Implications of EDM constraints in SUSY scenarios

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MSSM scenarios

Minimal Supersymmetric extension of the Standard Model (MSSM)
- More than 100 free parameters
- Not every parameter relevant for different studies
- EDMs relevant for CP violation

CPV-CMSSM: 10 parameters
- GUT-universal parameters: $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$
- + 6 phases: $\phi_{M_1}$, $\phi_{M_2}$, $\phi_{M_3}$, $\phi_{A_b}$, $\phi_{A_t}$, $\phi_{A_\tau}$

CPX: 9 parameters
- 1 unified sfermion mass: $M_S$
- with $\mu = 4 M_S$, $|A_{U,D,\ell}| = 2 M_S$, $|M_1| = |M_2| = 1 \text{ TeV}$, $|M_3| = 3 \text{ TeV}$
- + 2 Higgs parameters $\tan \beta$, $m_{H^+}$
- + 6 phases: $\phi_{M_1}$, $\phi_{M_2}$, $\phi_{M_3}$, $\phi_{A_b}$, $\phi_{A_t}$, $\phi_{A_\tau}$
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**CP violating pMSSM**

**CP violating phenomenological MSSM (CPV-pMSSM)**

→ 19 pMSSM parameters + 6 phases = 25 parameters

10 sfermion masses: \( M_{\tilde{e}_L} = M_{\tilde{\mu}_L}, M_{\tilde{e}_R} = M_{\tilde{\mu}_R}, M_{\tilde{\tau}_L}, M_{\tilde{\tau}_R}, M_{\tilde{q}_1 L} = M_{\tilde{q}_2 L}, M_{\tilde{q}_3 L}, M_{\tilde{\tau}_L}, M_{\tilde{\tau}_R}, M_{\tilde{\tau}_L}, M_{\tilde{\tau}_R}, M_{\tilde{\tau}_L}, M_{\tilde{\tau}_R}, M_{\tilde{\tau}_L}, M_{\tilde{\tau}_R}, M_{\tilde{\tau}_L}, M_{\tilde{\tau}_R} \)

3 gaugino masses: \(|M_1|, |M_2|, |M_3|\) + 3 gaugino phases: \(\phi_{M_1}, \phi_{M_2}, \phi_{M_3}\)

3 trilinear couplings: \(A_d = A_s = |A_b|, A_u = A_c = |A_t|, A_e = A_\mu = |A_\tau|\) + 3 trilinear coupling phases for the third generation fermions: \(\phi_{A_b}, \phi_{A_t}, \phi_{A_\tau}\)

3 Higgs/Higgsino parameters: \(M_{H^+}, \tan \beta, \mu\)

\[ M_\alpha = |M_\alpha|e^{i\phi_\alpha} \quad A_\beta = |A_\beta|e^{i\phi_\beta} \]

The CP phases can take values between -180 and 180 degrees, and modify the mixing matrices and couplings

3 neutral Higgs bosons \(h_1, h_2, h_3\) with scalar and pseudoscalar components

In the following, we consider only the case of neutralino LSP (= dark matter)
EDM constraints

Convention used thereafter:

\[ \mathcal{L}_{\text{EDM}} = -\frac{i}{2} d_f F^{\mu\nu} \bar{f} \sigma_{\mu\nu} \gamma_5 f \]

Current limits at 95% C.L.

<table>
<thead>
<tr>
<th>EDM</th>
<th>Upper limit (e.cm)</th>
<th>Equivalent limit (e.cm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thallium</td>
<td>$1.3 \times 10^{-24}$</td>
<td>$d_e : 2.1 \times 10^{-27}$</td>
<td>PRL 88 (2002) 071805</td>
</tr>
<tr>
<td>Thorium monoxide</td>
<td>-</td>
<td>$d_e : 1.1 \times 10^{-28}$</td>
<td>Science 343 (2014) 269</td>
</tr>
<tr>
<td>Muon</td>
<td>$1.9 \times 10^{-19}$</td>
<td>$d_\mu : 1.9 \times 10^{-19}$</td>
<td>PRD 80 (2009) 052008</td>
</tr>
<tr>
<td>Mercury</td>
<td>$7.4 \times 10^{-30}$</td>
<td>$d_n : 1.6 \times 10^{-26}$</td>
<td>PRL 116 (2016) 161601</td>
</tr>
<tr>
<td>Neutron</td>
<td>$4.2 \times 10^{-26}$</td>
<td>$d_n : 4.2 \times 10^{-26}$</td>
<td>PRL 97 (2006) 131801</td>
</tr>
</tbody>
</table>

