EDMs and flavor violation in SUSY models

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Contents of my talk

1, Introduction of SUSY SM and flavor violation

2, EDMs induced by flavor-violation

3, Correlation with EDMs and FCNCs

4, Summary

This review is based on works with Shimizu, Kakizaki, Nagai and also includes my latest work with Paradisi and Nagai.
1. Introduction

Supersymmetric standard model (SUSY SM):

- Hierarchy problem \( M_Z \ll M_{\text{Planck}} \)
- Gauge coupling unification \( M_{\text{GUT}} \simeq 10^{16}\text{GeV} \)
- Dark matter \( \Omega_{\text{DM}} \simeq 22\% \)
- Light Higgs mass \( m_{h^0} \lesssim 130 - 140\text{GeV} \)

SUSY SM is nowadays a most well-motivated model beyond SM.
SUSY breaking mass terms for SUSY particles are new sources of CP/flavor violation.

F-term SUSY breaking

\[-\mathcal{L}_F = \frac{1}{2} M_{\tilde{g}} \tilde{g} \tilde{g} + \frac{1}{2} M_{\tilde{W}} \tilde{W} \tilde{W} + \frac{1}{2} M_{\tilde{B}} \tilde{B} \tilde{B} + B \mu h_1 h_2 + A_{u} f_{u} h_{2} \tilde{q}_{L} \tilde{u}_{R} + A_{d} f_{d} h_{1} \tilde{q}_{L} \tilde{d}_{R} + A_{t} f_{t} h_{1} \tilde{l}_{L} \tilde{e}_{R} + h.c.\]  

(Gaugino mass terms)

(Mixing mass terms for two Higgs bosons)

(Higgs-squark-squark and Higgs-slepto-slepton terms)

These mass parameters may have CP phases and contribute to EDMs. Bounds on EDMs gives constraints on sizes of the phases or SUSY particle masses. (SUSY CP problem)

\[|\sin \phi_A| \lesssim \left( \frac{M_{\text{SUSY}}}{\text{TeV}} \right)^2\]

\[|\sin \phi_B| \lesssim \left( \frac{M_{\text{SUSY}}}{\text{TeV}} \right)^2 \times \frac{1}{\tan \beta}
\]

Some mechanism should suppress F-term phases.
D-term SUSY breaking

Squarks and sleptons mass terms may be flavor-violating.

\[-\mathcal{L}_D = (m_{q_L}^2)_{ij} \tilde{q}^\dagger_{Li} \tilde{q}_{Lj} + (m_{u_R}^2)_{ij} \tilde{u}^\dagger_{Ri} \tilde{u}_{Rj} + (m_{d_R}^2)_{ij} \tilde{d}^\dagger_{Ri} \tilde{d}_{Rj} + (m_{l_L}^2)_{ij} \tilde{l}^\dagger_{Li} \tilde{l}_{Lj} + (m_{e_R}^2)_{ij} \tilde{e}^\dagger_{Ri} \tilde{e}_{Rj} \quad (i, j: \text{generation index})\]

Off-diagonal (flavor-violating) terms are stringently constrained from FCNC processes $K^0 - \bar{K}^0$ mixing and $\mu \rightarrow e\gamma$ (SUSY FCNC problem).

Universal scalar mass hypothesis works well to suppress FCNC processes. (ex, gravity or gauge mediation of SUSY breaking)

\[(m_{\tilde{q}_L}^2)_{ij} \propto \delta_{ij}\]

Minimal flavor violation: flavor violation comes from only CKM ($V$).

\[(m_{\tilde{d}_L}^2)_{ij} \propto V_{3i}^* V_{3j} \quad \text{(radiative correction)}\]
We are searching for non-minimal flavor violation.

- Universal scalar mass hypothesis works well, but it is really right?
  Other solutions for SUSY flavor problem:
  Decoupling/split SUSY hypothesis
  Sfermion-fermion mass alignment hypothesis

- Universality of scalar mass is really exact? Radiative correction affects it.
  **Seesaw mechanism** (introduction of heavy right-handed neutrino, $N_R$)

\[-\mathcal{L} = f_L l_L N_R h_2 + \frac{1}{2} M_N N_R N_R + h.c. \quad \Rightarrow \quad m_\nu = \frac{f_L^2 \langle h_2 \rangle^2}{M_N} (\text{tiny but finite neutrino mass})\]

Radiative correction to (left-handed) slepton masses:

\[
(m_L^2)_{ij} \simeq -\frac{(f_\nu f_\nu^T)_{ij}}{(4\pi)^2} (3m_0^2 + A_0^2) \log \frac{M_N^2}{M_{\text{planck}}^2} \quad (\text{gravity mediation case})
\]

Lepton flavor violation, such as $\mu \rightarrow e\gamma$, is predicted.

