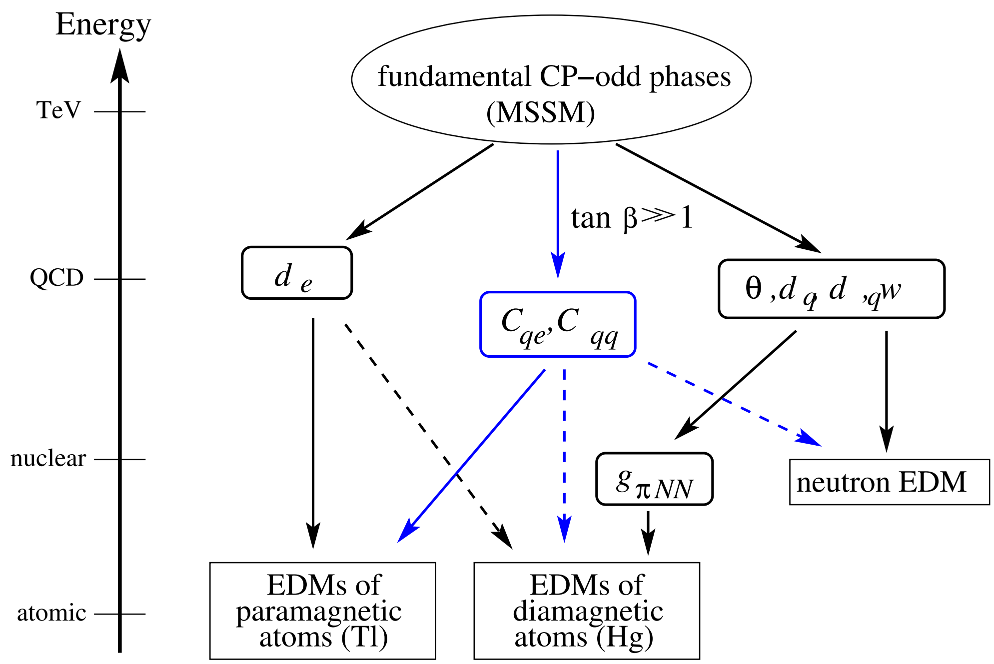
Objection 1. There is not enough CP violation. $\eta_B(\delta_{CKM})$ is suppressed by $J_{CP} < 10^{-15}$. $\eta_B(\theta_{QCD})$ is suppressed by $m_u m_d m_s m_c m_b m_t / T^6$.

Objection 2. The departure from equilibrium is *very small* because the cosntraint from LEPII, $m_h > 114$ GeV necessarily implies the *absence* of the first order electroweak phase transition.

New Physics is required
50+ scenarios have been put forward

Model of Baryogenesis	Axion required	EDMs are measurable	New Physics below TeV	$2\beta 0\nu$ decay	proton decay
GUT	+	−	−	±	+
Electroweak	+	+	+	−	−
Leptogenesis	−	−	−	+	−

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

in the spirit of Wolfenstein's superweak interaction, 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 functions of $\theta, d_i, \tilde{d}_i, w, C_{ij}$, which requires non-perturbative calculations. which I review in the next few transparencies.

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,

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

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.

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 $\bar{N}N i\bar{e}\gamma_5 e$. 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

$$d_{\rm Hg} = d_{\rm Hg}\left(S(\bar{g}_{\pi NN}[\tilde{d}_i, C_{q_1 q_2}]),\ C_S[C_{qe}],\ C_P[C_{eq}],\ d_e\right).$$

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:

$$d_{\rm Hg} = 7 \times 10^{-3}\, e\, (\tilde{d}_u - \tilde{d}_d) + \ldots$$

CP violation in softly-broken SUSY

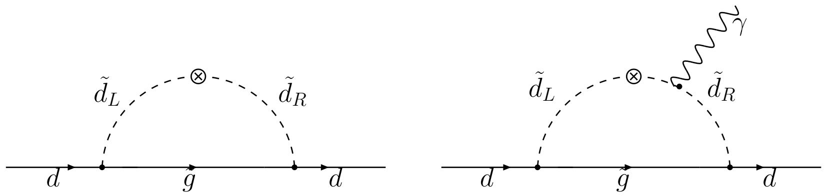
Generic MSSM contains many soft-breaking parameters, including $O(40)$ (?) complex phases.

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

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.