Prospective values for proton EDM

<table>
<thead>
<tr>
<th>Case</th>
<th>(e.cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$</td>
</tr>
<tr>
<td>Case 2</td>
<td>$d_p = (1.00 \pm 0.01) \times 10^{-27}$</td>
</tr>
</tbody>
</table>
Nucleon EDMs

Different possible parametrizations for the nucleon EDMs → EDM values can be changed by a factor of a few.

For simplicity, we use here the parton quark model parametrization:

\[ d_N = \eta^E (\Delta^N_d d_d + \Delta^N_u d_u + \Delta^N_s d_s) \]

where \( \eta^E = 1.53 \) and the \( \Delta \)'s are the quark polarisations in the nucleon.

For the neutron, the \( \Delta \)'s are precisely known:

\[ \Delta^n_d = 0.746, \ \Delta^n_u = -0.508, \ \Delta^n_s = -0.226 \]

For the proton, the spin structure of the proton is not well-known, and we consider the simplest isospin symmetric model:

\[ \Delta^p_u = 4/3, \ \Delta^p_d = -1/3, \ \Delta^p_s = 0 \]

Regardless of the chosen parameters, the neutron and proton EDMs are expected to be of the same order of magnitude.
EDM in the MSSM

\[ d_f = d_f^{\tilde{\chi}^\pm} + d_f^{\tilde{\chi}^0} + d_f^{\tilde{g}} + d_f^H \] where \( f = e, \mu, u, d, s. \)

Chargino-mediated one-loop EDMs

\[ d_f^{\tilde{\chi}^\pm} = -\frac{e}{16\pi^2} \sum_i \frac{m_{\tilde{\chi}^\pm_i}}{m_{\tilde{\nu}_i}^2} \text{Im} \left( g_{R_{\tilde{\chi}^\pm_i}} g^*_{L_{\tilde{\nu}_i}} \right) f \left( \frac{m_{\tilde{\chi}^\pm_i}^2}{m_{\tilde{\nu}_i}^2} \right) \]

\[ d_u^{\tilde{\chi}^\pm} = \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}^\pm_i}}{m_{\tilde{d}_j}^2} \text{Im} \left( g_{R_{\tilde{\chi}^\pm_i}} g^*_{L_{\tilde{d}_j}} \right) \left[ f \left( \frac{m_{\tilde{\chi}^\pm_i}^2}{m_{\tilde{d}_j}^2} \right) - \frac{1}{3} g \left( \frac{m_{\tilde{\chi}^\pm_i}^2}{m_{\tilde{d}_j}^2} \right) \right] \]

\[ d_d^{\tilde{\chi}^\pm} = \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}^\pm_i}}{m_{\tilde{u}_j}^2} \text{Im} \left( g_{R_{\tilde{\chi}^\pm_i}} g^*_{L_{\tilde{u}_j}} \right) \left[ -f \left( \frac{m_{\tilde{\chi}^\pm_i}^2}{m_{\tilde{u}_j}^2} \right) + \frac{2}{3} g \left( \frac{m_{\tilde{\chi}^\pm_i}^2}{m_{\tilde{u}_j}^2} \right) \right] \]

Neutralino-mediated one-loop EDMs

\[ d_f^{\tilde{\chi}^0} = \frac{e}{16\pi^2} \sum_{i,j} \frac{m_{\tilde{\chi}^0_i}}{m_{\tilde{f}_{ij}}^2} \text{Im} \left( g_{R_{\tilde{\chi}^0_i}} g^*_{L_{\tilde{f}_{ij}}} \right) Q_{\tilde{f}_i} g \left( \frac{m_{\tilde{\chi}^0_i}^2}{m_{\tilde{f}_{ij}}^2} \right) \]

