Probing CP Violation with EDMs (in the LHC Era)
Adam Ritz
University of Victoria
w/~ D. McKeen, M. Pospelov [1208.4597, 1303.1172, 1311.5537]

Reviews: M. Pospelov & AR [hep-ph/0504231]
T. Fukuyama [1201.4252]
J. Engel, M. Ramsey-Musolf, U. van Kolck [1303.2371]
Do we anticipate other CP-odd sources?

CP Violation in the Standard Model

\[ \sin(\delta_{KM}) \propto \text{Arg Det} [Y_u Y_u^\dagger, Y_d Y_d^\dagger] \]

\[ \sin(\bar{\theta}_{QCD}) \sim \text{Arg Det} [Y_u Y_d] \]

(in a basis where \( \theta_0 \rightarrow 0 \))

\( \delta_{KM} \sim O(1) \)

Explains CP-violation in K and B meson mixing and decays

\( \theta_{QCD} < 10^{-10} \)

Constrained experimentally (strong CP problem)

- Required for baryogenesis (Sakharov conditions)
- Generic with extra degrees of freedom
Experimental EDM Limits

- EDMs are powerful (amplitude-level) probes for new (T,P) violating sources, motivated e.g. by baryogenesis.
- Best current limits from neutrons, para- and dia-magnetic atoms and molecules

|                  | $|d_n| < 3 \times 10^{-26} \, e \, cm$ | [Baker et al. ‘06] |
|------------------|-------------------------------------|---------------------|
| Neutron EDM      |                                     |                     |
| Thallium EDM     | $|d_{Tl}| < 9 \times 10^{-25} \, e \, cm$ | [Regan et al. ‘02] |
| (paramagnetic)   |                                     |                     |
| YbF “EDM”        | $|d_{YbF}| < 1.4 \times 10^{-21} \, e \, cm$ | [Hudson et al. ’11] |
| (paramagnetic)   |                                     |                     |
| Mercury EDM      | $|d_{Hg}| < 3 \times 10^{-29} \, e \, cm$ | [Griffith et al. ’09] |
| (diamagnetic)    |                                     |                     |
EDMs are powerful (amplitude-level) probes for new (T,P) violating sources, motivated e.g. by baryogenesis.

Best current limits from neutrons, para- and dia-magnetic atoms and molecules

| Neutron EDM       | $|d_n| < 3 \times 10^{-26} \text{ e cm}$ | [Baker et al. ‘06] |
|-------------------|----------------------------------------|---------------------|
| ThO “EDM” (paramagnetic) | $|d_{ThO}| < 3 \times 10^{-22} \text{ e cm}$ | [Baron et al. ’13] |
| Mercury EDM (diamagnetic) | $|d_{Hg}| < 3 \times 10^{-29} \text{ e cm}$ | [Griffith et al. ’09] |

Negligible SM (CKM) background - contribution is (at least) 4-5 orders of magnitude below the current neutron sensitivity, and lower for the atomic EDMs
Experimental EDM Limits

\[ H = -d \vec{E} \cdot \frac{S}{S} \]

(Posters: Inoue, Uchiyama, Sakamoto, Ohtomo, Fukuda, Teruya, Hayamizu, Ishikawa, Harada, Yamaguchi, Ohno)

Talk by: Klaus Kirch

![Image](image.png)

<table>
<thead>
<tr>
<th>EDM Type</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron EDM</td>
<td>(</td>
<td>d_n</td>
</tr>
<tr>
<td>ThO “EDM” (paramagnetic)</td>
<td>(</td>
<td>“d_{ThO}”</td>
</tr>
<tr>
<td>Mercury EDM (diamagnetic)</td>
<td>(</td>
<td>d_{Hg}</td>
</tr>
</tbody>
</table>

Talks by: Inoue (Fr), Ichikawa (Xe), Aoki (FrSr), Sahoo (theory)
Difference of 7 orders of magnitude, but the sensitivity to many underlying CP-odd sources is similar...
CP-odd operator expansion (at $\sim 1\text{GeV}$)