**SUSY GUT with $N_R$**
Quarks and leptons are unified, and then

- CKM mixing $\rightarrow$ right-handed slepton mixing
- Neutrino mixing $\rightarrow$ right-handed down squark mixing

Rich (non-minimal) flavor structure is predicted in the SUSY breaking.
Notation:
Mass insertion parameters
\[ (\delta_{\tilde{f}_L})_{ij} \equiv \frac{(m^2_{\tilde{f}_L})_{ij}}{m^2_{\tilde{f}_L}} \quad (f = q, l), \quad (\delta_{\tilde{f}_R})_{ij} \equiv \frac{(m^2_{\tilde{f}_R})_{ij}}{m^2_{\tilde{f}_R}} \quad (f = u, d, e) \]
for \( i \neq j \). Here, \( \frac{m^2_{\tilde{f}_L/R}}{m^2_{\tilde{f}_L/R}} \) is averaged value.

Yukawa coupling
\[ -\mathcal{L}_{\text{Yukawa}} = (f_u)_{ij} q_{Li} u_{Rj} h_2 + (f_d)_{ij} q_{Li} d_{Rj} h_1 + (f_e)_{ij} l_{Li} e_{Rj} h_1 \]

Ratio of Higgs vevs
\[ \tan \beta \equiv \frac{\langle h^0_2 \rangle}{\langle h^0_1 \rangle} \]
\[ (2 - 3) \lesssim \tan \beta \lesssim (50 - 60) \]
\[ f_b \sim f_l \quad \text{(Yukawa unification)} \]
2, EDMs induced by flavor-violation

\[ -\mathcal{L}_{\text{edm}} = \sum_{f=u,d,s,e} d_f \frac{i}{2} \bar{f}(\sigma^{\mu\nu} F_{\mu\nu})\gamma_5 f + \sum_{q=u,d,s} d_q^c \frac{i}{2} \bar{q}(\sigma^{\mu\nu} g_s G_{\mu\nu})\gamma_5 q \]

electric dipole moment (EDM)  \hspace{1cm} chromoelectric dipole moment (CEDM)

In SM a phase in CKM is unique origin of CP violation. Quark (C)EDMs are proportional to generation-diagonal Jarlskog invariants as

\[ d_u \propto \text{Im} (A_d[A_d, A_u]A_u f_u)_{11} \quad d_d \propto \text{Im} (A_d[A_d, A_u]A_u f_d)_{11} \]

where \( A_q \equiv f_q f_q^\dagger \) (\( q = u, d \)). This implies

\[ d_q \sim 10^{-(33-34)} \text{e cm} \quad O(\alpha_s G_F^2) \]

What do EDM measurements probe?

- New CP odd threshold (talked by Ritz.)

\[ d_f \sim e \frac{g^2}{(4\pi)^2} \frac{m_f}{M_{NP}^2} \sin \phi_{\text{CP}} \]

In SUSY SM, flavor-diagonal CP violation in F-term SUSY breaking.

- Non-minimal flavor violation enhances (C)EDMs. \( \longrightarrow \) target of my talk.

New Jarlskog invariants involving flavor violation in squark or slepton mass terms contribute to (C)EDMs.
• $(\delta_{\tilde{q}_L})_{ij} \neq 0$

$$d_d \propto \text{Im} ([A_u, \delta_{\tilde{q}_L}] f_d)_{11} \quad d_u \propto \text{Im} ([A_d, \delta_{\tilde{q}_L}] f_u)_{11} \quad (A_q \equiv f_q f_q^\dagger \ (q = u, d))$$

Only charged Higgsino contributes to them at one-loop level, then $d_d > d_u$.

In minimal flavor violation $(\delta_{\tilde{q}_L})_{ij} \propto V_{3i}^* V_{3j}$, and the EDMs vanish.

Future EDM measurements might cover it.