The \( g^{\tilde{\chi}_{ff'}} \) contains the chargino/neutralino/squark mixing matrices, \( Q_{\tilde{f}_i} \) is the charge of \( \tilde{f} \).
EDM in the MSSM

\[ d_f = d_f^{\tilde{\chi}^\pm} + d_f^{\tilde{\chi}^0} + d_f^{\tilde{g}} + d_f^H \] where \( f = e, \mu, u, d, s. \)

Gluino-mediated one-loop EDMs

\[ d_q^{\tilde{g}} = \frac{e}{3\pi^2} \sum_i \frac{m_{\tilde{g}}}{m_{\tilde{q}_i}^2} \text{Im} \left( g_{R_i}^{\tilde{g}q\bar{q}^*} g_{L_i}^{\tilde{g}q\bar{q}} \right) Q_f g \left( \frac{m_{\tilde{g}}^2}{m_{\tilde{q}_i}^2} \right) \]

(Higher order) Higgs-mediated Barr-Zee diagrams:
MSSM scans and constraints

Methodology

Random scans in the CP violating pMSSM scenario
(Codes involved: CPsuperH, SuperIso Relic, micrOMEGAs, ...)


imposing many constraints:

- LEP and Tevatron direct search limits
- Light Higgs mass range
- Flavour physics limits, in particular from \( \text{BR}(B \to X_s \gamma), \text{BR}(B_s \to \mu^+ \mu^-), \text{BR}(B \to \tau \nu), \Delta M_{B_s} \)
- Muon anomalous magnetic moment, \((g - 2)_\mu\)
- Dark matter anomalous relic density
- Dark matter direct search limits
- Heavy Higgs mass limits
- Higgs production and decay rates
- LHC SUSY direct search limits
- Electric dipole moments (EDMs)

Problem: the EDMs impose so strong constraints that only zero phases are allowed, apart in some very restricted regions of the parameter space!
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**Geometric approach**

Method inspired by J. Ellis, J.S. Lee, A. Pilaftsis, JHEP 1010 (2010) 049

How to determine the direction in the phase parameter space minimizing the EDMs and maximizing other CP violating observables?

Let us consider a simple example: how to minimize the EDM $E$ while maximizing the observable $O$ in the 3 phases parameter space ($\phi_1, \phi_2, \phi_3$)?

\[ \vec{\nabla} O \]: direction corresponding to the maximal increase of $|O|$

\[ \vec{\nabla} E \]: direction corresponding to the maximal increase of $|E|$

Optimal direction $\vec{\phi}^*$

\[ = \text{intersection of the plane perpendicular to } \vec{\nabla} E \text{ with the plane defined by } \vec{\nabla} O \text{ and } \vec{\nabla} E \]

\[ = \text{direction minimizing } |E| \text{ and allowing for an increase in } |O| \]

Works well in the limit of small phases...
Improved geometric approach

In our study, we want to minimize the four strongest EDM constraints \((E^i)\) and maximize the CP asymmetry of \(b \to s\gamma\) \((O)\) over the six phases \(\phi_i\).

The optimal direction, computed for each choice of the 19 CP conserving pMSSM parameters, is given by:

\[
\phi^*_\alpha = \epsilon_{\alpha\beta\gamma\delta\mu\eta} \epsilon_{\eta\nu\lambda\rho\sigma\tau} E^a_\beta E^b_\gamma E^c_\delta E^d_\mu O_\nu E^a_\lambda E^b_\rho E^c_\sigma E^d_\tau
\]

with \(\phi_\alpha = \phi_{1,2,3,t,b,\tau}\), \(E^i_\alpha \equiv \partial E^i / \partial \phi_\alpha\) and \(O_\alpha \equiv \partial O / \partial \phi_\alpha\)

Iterative approach still necessary:

To go beyond the limit of small phases, we start with phases at 0, determine the optimal direction, move by at most 20 degrees, and iterate to determine the optimal direction at the new position.
Sectors weakly affected by CP violation

**Relic density**

Planck: $\Omega h^2 \sim 0.1$

**Higgs signal strengths** ($M_{h_1} \in [122, 128]$ GeV)
Effects of the EDMs on the CP-violating phases

Original sample with no EDM constraints

![Graphs showing distributions of CP-violating phases](image-url)
Adding EDM constraints: Muon
Adding EDM constraints: Muon, Thallium
Effects of the EDMs on the CP-violating phases

