EDMs as probes of SUSY

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OUTLINE:

0* Warning: here Lepton EDM (LEDM)

1* Constraints from LEDMs on slepton masses

2* LEDMs from RGE-induced CPV Sources
  - See-Saw
  - See-Saw + minSU(5)
  - Semi-Realistic SO(10)

3* Outlook

potentially observable LFV!
Beyond SM & ALL from DIPOLE OPERATOR

\[ BR(\ell_i \rightarrow \ell_j \gamma) \propto |A_{ij}|^2 \]

\[ \delta a_{\ell_i} = Re A_{ii} \]

\[ d_{\ell_i} = Im A_{ii} \]

\[ L_{d=5} = \frac{1}{2} \bar{\psi}_{Ri} A_{ij} \psi_{Lj} \sigma^{\mu\nu} F_{\mu\nu} + h.c. \]

em.charge chir flip

adim coupl of NP with lept encodes F&CP violations

1-loop NP

\[ \frac{e m_i}{(4\pi)^2} \]

loop factor

NP mass scale

\[ \frac{\Gamma_{ij}}{M^2} \]
\[ BR(\ell_i \to \ell_j \gamma) \propto |A_{ij}|^2 \]

\[ \delta a_{\ell_i} = Re A_{ii} \]

\[ d_{\ell_i} = Im A_{ii} \]

**Loops w/ Sleptons & Gauginos**

**Mass Insertion:**

\[ \tilde{m}_L^2 (1 + \delta^{LL}) \quad \tilde{m}_R^2 (1 + \delta^{RR}) \quad \tilde{m}_e (\tilde{a}_e^* - \mu \tilde{t}_R \beta) + \bar{m}_L \bar{m}_R \delta^{LR} \]

**SUSY**

**lep-slept misalignment**

\[ \gamma \]

\[ e \frac{m_i}{(4\pi)^2} \]

\[ \frac{\Gamma_{ij}}{M^2} \]
Expansion in powers of the FV $\delta$'s

$$BR(\ell_i \to \ell_j \gamma) \propto |A_{ij}|^2 = f_{LL} |\delta_{ji}^{LL}|^2 + f_{RR} |\delta_{ji}^{RR}|^2 + f_{LR} |\delta_{ji}^{LR}|^2 + f_{RL} |\delta_{ji}^{RL}|^2 + \ldots$$

$$\delta a_{\ell_i} = Re A_{ii} = f_\mu m_{\ell_i}^2 Re \mu + \ldots$$

$$d_{\ell_i} = Im A_{ii} = f_\mu m_{\ell_i} Arg \mu + f_a m_{\ell_i} Im a + f_{LLRR} Im (\delta_{LL}^L m_d \delta_{RR}^R)_{ii} + \ldots$$

**FC**

**FV**
\[BR(\ell_i \to \ell_j \gamma) \propto |A_{ij}|^2 = f_{LL} |\delta_{jj}^{LL}|^2 + f_{RR} |\delta_{jj}^{RR}|^2 + f_{LR} |\delta_{jj}^{LR}|^2 + \ldots\]

\[\delta a_{\ell_i} = Re A_{ii} = f_\mu m_{\ell_i}^2 Re \mu + \ldots\]

\[d_{\ell_i} = Im A_{ii} = f_\mu m_{\ell_i} Arg \mu + f_a m_{\ell_i} Im \mu + f_{LLRR} Im (\delta^{LL} m_e \delta^{RR})_{ii} + \ldots\]

No canc: \textit{pr lim in mSugra} in susy region preferred by \(g_\mu\) with \(tg_\beta=10\)

\[\mu \to e\gamma \implies |\delta_{21}^{LL}| \leq 10^{-3} \quad |\delta_{21}^{RR}| \leq (10^{-2} - 1)\]

\[d_e \implies Arg \mu \leq 2 \times 10^{-3} \quad Im \epsilon / m_R \leq 0.2 \quad Im (\delta^{LL} m_e \delta^{RR})_{ee} / m_t \leq 10^{-5}\]

\[d_\mu @ 10^{-23}\text{ecm} \implies Arg \mu \leq 10^{-1} \quad - \quad Im (\delta^{LL} m_\mu \delta^{RR})_{\mu\mu} / m_t \leq 10^{-1}\]