• $(\delta_{\tilde{d}_R})_{ij} \neq 0$ or $(\delta_{\tilde{u}_R})_{ij} \neq 0$

$$d_d \propto \text{Im} (A_u f_d \delta_{\tilde{d}_R})_{11} \quad d_u \propto \text{Im} (A_d f_u \delta_{\tilde{u}_R})_{11}$$

One-loop contribution is absent.
\( (\delta_{\tilde{q}_L})_{ij} \neq 0 \) and \( (\delta_{\tilde{d}_R})_{ij} \neq 0 \) or \( (\delta_{\tilde{q}_L})_{ij} \neq 0 \) and \( (\delta_{\tilde{u}_R})_{ij} \neq 0 \)

\[
d_d \propto \text{Im} (\delta_{\tilde{q}_L} f_d \delta_{\tilde{d}_R})_{11} \quad \text{and} \quad d_u \propto \text{Im} (\delta_{\tilde{q}_L} f_u \delta_{\tilde{u}_R})_{11}
\]

SUSY GUTs favor nonzero \( (\delta_{\tilde{q}_L})_{ij} \neq 0 \) and \( (\delta_{\tilde{d}_R})_{ij} \neq 0 \). Gluino contributes to EDMs at one-loop level and they are enhanced by heavy quark masses.

\[
d_d/e \sim \frac{\alpha_3}{4\pi} \frac{m_b}{M_{SUSY}^2} \tan \beta \times \text{Im}[(\delta_{\tilde{q}_L})_{13}(\delta_{\tilde{d}_R})_{31}]
\]

\[
\sim 1 \times 10^{-26}\text{cm} \tan \beta \times \frac{(\delta_{\tilde{d}_R})_{31}}{0.2^3} \left(\frac{M_{SUSY}}{500\text{GeV}}\right)^{-2}
\]

(Here, we assume max phase and \( (\delta_{\tilde{q}_L})_{13} = 0.2^3 \).)

Models has been already constrained from current EDM bounds.
Higgs mediation contribution at two-loop level in a case of \( (\delta_{\tilde{d}_R})_{ij} \neq 0 \)

Radiative correction to down quark mass matrix

\[
(m_d)_{ij} \simeq m_{d_i}^{\text{tree}} \delta_{ij} - \frac{\alpha_s \tan \beta}{9\pi} m_{d_i}^{\text{tree}} (\delta_{\tilde{d}_R})_{ij}
\]

This is not decoupled even in \( M_{\text{SUSY}} \rightarrow \infty \).

Charged Higgs coupling:

\[
\mathcal{L} = \frac{g_2}{\sqrt{2} m_W} \left\{ (V_{ik} m_{d_k} (U_R^\dagger)_{kj}) \tan \beta \, \bar{u}_i P_R d_j H^+ + m_{u_i} V_{ij} \cot \beta \, \bar{u}_i P_L d_j H^+ \right\}
\]

Where \( (U_R)_{i3} \simeq \frac{\alpha_s \tan \beta}{9\pi} (\delta_{\tilde{d}_R})_{i3} \).

Right-handed down coupling is enhanced by heavy quark mass.

Charged Higgs contributes to EDMs.

\[
d_d/e \sim \frac{\alpha_2}{4\pi} \frac{m_b}{m_{\tilde{d}_R}^2} \frac{m_t^2}{m_W^2} \times \frac{\alpha_s \tan \beta}{9\pi} \text{Im}[\delta_{\tilde{d}_R})_{13} V_{31}]
\]

\[
\propto \text{Im} \left( A_u f_d \delta_{\tilde{d}_R} \right)_{11}
\]

(JH, Nagai, Paradisi)
Higgs mediation contribution at two-loop level in a case of $(\delta_{\tilde{d}_{R}})_{ij} \neq 0$ (cont.)

- Charged Higgs contribution is already constrained from EDMs.

- This may dominate over 1-loop (gluino) contribution for $M_{\text{SUSY}} > (1 \sim 2)\text{TeV}$. SUSY parameter dependence is almost cancelled out in ratio of the gluino and charged Higgs loops, and the ratio is sensitive to only $m_{H^-}/M_{\text{SUSY}}$.

- It is more smoothly decoupled for heavy charged Higgs mass.

\[ d_d \propto \frac{1}{m_{H^-}^2} \times \log(m_t/m_{H^-}) \quad (m_{H^-} \gg m_t) \]
• \((\delta_{\bar{u}_R})_{ij} \neq 0\) case

\[
d_u/e \sim \frac{\alpha_2}{4\pi} \frac{m_t}{m_W^2} \times \frac{\alpha_s}{9\pi} \text{Im}\left[(\delta_{\bar{u}_R})_{13} V_{31}\right] \\
\quad \times \text{Im}\left(A_d f_u \delta_{\bar{u}_R}\right)_{11}
\]

Thus, \(d_u\) is suppressed by \(m_b/m_t\) compared with \(d_d\).

