Electric Dipole Moment of Neutron, Deuteron and Mercury in Supersymmetry w/o R-parity

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Introduction

EDMs: Why should one care?

Energy resolutions in modern EDM experiment:

$$\Delta E \sim 10^{-6}\mathrm{Hz} \sim 10^{-21}\mathrm{eV}$$

Translates to limits on EDMs

$$|d| < \frac{\Delta E}{Electric\ Field} \sim 10^{-25}\mathrm{e} \times \mathrm{cm}$$

Comparing to theoretically inferred scaling

$$d \sim \frac{1}{\Lambda_{\mathrm{CP}}^2} \Rightarrow \Lambda_{\mathrm{CP}} \sim 1\mathrm{TeV}$$

Compares with the scale being probed at LHC

TeV scale background-free physics from sub-eV budget

Where to look for CPV new physics ?

B Decays

Though it is like hunting for needle in a haystack, there is no escape. B decays are our best bet to discover CPV in flavor changing sector.

Electric Dipole Moment

- the only place to hunt for flavor diagonal menifestation of CPV
- table top experiments (Compare this with B factories !)
- provide essentially background free probe
- proposed EDM exp. to probe CPV to unprecedented sensitivity
- ideal playground to study interplay of leptons, quarks, hadrons, nuclei, atoms and molecules.

An Elementary Slide

Classical EDM: $\vec{d} = q\vec{x}$

$\Rightarrow$ its a polar vector

$\Rightarrow$ $P\vec{d} = -\vec{d} \quad T\vec{d} = \vec{d}$

A Quantum EDM

$\Rightarrow$ Coefficient of dim 5 operator

$\Rightarrow$ $\vec{d} \propto \vec{s}$ An axial vector !!

$\Rightarrow$ $P\vec{d} = \vec{d} \quad T\vec{d} = -\vec{d}$

$\Rightarrow$ It violats P and T

Classical MDM: $\vec{\mu} = I\vec{A}$

$\Rightarrow$ its an axial vector

$\Rightarrow$ $P\vec{\mu} = \vec{\mu} \quad T\vec{\mu} = -\vec{\mu}$

A Quantum MDM:

$\Rightarrow$ Coefficient of dim 5 operator

$\Rightarrow$ $\vec{\mu} \propto \vec{s}$

$\Rightarrow$ $P\vec{\mu} = \vec{\mu} \quad T\vec{\mu} = -\vec{\mu}$

$\Rightarrow$ It conserves P and T

Current EDM searches

Three main categories

- EDMs of paramagnetic atoms and molecules $({}^{85}Rb, {}^{133}Cs, {}^{205}Tl)$
  most sensitive to leptonic sources of $P - T$ violation
  Best bound so far: $|d_{Tl}| < 6.9 \pm 7.4 \times 10^{-28}$ e cm
- EDMs of diamagnetic atoms $({}^{129}Xe$ and ${}^{199}Hg$
  most sensitive to hadronic sources of $P - T$ violation
  Best bound so far: $|d_{Hg}| < 3.1 \times 10^{-29}$ e cm (95% C.L.)
- EDMs of hadrons and nucleons
  Best bound so far: $d_n < 2.9 \times 10^{-26}$ e cm (90 % C.L.)

Shiff's Theorem and its Violation

Shiff showed that EDM interaction of a non-relativistic atom vanishes irrrespective of whether its constituents have EDMs or not

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Shiff’s Theorem and its Violation

It is based on two assumptions

- Atoms consist of non-relativistic particles which interact only electrostatically
- The EDM distribution of each atomic constituent is identical to its charge distribution

EDM vanishes due to screening of applied electric field

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EDM vanishes due to screening of applied electric field

Parmagnetic and diamagnetic EDMs result due to relativistic and finite size effects and such effects are maximized in heavy atoms