(Flavor-diagonal) CP-violating operators at $\sim 1\text{GeV}$ (*)

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}^{(n)}_d$$

$$\mathcal{L}_{\text{dim 4}} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\bar{\theta} = \theta_0 - \text{ArgDet}(M_u M_d) \equiv \theta_0 - \theta_q$$

*NB: (i) Assumes new physics is heavier than $\sim 1$ GeV
   (ii) Basis at $\sim 1$ GeV simpler than EW scale, as we can integrate out
   $W,Z,h$, but importantly we assume L-R chirality structure of the
   Standard Model
CP-odd operator expansion (at ~1GeV)

(Flavor-diagonal) CP-violating operators at ~1GeV

\[ \mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)} \]

\[ \mathcal{L}_{\text{dim} \, 4} \supset \bar{\theta} \alpha_s G \tilde{G} \]

\[ d_i \sim c Y_i \frac{v}{\Lambda^2} \]

\[ \mathcal{L}^{\text{"dim} \, 6\text{"}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l \]

\[ \mathcal{L}_{\text{dim} \, 6} \supset w g_s^3 G G \tilde{G} \]
CP-odd operator expansion (at $\sim 1\, \text{GeV}$)

(Flavor-diagonal) CP-violating operators at $\sim 1\, \text{GeV}$

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

$$\mathcal{L}_{\text{dim } 4} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\mathcal{L}^{\text{"dim } 6\text{"}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l$$

$$\mathcal{L}_{\text{dim } 6} \supset w g_s^3 G G \tilde{G} + \sum_{f,\Gamma} C'_{f,f} (\bar{f} \Gamma f)_{LL} (\bar{f} \Gamma f)_{RR}$$

Suppressed without new sources of LR mixing
CP-odd operator expansion (at $\sim 1\text{GeV}$)

(Flavor-diagonal) CP-violating operators at $\sim 1\text{GeV}$

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{c_n}{\Lambda^{d-4}} \mathcal{O}_d^{(n)}$$

$$\mathcal{L}_{\text{dim 4}} \supset \bar{\theta} \alpha_s G \tilde{G}$$

$$\mathcal{L}^{\text{"dim 6"}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l$$

$$\mathcal{L}_{\text{dim 6}} \supset w g_s^3 G G \tilde{G} + \sum_{f,\Gamma} C'_f (\bar{f} \Gamma f)_{LL} (\bar{f} \Gamma f)_{RR}$$

$$\mathcal{L}^{\text{"dim 8"}} \supset \sum_{q,\Gamma} C_{qq} \bar{q} \Gamma q \bar{q} \Gamma i \gamma_5 q + C_{qe} \bar{q} \Gamma q \bar{e} \Gamma i \gamma_5 e + \cdots$$

$$C_{ij} \sim c Y_i Y_j \frac{v^2}{\Lambda^4}$$
(Flavor-diagonal) CP-violating operators at ~1GeV

\[ \mathcal{L}_{\text{eff}} = \sum_{n} \frac{c_n}{\Lambda^{d-4}} O_d^{(n)} d_N \bar{N} F \sigma \gamma_5 N + g_{\pi N N}^{(1)} \pi^0 \bar{N} N + \ldots \]

\[ \mathcal{L}_{\text{dim 4}} \supset \bar{\theta} \alpha_s G \tilde{G} \]

\[ \mathcal{L}^{\text{"dim 6"}} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma \gamma_5 q + \tilde{d}_q \bar{q} G \sigma \gamma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma \gamma_5 l \]

\[ \mathcal{L}_{\text{dim 6}} \supset w g_s^3 G G \tilde{G} + \sum_{f,\Gamma} C'_f f (\bar{f} \Gamma f)_{LL} (\bar{f} \Gamma f)_{RR} \]

\[ \mathcal{L}^{\text{"dim 8"}} \supset \sum_{q,\Gamma} C_{qq} \bar{q} \Gamma q \bar{q} \Gamma i \gamma_5 q + C_{q e} \bar{q} \Gamma e \bar{q} \Gamma i \gamma_5 e + \ldots \]

\[ C_S \bar{N} N \bar{e} i \gamma_5 e + \ldots \]
**Fundamental CP phases**

- $d_e$
- $C_{qE}, C_{qq}$
- $\theta,\, d_q, \, \tilde{d}_q, \, w$

**pion-nucleon coupling ($\tilde{g}_{\pi NN}$)**

- EDMs of nuclei and ions (deuteron, etc)