• \((\delta_{\bar{q}_L})_{ij} \neq 0\) case

EDMs are suppressed by light fermion masses, such as \(m_d/m_b\) or \(m_u/m_t\).
Leptonic EDM induced by flavor violation

Sources of flavor violation: $\delta_{L}^{L}$ and $\delta_{R}^{e}$.

New Jarskog invariants: $d_e \propto \text{Im} \left( \delta_{L}^{L} f_{e} \delta_{R}^{e} \right)_{11}$

Bino contributes to them at one-loop level and EDM is enhanced by heavy lepton mass.

\[
\frac{d_e}{e} \sim \frac{\alpha_Y}{4\pi} \frac{m_{\tau}}{M_{\text{SUSY}}^2} \tan \beta \times \text{Im}\left[ (\delta_{L}^{L})_{13}(\delta_{R}^{e})_{31} \right]
\]

\[
\sim 6 \times 10^{-27} \text{cm} \tan \beta \times \frac{(\delta_{L}^{L})_{13}(\delta_{R}^{e})_{31}}{0.26} \left( \frac{M_{\text{SUSY}}}{100 \text{GeV}} \right)^{-2}
\]  \hspace{1cm} \text{(max phase)}

Models has been already constrained from current EDM bound.

Charged Higgs contribution is not present. Neutral Higgs might contribute to EDM for large $\tan \beta$. This is under works.
3, Correlation with EDMs and FCNCs

Let us adopt flavor violation motivated by SUSY GUTs as working hypothesis.

In MSSM with right-handed neutrinos,

\[
\begin{align*}
(\delta_{\tilde{q}_L})_{ij} & \sim \frac{3}{(4\pi)^2} f_t^2 V_{3i}^* V_{3j} \log \frac{M^2_{\text{SUSY}}}{M^2_{\text{Planck}}} \sim V_{3i}^* V_{3j} \\
(\delta_{\tilde{L}})_{ij} & \sim \frac{1}{(4\pi)^2} f_{\nu_T}^2 U_{i3} U_{j3}^* \log \frac{M^2_N}{M^2_{\text{Planck}}} \\
(\delta_{\tilde{d}_R})_{ij} & \sim \frac{3}{(4\pi)^2} f_{\nu_T}^2 U_{3i}^* U_{3j} \log \frac{M^2_{\text{GUT}}}{M^2_{\text{Planck}}} \\
(\delta_{\tilde{e}_R})_{ij} & \sim \frac{3}{(4\pi)^2} f_t^2 V_{3i} V_{3j}^* \log \frac{M^2_{\text{GUT}}}{M^2_{\text{Planck}}} \\
(\delta_{\tilde{u}_R})_{ij} & \sim \frac{2}{(4\pi)^2} f_b^2 V_{i3}^* V_{j3} \log \frac{M^2_{\text{GUT}}}{M^2_{\text{Planck}}}
\end{align*}
\]

(\text{top quark Yukawa with CKM})

(\text{neutrino Yukawa})

(\text{top quark Yukawa with CKM})

(\text{bottom quark Yukawa with CKM})

Colored Higgs, which is SU(5) partner of SU(2) Higgs, induces right-handed mixing.

Under some assumptions neutrino sector,

\[ m_{\nu_T} = \frac{f_{\nu_T}^2 \langle h_2 \rangle^2}{M_N} \quad \text{and} \quad U : \text{MNS matrix} \]
Lepton flavor violation

- $\mu \to e\gamma$

\[\delta_{i_L} \text{ or } \delta_{i_R} \neq 0\]

\[\delta_{i_L} \text{ and } \delta_{i_R} \neq 0\]

\[\begin{align*}
Br(\mu \to e\gamma) &\sim 5 \times 10^{-5} \tan^2 \beta \left(\frac{M_{SUSY}}{100\text{GeV}}\right)^{-4} \\
&\times \left\{ |(\delta_{i_L})_{12} + 2.(\delta_{i_L})_{13}(\delta_{i_R})_{32}|^2 + |0.05(\delta_{i_R})_{12} + 2.(\delta_{i_R})_{13}(\delta_{i_L})_{32}|^2 \right\}
\end{align*}\]

- $\mu \to 3e$, $\mu - e$ conversion

\[\begin{align*}
Br(\mu \to 3e) &\approx 7 \times 10^{-3} Br(\mu \to e\gamma) \\
R(\mu - 3 : T\bar{\nu}) &\approx 6 \times 10^{-3} Br(\mu \to e\gamma)
\end{align*}\]
In a typical case of SUSY SU(5) GUT with NR, \((\delta_{i_L})\) terms dominate.