[For more details see e.g.: IM\&Savoy, ph/0211283]
\[ BR(\ell_i \rightarrow \ell_j \gamma) \propto |A_{ij}|^2 = f_{LL} |\delta_{j\ell_i}^{LL}|^2 + f_{RR} |\delta_{j\ell_i}^{RR}|^2 + f_{LR} |\delta_{j\ell_i}^{LR}|^2 + f_{RL} |\delta_{j\ell_i}^{RL}|^2 + \ldots \]

\[ \delta a_{\ell_i} = Re A_{\ell_i} = f_\mu m_{\ell_i}^2 Re \mu + \ldots \]

\[ d_{\ell_i} = Im A_{\ell_i} = f_\mu m_{\ell_i} Arg \mu + f_a m_{\ell_i} Im \mu + f_{LLR} Im (\delta_{j\ell_i}^{LL} m_\ell \delta_{j\ell_i}^{RR})_{\ell_i} + \ldots \]

**FC**

Scaling d_e/m_e = d_\mu/m_\mu

**FV**

Scaling violation (in general)

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No canc: \( pr \) lim in mSugra in susy region preferred by \( g_\mu \) with \( tg\beta = 10 \)

[For more details see e.g.: IM&Savoy, ph/0211283]

\( \mu \rightarrow e\gamma \Rightarrow |\delta_{LL}^{21}| \leq 10^{-3} \quad |\delta_{RR}^{21}| \leq (10^{-2} - 1) \)

\( d_e \Rightarrow Arg \mu \leq 2 \times 10^{-3} \quad Im a_e/m_\tau \leq 0.2 \quad Im (\delta_{LL}^{21} m_\ell \delta_{RR}^{21})_{ee}/m_\tau \leq 10^{-5} \)

would need \( d_\mu @ 2 \times 10^{-25} \) ecm

Measure of \( d_\mu \) = scaling violation \( \Rightarrow \) Focus on CPV sources which violate scaling
**a-term and FV δ's a source of EDM**

At low energy

\[
\alpha = \alpha^{(0)} + \alpha^{(\text{rad})}
\]

\[
\delta = \delta^{(0)} + \delta^{(\text{rad})}
\]

In soft masses at \(M_{\text{Pl}}\)

Assume **INHIBITION** mechanism at work (e.g., mSUGRA)

Radiatively induced running from \(M_{\text{Pl}}\) to \(m_{\text{susy}}\) by FV&CPV YUKAWAS of Heavy States

**What about EDM exp's?**

1) **See-Saw:** \(\nu^c\)

\[
L_{\text{SS}} = \nu^c Y_{\nu} \nu H_D^{u+} + \nu^c M_R \nu^c
\]

Dirac \(\nu\)-Yukawa coupling \(\nu^c\) mass matrix

2) **GUTs:** \(\nu^c + H_T\)

Heavy colored Higgs Triplets (inducing p-decay)

E.g., in SU(5):

\[
\begin{pmatrix} 5 \\ \bar{\nu} \end{pmatrix} = (H_D, H_T) \quad \begin{pmatrix} \bar{\nu} \\ 5 \end{pmatrix} = (\bar{H}_D, \bar{H}_T)
\]
See-Saw

[RomaninoStrumia; EllisHisanoLolaRaidalShimizu; MSavoy; FarzanPeskin; ....]
**See-Saw \( \nu^c-deq \)**

Solve RGE approx

\[
1 \gg \delta_{i,j}^{LL} \propto (Y_\nu^\dagger Y_\nu)_{i,j} \ln \frac{\Lambda}{M}
\]

strong impact on SS models!