Adding EDM constraints: Muon, Thallium, Mercury
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![Graphs showing the effects of EDMs on CP-violating phases.](image-url)
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Adding EDM constraints: Proton only
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Original sample with no EDM constraints
Adding EDM constraints: Proton only
Adding EDM constraints: Proton 2 only
CP violation in the Higgs sector

The Higgs bosons can be mixtures of scalar and pseudoscalar components. The LHC constraints impose the $h_1$ to be a scalar with negligible pseudoscalar component. We define ($g_{S,P}^{h_i\bar{f}f}$: scalar, pseudoscalar coupling of $h_i$ to $\bar{f}f$):

$$\tan \phi_{\tau}^{h_i} \equiv \frac{g_P^{h_i\tau\tau}}{g_S^{h_i\tau\tau}}, \quad \tan \phi_{t}^{h_i} \equiv \frac{g_P^{h_i\bar{t}t}}{g_S^{h_i\bar{t}t}}$$

Original sample with no EDM constraints

Similar plots for $h_3$
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$$
\tan \phi^h_{\tau} \equiv \frac{g^h_{i\tau\tau}}{g^h_{i\tau\tau}}, \quad \tan \phi^h_{t} \equiv \frac{g_P^{h_i\bar{t}t}}{g^h_{i\bar{t}t}}
$$

Adding EDM constraints: Muon.

![Graphs showing CP violation](image)

Similar plots for $h_3$
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Adding EDM constraints: Muon, Thallium

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Adding EDM constraints: Muon, Thallium, Mercury

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\[
\tan \phi^{h_i}_{\tau \tau} \equiv \frac{g^{h_i \tau \tau}_{P}}{g^{h_i \tau \tau}_{S}}, \quad \tan \phi^{h_i}_{t \bar{t}} \equiv \frac{g^{h_i t \bar{t}}_{P}}{g^{h_i t \bar{t}}_{S}}
\]

Adding EDM constraints: Muon, Thallium, Mercury, Neutron

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Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde

![Graphs showing similar plots for $h_3$]
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Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton

Similar plots for $h_3$
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Adding EDM constraints: Muon, Thallium, Mercury, Neutron, Thorium Monoxyde + Proton 2

![Graphs showing the distribution of CP violation parameters for $h_3$.](image)

Similar plots for $h_3$. 

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CERN, March 26th 2018
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Original sample with no EDM constraints

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Adding EDM constraints: Proton only

![Graphs showing number of points for different variables](image_url)
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\]

Adding EDM constraints: Proton 2 only

Similar plots for $h_3$
Flavour sector

CP asymmetry in $b \rightarrow s\gamma$

$B_s$ meson mixing $\Delta M_{B_s}^{NP}$

Current experiment limits superseded by EDM constraints

Constraints limited by the theoretical uncertainties

Good perspectives if order of magnitude improvement on theoretical uncertainties
Flavour sector

CP asymmetry in \(b \rightarrow s\gamma\)

\[A_{\text{CP}}(b\rightarrow s\gamma)\]

\[\text{Number of points} \quad \begin{array}{c} 10^5 \quad 10^4 \quad 10^3 \quad 10^2 \quad 10 \quad 1 \end{array}\]

-0.05 \quad 0 \quad 0.05

\(B_s\) meson mixing \(\Delta M^{NP}_{B_s}\)

\[\text{Number of points} \quad \begin{array}{c} 10^5 \quad 10^4 \quad 10^3 \quad 10^2 \quad 1 \end{array}\]

\(\Delta M^{NP}_{B_s} (\text{ps}^{-1})\)

- \(\text{gray: without EDMs} \quad \text{black: with EDMs}\)
- \(\text{blue: + prospective proton EDM 2}\)
- \(\text{red: current limits} \quad \text{green: prospective Belle-II}\)

Current experiment limits superseded by EDM constraints

Good perspectives for the future

Constraints limited by the theoretical uncertainties

Good perspectives if order of magnitude improvement on theoretical uncertainties
CP violating MSSM strongly constrained...

... but still a viable model

Electric dipole moments very constraining...

... but large CP violating phases still possible

Measuring the proton EDM with a precision of $10^{-29}$ would have a huge impact for the search for CP violation in the MSSM

Such a measurement would be competitive to $B$ physics constraints at Belle II for search for CP violation.
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Conclusions

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