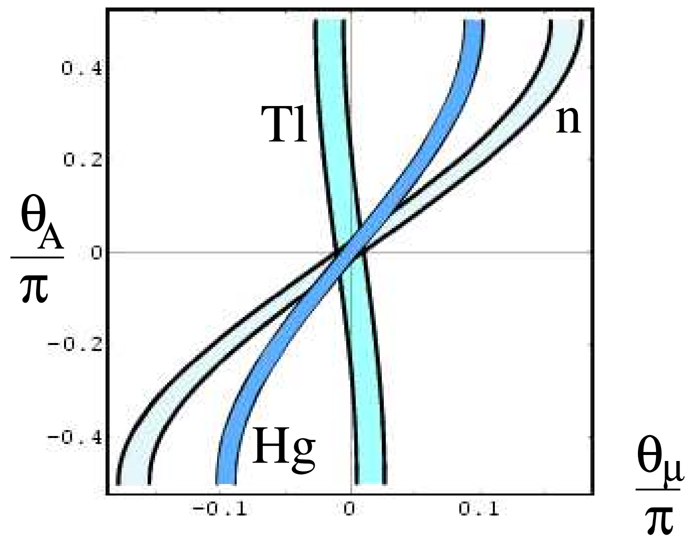
$$\begin{aligned}
\frac{d_e}{e\kappa_e} &= \frac{g_1^2}{12}\sin\theta_A + \left(\frac{5g_2^2}{24} + \frac{g_1^2}{24}\right)\sin\theta_\mu \tan\beta, \\
\frac{d_q}{e_q\kappa_q} &= \frac{2g_3^2}{9}(\sin\theta_\mu[\tan\beta]^{\pm 1} - \sin\theta_A) + O(g_2^2, g_1^2), \qquad (1) \\
\frac{\tilde{d}_q}{\kappa_q}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

The notation $[\tan\beta]^{\pm 1}$ 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,

$$\kappa_i = \frac{m_i}{16\pi^2 M_{\rm SUSY}^2} = 1.3\times 10^{-25}{\rm cm}\times \frac{m_i}{1{\rm MeV}}\left(\frac{1{\rm TeV}}{M_{\rm SUSY}}\right)^2.$$

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.

Current experimental sensitivity is on the verge of being senstitive to the two-loop effects with weak-scale particles and to the CP-odd couplings of the Higgs bosons to light fermions.

Sensitivity to scales of New Physics

Standard Model + New Physics at Λ

Phenomenon	Limit/Reach in GeV	Source
p decay	$\Lambda_{\not B} \gtrsim few \times 10^{15}$	p lifetime
ν oscillations	$\Lambda_R \sim 10^{15} - 10^{16}$	Δm_ν^2
$\Delta F = 2$ meson mixing	$\Lambda_{QF} \gtrsim 10^7 - 10^8$	$\Delta m_{K(B)}$; ϵ_K
EDMs	$\Lambda_{CP} \gtrsim 10^6$	EDMs of n, Tl, Hg
lepton flavour	$\Lambda_{LF} \gtrsim 10^6$	$\mu \to e$ conversion
PNC	$\Lambda_{Z'} \gtrsim 10^2 - 10^3$	Cs; Moller sc.

Supersymmetric SM + New Physics at Λ

Phenomenon	Limit/Reach in GeV	Source
p decay	$\Lambda_{\not B} \gtrsim 10^{24}$	SuperK
ν oscillations	$\Lambda_R \sim 10^{15} - 10^{16}$	Δm_ν^2
$\Delta F = 2$ meson mixing	$\Lambda_{QF} \gtrsim 10^7 - 10^8$	$\Delta m_{K(B)}$; ϵ_K
EDMs	$\Lambda_{CP} \gtrsim 10^8 - 10^9$	EDMs of n, Tl, Hg
lepton flavour	$\Lambda_{LF} \gtrsim 10^8$	$\mu \to e$ conversion
PNC	$\Lambda_{Z'} \gtrsim 10^2 - 10^3$	Cs; Moller sc.

"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. S. Huber, MP, A. Ritz, M. Pospelov, PRD2007

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

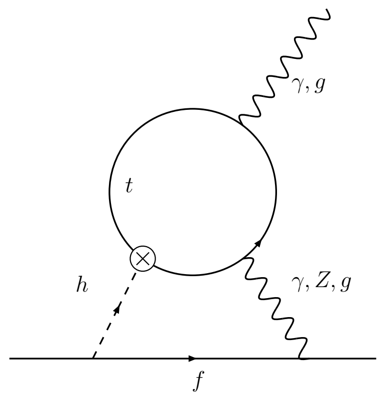
can make strong enough first order phase transition for 300 GeV $< M <$ 800 GeV.