**EDM**

needs \( \text{Im(non-herm)}_{ii} \)

\(-\) go at 4\(^{\circ}\) order

\[
\text{Im}(Y_\nu^\dagger Y_\nu[Y_\nu^\dagger Y_\nu,Y_\ell^\dagger Y_\ell]Y_\nu^\dagger Y_\nu)_{ii}
\]

a negligible effect...

deg->hier: EDM get STRONGLY enhanced, LFV not
**See-Saw $\nu^c$-hier**

Solve RGE approx

$Y_v$

ew $\rightarrow$ $M_1$ $M_2$ $M_3$ $\Lambda$

LFV: at 1° order

$$\delta_{ij}^{LL} \propto \sum_{k=1,2,3} Y^\dagger_{v,ik} \ln \frac{\Lambda}{M_k} Y_{v,kj} = (C^k)_{ij}$$

*strong impact on SS models!*

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**EDM**

FC: at 2° order

[$01$ EllisHisanoLolaRaidalShimizu]

$$\text{Im}(a_i) \propto \sum_{k>k'} \frac{\ln(M_k/M_{k'})}{\ln(\Lambda/M_{k'})} \text{Im}(C^k C^{k'})_{ii}$$

FV: at 3° order $\tan\beta^3$

[$03$ IM]

$$\text{Im}(\delta_{RR} m_\ell \delta_{LL})_{ii} \propto \sum_{k>k'} \text{ln}_{k'} \text{Im}(C^k m_\ell^2 C^{k'})_{ii}$$

*dominant for $\tan\beta > 10$*

[formulae written as in IM&Savoy, ph/0501166]
See-Saw $\nu^c$-hier

Solve RGE approx

$Y_v$

ew

$M_1$ $M_2$ $M_3$ $\Lambda$

LFV: at 1° order

$\delta_{ij}^{LL} \propto \sum_{k=1,2,3} Y_{\nu i k}^\dagger \ln \frac{\Lambda}{M_k} Y_{\nu k j} = (C^k)_{ij}$

strong impact on SS models!

EDM

FC: at 2° order

'01 EllisHisanoLolaRaidalShimizu

$\text{Im}(a_i) \propto \sum_{k > k'} \frac{\ln (M_k/M_{k'})}{\ln (\Lambda/M_{k'})} \text{Im}(C^k C^{k'})_{ii}$

FV: at 3° order

'03 IM

$\text{Im}(\delta^{RR} m_\ell \delta^{LL})_{ii} \propto \sum_{k > k'} \tilde{\ln} k' \text{Im}(C^k m_\ell^2 C^{k'})_{ii}$

$g_\mu - 2$ region with $\tan \beta = 20$

$\left\{\begin{array}{c}
\text{dss} \\
10^{-25} \text{ecm}
\end{array}\right.$

below planned...

$\left\{\begin{array}{c}
\text{dss} \\
1/2 \times 10^{-27} \text{ecm}
\end{array}\right.$

At hand! Strong SS-model dependence
See-Saw + minSU(5)
**See-Saw+mSU(5)**

**LFV at 1° order:**
\[
\delta_{ij}^{LL} \propto \sum_k Y_{\nu ik}^\dagger \ln \left( \frac{\Lambda}{M_k} \right) Y_{\nu kj} = C_{ij}
\]
not changed

**not significant (now)**

**EDM [03 IM]**

**FC: at 2° order**
\[
\text{Im}(a_i) \propto \sum_{k \neq k'} \frac{\ln(M_k/M_{k'})}{\ln(\Lambda/M_{k'})} \text{Im}(C_k^k C_{k'}^{k'})_{ii}
\]
same as only See-Saw

**FV: at 2° order \( \bigstar \) \( \text{tg}\beta \)**
\[
\text{Im}(\delta_{ij}^{RR} m_{\ell} \delta_{LL})_{ii} \propto \text{Im}(C m_\ell Y_u^T Y_u^*)_{ii} \ln \left( \frac{\Lambda}{M_T} \right)
\]
MIXED

from
\[
U_c^c Y_u^T E_c^T H_{Tu}
\]
See-Saw+mSU(5)

even w/νc-deg

LFV at 1° order:

\[ \delta^{LL}_{ij} \propto \sum_k Y_{\nu ik} \ln \frac{\Lambda}{M_k} Y_{\nu kj} = C_{ij} \]

not changed

\[ \delta^{RR}_{ij} \propto (Y^T_u Y_u^*)_{ij} \ln \frac{\Lambda}{M_T} \]

not significant (now)