**EDMs of paramagnetic atoms and molecules**
- (Tl,YbF, ThO, HfF+, ...)
- Atoms in traps (Rb,Cs,Fr) solid state

**EDMs of diamagnetic atoms**
- (Hg,Xe,Ra,Rn,...)
Atoms (e.g. Tl [Berkeley]) [Regan et al '02] (relativistic violation of Schiff screening)

\[ d_{\text{Tl}} \sim -20\alpha^2 Z^3 d_e + \mathcal{O}(C_S) \]

\[ \mathcal{O}(500 - 600) \text{ for Tl} \]

[e.g. Liu & Kelly '92]

\[ \alpha^2 Z^3 \vec{E} \] [Salpeter '58; Sandars '65]
Paramagnetic EDMs - “Schiff enhancement”

Polar molecules (e.g. ThO [Harvard/Yale], YbF [Imperial])
[Baron et al ‘13, Hudson et al ’11]

\[ \Delta E_{\text{ThO}} \sim \mathcal{E}_{\text{eff}}(E_{\text{ext}})d_e + \mathcal{O}(C_S) \]

Nonlinear function of \( E_{\text{ext}} \)

\[ "d_{\text{YbF}}" \sim 10\alpha^2 Z^3 \frac{\mu_{\text{nuc}}}{m_e} d_e + \mathcal{O}(C_S) \]

[Sandars; Sushkov & Flambaum, ’78]
Paramagnetic EDMs - “Schiff enhancement”

**Polar molecules (e.g. ThO [Harvard/Yale], YbF [Imperial])**  
[Baron et al ‘13, Hudson et al ’11]

\[
\Delta E_{\text{ThO}} \sim -84 \text{ GeV} \left( \frac{d_e}{e \text{ cm}} \right) + \mathcal{O}(C_S(C_{qe}))
\]

\[
\Delta E_{\text{YbF}} \sim -15 \text{ GeV} \left( \frac{d_e}{e \text{ cm}} \right) + \mathcal{O}(C_S(C_{qe}))
\]

[Kozlov et al. 94-98; Quiney et al ’98; Parpia ’98; Chaudhuri & Nayak ’08, Meyer & Bohn ’08; Dzuba et al ’11; Skripnikov et al ’13]
Atoms (e.g. Hg [Washington], also Xe) [Griffith et al '09]  

charge distribution  (finite size violation of Schiff screening)  

\[ d_{Hg} \sim 10Z^2\left(\frac{R_N}{R_A}\right)^2d_{\text{nuc}} \]

\[ O(10^{-3}) \]

\[ d_{Hg} \sim -3 \times 10^{-17} S [e \text{ fm}^2] + \mathcal{O}(d_e, C_{qe}, C_{qq}) \]

[Flambaum et al '86; Dzuba et al. '02]

Schiff moment  [Schiff '63]
Diamagnetic EDMs - “Schiff suppression”

Atoms (e.g. Hg [Washington], also Xe) [Griffith et al ’09]

charge distribution (finite size violation of Schiff screening)

\[ d_{\text{Hg}} \sim -3 \times 10^{-17} S[e \text{ fm}^2] + \mathcal{O}(d_e, C_{qe}, C_{qq}) \]

\[ S = S(\tilde{g}_{\pi NN}^{(i)}, d_N, \ldots) \]
\[ \sim -0.06 g_{\pi NN} \tilde{g}_{\pi NN}^{(1)} \text{ fm}^3 + \cdots \quad \text{NB: concerns over precision} \]

\[ \tilde{g}_{\pi NN}(\tilde{d}_q) \sim (1 - 6)(\tilde{d}_u - \tilde{d}_d) + \mathcal{O}(\tilde{d}_u + \tilde{d}_d, \tilde{d}_s, w) \] [Pospelov ’01]