When \(\mu \rightarrow e\gamma\) is discovered, next problems are

- \(C_R\) or \(C_L\). Measured by polarized muon decay.

\[
H_{\text{eff}} = C_L \bar{e}_L (\sigma \cdot F) \mu_R + C_R \bar{e}_R (\sigma \cdot F) \mu_L
\]

\((\delta_{i_L})_{12} \neq 0 \Rightarrow C_L \neq 0\) and \((\delta_{\tilde{e}_R})_{12} \neq 0 \Rightarrow C_R \neq 0\)

- \((\delta_{i_L})_{12} \neq 0\) and/or \((\delta_{\tilde{e}_R})_{12} \neq 0\). Indirectly probed by electron EDM.

In case that terms with L and R mixing dominate,

\[
d_e/e \simeq 2.5 \times 10^{-26} \text{cm} \times \sqrt{Br(\mu \rightarrow e\gamma)/1.2 \times 10^{-12}}
\times \left( |(\delta_{i_L})_{23}/(\delta_{i_L})_{13}|^2 + |(\delta_{\tilde{e}_R})_{23}/(\delta_{\tilde{e}_R})_{13}|^2 \right)^{-1/2}
\]
Hadronic flavor violation and EDMs

Flavor mixing in squark sector is constrained from K/D/Bd/Bs meson mixing. When both left- and right-handed squarks have mixing,

\[ \Delta M_{K^0} : |Re[(\delta_{\bar{q}_L})_{12}(\delta_{\bar{d}_R})_{12}]| \lesssim 7 \times 10^{-6} \]
\[ \Delta M_{B_d^0} : |Re[(\delta_{\bar{q}_L})_{13}(\delta_{\bar{d}_R})_{13}]| \lesssim 3 \times 10^{-4} \]
\[ \Delta M_{B_s^0} : |Re[(\delta_{\bar{q}_L})_{23}(\delta_{\bar{d}_R})_{23}]| \lesssim 9 \times 10^{-3} \]
\[ \Delta M_{D^0} : |Re[(\delta_{\bar{q}_L})_{12}(\delta_{\bar{u}_R})_{12}]| \lesssim 3 \times 10^{-4} \]

where \( M_{SUSY} = 500\text{GeV} \).

Hg (neutron) EDM also gives constraints as

- **down quark (C)EDM**
  \[ |\text{Im}[(\delta_{\bar{q}_L})_{12}(\delta_{\bar{d}_R})_{21}]| \lesssim 0.6(1) \times 10^{-3} \]
  \[ |\text{Im}[(\delta_{\bar{q}_L})_{13}(\delta_{\bar{d}_R})_{31}]| \lesssim 3(0.2) \times 10^{-3} \]

- **up quark (C)EDM**
  \[ |\text{Im}[(\delta_{\bar{q}_L})_{12}(\delta_{\bar{u}_R})_{21}]| \lesssim 0.8(1) \times 10^{-3} \]
  \[ |\text{Im}[(\delta_{\bar{q}_L})_{13}(\delta_{\bar{u}_R})_{31}]| \lesssim 3(5) \times 10^{-5} \]

where \( M_{SUSY} = 500\text{GeV} \) and \( \tan \beta = 10 \).

- EDMs work well only except for 1-2 mixing in down quarks.
- What about 2-3 mixing in down quark?
Strange quark CEDM
Strange quark component in nuleo is not negligible. From baryon mass and sigma term in chiral perturbation theory,
\[ \langle p|\bar{u}u|p\rangle \simeq 4.8 , \quad \langle p|d d|p\rangle \simeq 4.1 , \quad \langle p|\bar{s}s|p\rangle \simeq 2.8 \] (Zhitnitsky)
Thus, hadronic EDMs depend on the strange quark CEDM via K or eta meson interaction. Using the QCD sum rule, ex,
\[ g_{pp\eta}^{CP} \simeq -\frac{2}{3\sqrt{3}f_\pi} \langle p|\bar{s}s|p\rangle m_0^2 d_s^c \quad (m_0^2 \simeq 0.8\text{GeV}^2) \] (Falk et al)
\[ \Rightarrow \quad d_{\text{Hg}}/e(d_s^c) \sim 4 \times 10^{-5} d_s^c , \quad d_n/e(d_s^c) \sim -0.2 d_s^c \] (JH, Shimizu)
This is close to an order of magnitude discussion, and further investigation, such as by lattice, should be needed.