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**EDM [‘03 IM]**

**FC:** at 2° order

\[ \text{Im}(a_i) \propto \sum_{k>k'} \frac{\ln(M_k/M_{k'})}{\ln(\Lambda/M_{k'})} \text{Im}(C^k C^{k'})_{ii} \]

**FV:** at 2° order \( \star \) \( \tan \beta \)

\[ \text{Im}(\delta^{RR} m_\ell \delta^{LL})_{ii} \propto \text{Im}(C m_\ell Y^T_u Y_u^*)_{ii} \ln \frac{\Lambda}{M_T} \]

\( g_\mu \) region, \( \tan \beta = 20 \)

\( M_T = 2 \times 10^{16} \text{ GeV} \)

\( M_3 = 10^{15} \text{ GeV} \)

\( d^{SS5}_\mu \) \( 5 \times 10^{-25} \text{ ecm} \) below planned...

\( d^{SS5}_e \) \( 10^{-25} \text{ ecm} \) ABOVE present! \( \rightarrow \) \( \text{Im} (e^{-i\beta} C_{13}) < 0.1 \)
More realistic GUTs

N.B. minSU(5) ruled out by p-decay induced by $H_T$

(that requires $M_T \gg M_{\text{GUT}}$)

e.g. in SO(10) p-decay rate can be suppressed by introducing more Higgs triplets with particular mass matrix

What predictions for $d_e$?

[IM&Savoy, hep-ph/0309067]
**Semi-Realistic SO(10)**

Introduce:

\[ 16_i \quad 10^u_H = (H^u_D, H^u_T) + (\bar{H}^u_D, \bar{H}^u_T) \]

\[ 10^d_H = (H^d_D, H^d_T) + (\bar{H}^d_D, \bar{H}^d_T) \]

Fermion Masses

- u-quarks & Dirac-ν: \[ Y_u = Y_ν \]
- d-quarks & ch-lept: \[ Y_d = Y_e \]

→ T-Yukawas determined

**Masses of DOUBLETS**

\[ \begin{pmatrix} H^u_D & H^d_D \\ \bar{H}^d_D & e.w. \\ \bar{H}^u_D & 0 \end{pmatrix} \]

**TRIPLETS**

\[ \begin{pmatrix} H^u_T & H^d_T \\ \bar{H}^d_T & ? \\ \bar{H}^u_D & M_{GUT} \end{pmatrix} \times M_{GUT} \]

- (splitting problem)
- deg: \[ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \]
- cpD: \[ \begin{pmatrix} 0 & 1 \\ 1 & r < 1 \end{pmatrix} \]

(as D-W!)
From $d=5$ op generated by TRIPLET exchange

['82: Weinberg, Sakai, Yanagida, ... ]

$\tau_p$ depends A LOT on $M_T$-structure

deg: KO  cpD: SAFE

$g_{\mu}$ region & $tg\beta=3$

$\tau_p$ [yrs]
From $d=5$ op generated by TRIPLET exchange

['82: Weinberg, Sakai, Yanagida, ... ]

$\tau_p$ depends A LOT on $M_T$-structure

$deg$: KO  $cpD$: SAFE

$g_\mu$ region & $tg\beta=3$

From RGE where contributions of the many heavy states sum up

$de_e$ INSENSITIVE to $M_T$-structure

With (naturally) $O(1)$ phase:

Complementary in constraining SUSY GUTs
In this model \[
\frac{d_\mu}{d_e} \sim \left| \frac{V_{ts}}{V_{td}} \right|^2 \approx 25
\]

\[d_\mu < \text{planned}\]

When \(d_\mu > \text{planned}\) ?

May happen in L-R symm GUT models

[see: ’00 BabuDuttaMohapatra]
**Outlook**

EDMs are effective probes of TeV-scale NP beyond SM

in particular SUSY

Even thought it is interesting to compare their sensitivities by considering just ONE CPV source (like Argμ in SUSY) in general EDMs probe many different CPV sources

This is the case for RGE-induced LEDMs where CPV sources are Heavy State's Yukawas

See-Saw: EDMs generically below exp sensitivity

GUTs: EDMs possibly at hand

Planned EDM exp's have a strong impact on susy/seesaw/GUTs