• Octopole enhancements (e.g. Ra, Rn) [R. Holt, Z.-T. Lu, et al, T. Chupp et al]
  - Schiff moment $O(100-1000)$ larger than Hg [Flambaum et al.]
Nuclear EDMs - avoiding Schiff screening

- Neutron EDM via UCN bottles

 Cálculation using: chiralPT, NDA, QCD sum rules, ...

\[ d_n(\bar{\theta}) \sim 3 \times 10^{-16} \bar{\theta} \text{ecm} \Rightarrow |\theta| < 10^{-10} \]

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

NB: precision limited by: sum rules analysis, s-quark content, nucleon coupling,...

[Hisano et al '12]

[Pospelov & AR '99,'00]
Nuclear EDMs - avoiding Schiff screening

- Neutron EDM via UCN bottles  
  [...., PSI, Sussex/ILL, SNS, PNPI, TRIUMF, TUM, J-PARC...]

- Nuclear EDMs (e.g. \(p, D, ^3He, \ldots\)) in storage rings  
  [BNL, FNAL? COSY/Julich]

\[ d_{Hg} \sim 10Z^2(R_N/R_A)^2d_{\text{nuc}} \]

\(O(10^{-3})\) suppression could be avoided with a direct measurement of the nuclear EDM.
Nuclear EDMs - avoiding Schiff screening

• Neutron EDM via UCN bottles [....., PSI, Sussex/ILL, SNS, PNPI, TRIUMF, TUM, J-PARC...]
• Nuclear EDMs (e.g. p,D,${^3}$He,...) in storage rings [BNL, FNAL?, COSY/Julich]

- proton - similar sensitivity to the neutron (d ↔ u)

\[ d_p(\bar{\theta}) \sim -4 \times 10^{-16} \bar{\theta} \ e_{\text{cm}} \]  

\[ d_p^{(PQ)} \sim (0.4 \pm 0.2) [4d_u - d_d - 5.3e (\tilde{d}_u + 0.13\tilde{d}_d) + \cdots] + \mathcal{O}(d_s, w, C_{qq}) \]  

[Lebedev, Olive, Pospelov, AR ’99,’00]

- deuteron

\[ d_D = (d_n + d_p)(\bar{\theta}, d_q, \tilde{d}_q) + d_D^{\pi N N}(\bar{\theta}, \tilde{d}_q) \approx -2 \times 10^{-14} g_{\pi N N}^{(1)}(\bar{\theta}, \tilde{d}_q)e_{\text{cm}} + \mathcal{O}(g_{\pi N N}^{(0)}) \]  

[Khriplovich & Korkin ‘00; Liu & Timmermans ’04; de Vries et al ’11; Bsaisou et al ’12]

via $\eta$-$\pi$ mixing

\[ \approx -5e (\tilde{d}_d - \tilde{d}_u) + \cdots \]

- extended to other light nuclei (e.g. ${^3}$H, ${^3}$He) in recent work

[Stetcu et al ’08, de Vries et al ’11]
EDMs of paramagnetic atoms and molecules (Tl,YbF, ThO, HfF\(^+\),...) Atoms in traps (Rb,Cs,Fr) solid state

EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn,...)