Hg (neutron) EDM gives a constraint on squark mixing via \( d_s^c \)
\[ |\text{Im}[(\delta q_{L})_{23}(\delta q_{R})_{32}]| \lesssim 3(0.2) \times 10^{-3} \]
This is competitive to Bs mixing, \[ |\text{Re}[(\delta q_{L})_{23}(\delta q_{R})_{23}]| \lesssim 9 \times 10^{-3} \].
Strange quark CEDM v.s. b-s penguin

b-s penguin process, \( b \to s\bar{s}s \), is a radiative process, and sensitive to non-minimal flavor violation in SUSY SM. Measured CP asymmetry in \( B_d \to \phi K^0 \) is \( S_{\phi K} = 0.47 \pm 0.19 \) while SM prediction from \( b \to c\bar{c} s \) is \( \sin 2\beta = 0.726 \pm 0.037 \)

In SUSY GUT with NR, right-handed down squark mixing is introduced, and it contributes to the penguin processes. But, it is correlated with strange quark CEDM.

\[
H_{eff} = -C_8 \frac{g_s m_b}{(4\pi)^2} \bar{s}_L (\sigma \cdot G) b_R - C_8' \frac{g_s m_b}{(4\pi)^2} \bar{s}_R (\sigma \cdot G) b_L
\]

\[
\Rightarrow d_s^c = \frac{m_b}{8\pi^2} \frac{11}{21} \text{Im}[(\delta_{q_L})_{23}C_8']
\]
Correlation between $S_{\phi K}$ and $d_s^c$ (\[ d_s^c = \frac{m_b}{8\pi^2} \frac{11}{21} \text{Im}[\delta_{\text{qL}}_{23} C_8'] \])

Similar relation can be derived in charged Higgs mediation case.

\[ d_s^c = \frac{m_b}{8\pi^2} \text{Im}[V_{32} C_8'] \]
Future neutron and deuteron EDM measurements will give deep impacts on this model.
4, Summary

• SM works well to explain flavor violation, but now we are searching non-minimal flavor structure. EDMs probes it since non-minimal structure might enhances them. Future high sensitivity measurements of the EDMs would give a clue to it.

• In SUSY SM, the flavor violation generically predicts the EDMs when sfermion mass terms have non-minimal structure. The right-handed down squarks flavor mixing terms are already constrained whether left-handed squark mixing terms is zero (two-loop) or not (one-loop)

• Charged Higgs meditation effect on the EDMs at two loop level is discussed. It is not decoupled even if SUSY scale is larger. When squark masses is larger than a few TeV, it can be dominant. And it has moderate a decoupling property for the charged Higgs mass.

• Even when non-zero hadronic EDMs are measured, we cannot identify the origin. In that case, experimental studies of the FCNC processes and also more serious studies of the hadronic systems would be important.
• Future measurements of mu-e transition processes would also have a high sensitivity to the non-minimal structure in the lepton sector. SUSY SM is a good target for them.

• When mu-e transition processes are discovered, polarized muon experiments and electron EDM measurements would give a clue to understand the origin. Left-handed and/or right-handed slepton mixing?
Backup slide
Current bounds on EDMs

\[ |d_{\text{Tl}}| < 9 \times 10^{-25} \text{ ecm} \]
\[ |d_e| < 1.7 \times 10^{-27} \text{ ecm} \]
\[ |d_{\text{Hg}}| < 2 \times 10^{-28} \text{ ecm} \]
\[ |d_n| < 6 \times 10^{-26} \text{ ecm} \rightarrow 3 \times 10^{-26} \text{ ecm} \]

Future prospects on EDMs

- PbO, YbF molecule EDMs
  \[ d_e \rightarrow 10^{-29} \text{ ecm} \]
- muon EDMs
  \[ d_\mu \rightarrow 10^{-24} \text{ ecm} \]

(from Semertzidis’s presentation)