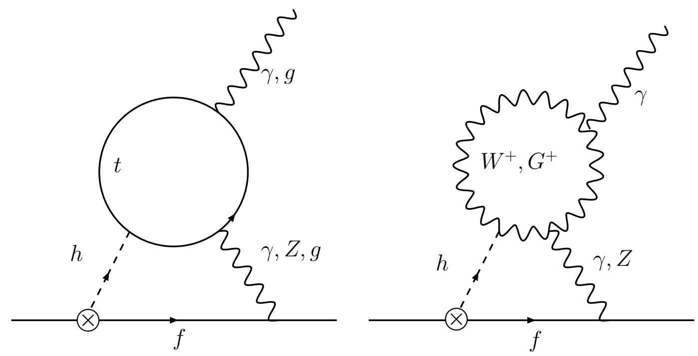
CP violation comes from

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

when y and y' have relative complex phase. Only the top operator is important for η_B.

Barr-Zee diagrams

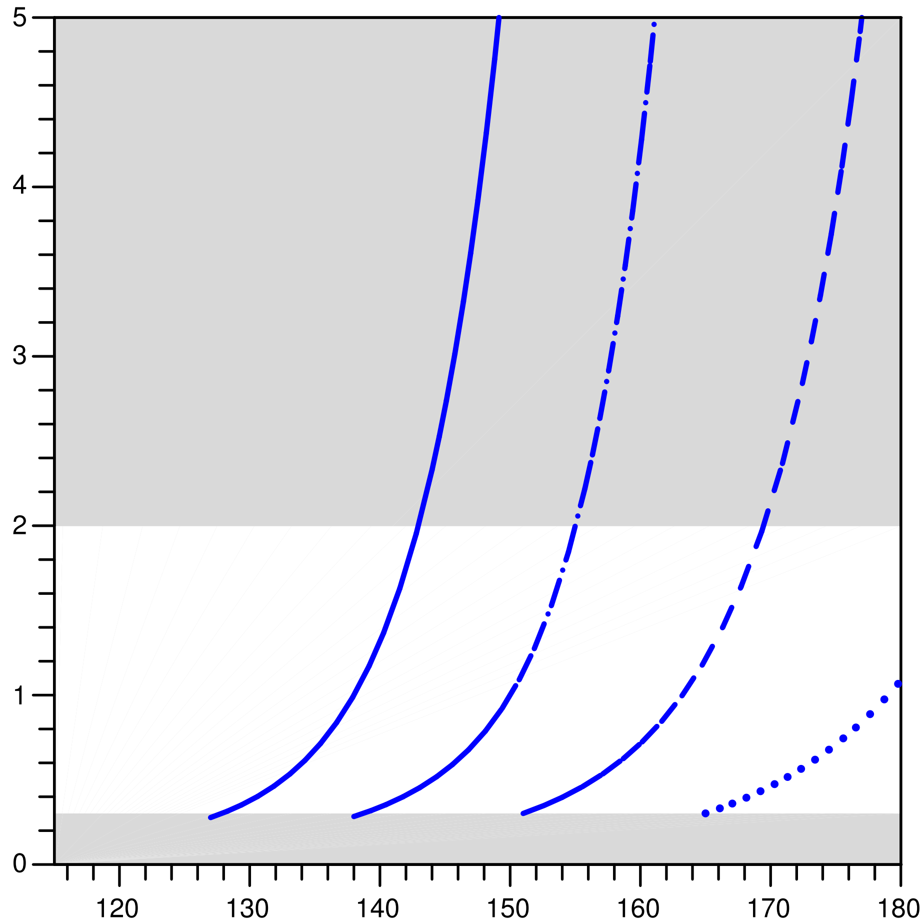




Stategy: calculate $\eta_B(M, M', m_h)$, equate it to 6×10^{-10}, and use it as an input for e.g. $d_n(M, M', m_h)$.

The 2-loop contributions to d_f and $\tilde{d}_f$ mediated by the top loop.
$h\bar{t}i\gamma_5 t \;\rightarrow\; hF_{\mu\nu}\tilde{F}_{\mu\nu} \;\rightarrow\; \overline{\psi}i(F\sigma)\gamma_5\psi$

Neutron EDM as a function of Higgs mass



Fixing several values of M, d_n in units of experimetnal bound of 3×10^{-26} is plotted against m_h, with M' fixed to ensure that η_b matches its observed value. From left to right $M = 600, 550, 500, 450$ GeV. **An improvement of sensitivity to d_n by a factor of 10 would either find EDM, or put EW baryogenesis in trouble.**

Conclusions

- **EDM measurements are sensitive to sources of CP violation other than the CKM phase.**
- **New searches are motivated by cosmology, and by the search for scalar particles at a TeV scale.**
- **Electroweak scale SUSY with CP-odd phases in the soft-breaking sector can create EDMs at one loop level, well above the current experimental EDM sensitivity.**
- **EW baryogenesis can be driven by the the CP-odd Higgs-top coupling. d_n is predicted to be comparable to the existing bounds, and a future improvement by a factor of ~ 5 may rule out the electroweak baryogenesis scenario.**