EDMs of nuclei and ions (deuteron, etc)

Nucleon EDMs (n,p)

pion-nucleon coupling (\(\tilde{g}_{\pi NN}\))

Fundamental CP phases

\[ d_e \]

\[ C_{qe}, C_{qq} \]

\[ \theta, d_q, \tilde{d}_q, w \]

Energy

TeV

QCD

atomic

nuclear

\( \mu \) EDM

\( C_{S,P,T} \)
Constraints on CP-violation

EDM constraints

Fundamental CP phases

Energy

TeV

QCD

nuclear

atomic
### Resulting Bounds on fermion EDMs & CEDMs

<table>
<thead>
<tr>
<th></th>
<th>Formula</th>
<th>Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>YbF EDM [±20%]</strong></td>
<td>$</td>
<td>d_e + e(21 \text{ MeV})^2 \left(3 \frac{C_{ed}}{m_d} + 11 \frac{C_{es}}{m_s} + 5 \frac{C_{eb}}{m_b}\right)</td>
</tr>
<tr>
<td><strong>TI EDM [±20%]</strong></td>
<td>$</td>
<td>d_e + e(26 \text{ MeV})^2 \left(3 \frac{C_{ed}}{m_d} + 11 \frac{C_{es}}{m_s} + 5 \frac{C_{eb}}{m_b}\right)</td>
</tr>
<tr>
<td><strong>Neutron EDM [±50%?]</strong></td>
<td>$</td>
<td>e(d_{\tilde{d}} + 0.5d_{\tilde{u}}) + 1.3(d_d - 0.25d_u) + O(d_{\tilde{s}}, w, C_{qq})</td>
</tr>
<tr>
<td><strong>Hg EDM [±O(few)?]</strong></td>
<td>$e</td>
<td>d_{\tilde{d}} - d_{\tilde{u}} + O(d_e, d_{\tilde{s}}, C_{qq}, C_{qe})</td>
</tr>
</tbody>
</table>

**Generic scaling:** $d_f \sim \text{(couplings)} \times \frac{m_f}{\Lambda_{CP}^2}$

**See also recent compilation of limits:** [Engel, Ramsey-Musolf, van Kolck ’13 ]
### Resulting Bounds on fermion EDMs & CEDMs

<table>
<thead>
<tr>
<th>EDM</th>
<th>Expression</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ThO EDM [±20%]</td>
<td>[d_e + e(26\text{MeV})^2 \left(3 \frac{C_{ed}}{m_d} + 11 \frac{C_{es}}{m_s} + 5 \frac{C_{eb}}{m_b}\right)]</td>
<td>(&lt; 8.7 \times 10^{-29} e, cm)</td>
</tr>
<tr>
<td>Neutron EDM [±50%?]</td>
<td>[</td>
<td>e(\tilde{d}_d + 0.5\tilde{d}_u) + 1.3(d_d - 0.25d_u) + O(\tilde{d}<em>s, w, C</em>{qq})</td>
</tr>
<tr>
<td>Hg EDM [±O(few)?]</td>
<td>[e</td>
<td>\tilde{d}_d - \tilde{d}<em>u + O(d_e, \tilde{d}<em>s, C</em>{qq}, C</em>{qe})</td>
</tr>
</tbody>
</table>

**Generic scaling:** \(d_f \sim (couplings) \times \frac{m_f}{\Lambda_{CP}^2}\)

**See also recent compilation of limits:** [Engel, Ramsey-Musolf, van Kolck '13]
Summary of the bounds

Difference of 7 orders of magnitude, but the sensitivity to many underlying CP-odd sources is similar...
Summary of the bounds

\[ \log(d \text{ [e cm]}) \]

-22
-24
-26
-28
-30
-32
-34

-22
-24
-26
-28
-30
-32
-34

-22
-24
-26
-28
-30
-32
-34

\( d_q \) and \( \tilde{d}_q \) from the neutron

\( \tilde{d}_q \) from Hg

\( d_e \) from ThO

Given \( d_f \propto m_f \) the overall sensitivities to generic new physics are even closer
EDMs in the Standard Model (CKM phase)

$\log(d [\text{e cm}])$

$-22$

$-24$

$-26$

$-28$

$-30$

$-32$

$-34$

$\nu_n(\text{CKM}) \propto C_{qq}(J) \propto J G_F^2$

neutron EDM limit

Next generation sensitivity?

$\mathcal{d}(\text{CKM}) \propto J \sim \text{Im}(VVVV)$

[Khriplovich & Zhitnitsky ’82; McKellar et al ’87; Mannel & Uraltsev ’12]
EDMs in the Standard Model (CKM phase)

\[ d(\text{CKM}) \propto J \sim \text{Im}(VVVV) \]

\[ d_{Hg}(\text{CKM}) \propto C_{qq}(J) \propto JG_F^2 \]

[Flambaum et al ’84; Donoghue et al ’87]
EDMs in the Standard Model (CKM phase)

\[ d(\text{CKM}) \propto J \sim \text{Im}(VVVV) \]

Paramagnetic EDMs in the SM determined by \( C_S \) rather than \( d_e \)

\[ "d_{ThO}(\text{CKM})" \propto C_S(J) \propto JG_F^2 \]

[Pospelov & AR '13]
LHC-era tests of CP-violating new physics

Expectation of new EW-scale physics is (or was) primarily associated with stabilizing the Higgs sector...

• This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...

⇒ EDMs at 2-loops
E.g. - CP-odd Higgs couplings

- Hints in 2012 that $\text{Br}(h \rightarrow \gamma \gamma) > \text{Br}_\text{SM}$ (still present in ATLAS data)
- EDMs significantly constrain any CP-odd contribution to $h \rightarrow \gamma \gamma$

$$
\Delta \mathcal{L} = \frac{1}{e^2 \tilde{\Lambda}^2} H^\dagger H \left( a_h g_1^2 B_{\mu \nu} \tilde{B}^{\mu \nu} + b_h g_2^2 W_{\mu \nu} \tilde{W}^{\mu \nu} \right) \rightarrow \frac{\tilde{c}_h v}{\tilde{\Lambda}^2} h F_{\mu \nu} \tilde{F}^{\mu \nu} + \ldots
$$

This interaction corrects the Higgs width, but also generates 2-loop EDMs!

$$
\frac{\Gamma_{\gamma \gamma}}{\Gamma_{\gamma \gamma}^{\text{SM}}} \approx 1 + \left| \tilde{c}_h \frac{v^2}{\tilde{\Lambda}^2} \frac{8\pi}{\alpha A_{\text{SM}}} \right|^2
$$

Current limit on $d_e$ limits the shift of $\text{Br}(h \rightarrow \gamma \gamma)/\text{Br}_\text{SM}$ to $O(10^{-5})$!

[McKeen, Pospelov & AR ’12]
[Harnik et al ’12; Fan & Reece ’13]
Expectation of new EW-scale physics is (or was) primarily associated with stabilizing the Higgs sector...

- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...
  \[ \Rightarrow \text{EDMs at 2-loops} \]
LHC-era tests of CP-violating new physics

Expectation of new EW-scale physics is (or was) primarily associated with stabilizing the Higgs sector...

- This predominantly suggests new physics coupling strongly to the Higgs, 3rd generation, ...
  \[ \Rightarrow \text{EDMs at 2-loops} \]

- SUSY provides new physics with strong coupling to 1st generation
  \[ \Rightarrow \text{EDMs at 1-loop!} \]
  \[ \Rightarrow \text{SUSY CP problem!} \]
E.g. - SUSY CP Problem (given LHC constraints)

(pre-LHC)

\[ M_{\text{susy}} = 500 \text{ GeV} \]

(2012/13)

\[ M_{\text{susy}} = 2 \text{ TeV} \]

EDMs have for many years required (tuned) \( O(10^{-3}) \) CP-odd phases for generic weak-scale SUSY. The LHC appears to have “resolved” this by pushing mass limits on 1st generation sfermions above a TeV.
E.g. - SUSY CP Problem (given LHC constraints)

(pre-LHC)

$M_{\text{susy}} = 500$ GeV

1st gen squarks excluded by direct searches at ~1 TeV

(EPJ)

$M_{\text{susy}} = 2$ TeV

1st gen squarks excluded by direct searches at ~1 TeV

EDMs have for many years required (tuned) $O(10^{-3})$ CP-odd phases for generic weak-scale SUSY. The LHC appears to have “resolved” this by pushing mass limits on 1st generation sfermions above a TeV. Now tuning (at a TeV) being re-introduced via ThO limit on $d_e$. 

35
Within minimal SUSY, $m_h \gg m_Z$ points to PeV-scale s-partners (tuning, no soln to “little hierarchy” problem)

$$m_h^2 \sim M_Z^2 + \frac{3}{\sqrt{2}\pi^2} G_F m_t^4 \ln \frac{m_t^2}{v^2}$$

Need a large log correction

$$m_{\text{squark}} > 100-1000 \text{ TeV}$$

E.g. - PeV-scale SUSY sensitivity
E.g. - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h >> m_Z$ points to PeV-scale s-partners
- The PeV scale allows a generic flavour structure and, with TeV gauginos, (hadronic) EDMs are one of the few observables able to probe this scale via log-enhanced quark CEDMs

[McKeen, Pospelov & AR '13]

[also recent work by Altmannshofer et al '13; Fuyuto et al '13]
E.g. - PeV-scale SUSY sensitivity

- Within minimal SUSY, $m_h >> m_Z$ points to PeV-scale $s$-partners
- The PeV scale allows a generic flavour structure and, with TeV gauginos, (hadronic) EDMs are one of the few observables able to probe this scale via log-enhanced quark CEDMs

\[
|m_{\tilde{B}}| = |m_{\tilde{W}}| = 3 \text{ TeV} \ , \ |m_{\tilde{g}}| = 10 \text{ TeV}
\]

New electron EDM limit from ThO

[Altmannshofer et al '13]
EDMs are an important class of flavour-diagonal CP-odd observables, testing/limiting new physics (motivated by the need for baryogenesis)

• Disentangling multiple CP-odd operators at 1 GeV requires multiple observables

• Useful interplay between EDM constraints and precision tests of CP-odd Higgs couplings

• The SUSY CP problem, hinted at by (1-loop) EDMs for more than 20 years, has been “confirmed” by the LHC, with no squarks seen near the weak scale (thus far). EDMs probe the very high (PeV) sfermion scales characteristic of the “large” observed Higgs mass

Role of the EW scale? Baryogenesis requires new CP-odd physics, but is it at much higher scales? Or possibly at low scales (< GeV)?
Issues affecting precision, and tests:

– numerical coefficients are consistent with NDA, NQM (for \(d_q\)), and the chiral log (for \(\theta\))

– another test for \(d_n(d_q)\) via (LQCD) nucleon tensor charge

\[
\langle N | \frac{1}{2} d_q \bar{q} \tilde{F} \sigma q | N \rangle = \frac{1}{2} d_q \tilde{F}^{\mu \nu} \langle N | \sigma_{\mu \nu} | N \rangle = \frac{1}{2} g_T q d_q \bar{N} \tilde{F} \sigma N
\]

\[
\Rightarrow d_n(d_q) = g_T^d (1 \text{ GeV}) d_d + g_T^u (1 \text{ GeV}) d_u \sim 1.1 d_d - 0.25 d_u
\]

– sum-rules fixes \((d_n \sim \langle qq \rangle / \lambda^2)\), so the normalization of the coupling matters

\[
\lambda \sim 0.025 \text{ GeV}^3
\]

from analysis of CP-even sum rules for \(m_n\), sigma term, etc (or lattice result for tensor charge above)

\[
\text{[Pospelov \\& AR '99,'00]}
\]

\[
\lambda \sim 0.044 \pm 0.01 \text{ GeV}^3
\]

from LQCD [Aoki et al '08] run down from 2 GeV, *BUT* \(\langle qq \rangle\) is also larger with LQCD values for \(m_q\)

\[
\text{[Hisano et al '12, Fuyuto et al '12]}
\]

– higher order dependence on s-quark EDM?