EDM: Hierarchy of Scales

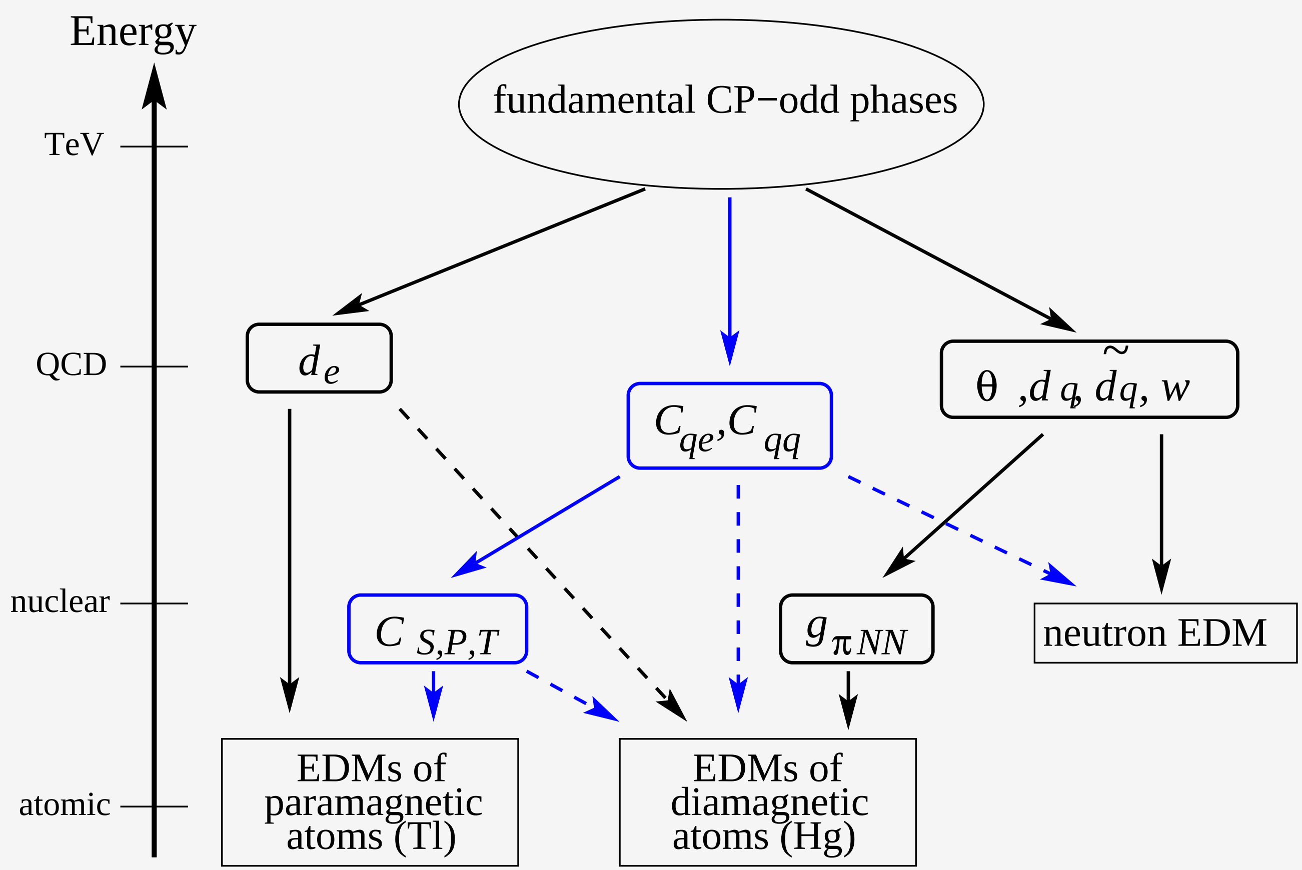

Figure source: M. Pospelov and A. Ritz *Annals of Physics 318 (2005) 119-169.*

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Neutron EDM

Three fundamental sources of contributions

- QCD θ-term $\frac{g_s^2}{32\pi^2}\bar{\theta}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$
- quark EDMs $d_i\bar{\psi}_i(F\sigma)\gamma_5\psi_i$ & CEDMs $d_i^c\bar{\psi}_i g_s(G\sigma)\gamma_5\psi_i$

Three different techniques

- Non-relativistic SU(6) quark model
- Chiral Lagrangian technique
- QCD sum rules

Non-relativistic SU(6) (Naive) quark model

Associate a non-relativistic wavefunction to the neutron consisting of three constituent quarks with two spin states each.

$$d_n = \Delta q d_q$$

where $\langle N|\bar{q}\gamma_\mu\gamma_5 q|N\rangle = \Delta q \bar{N}\gamma_\mu\gamma_5 N$ and $q = u, d$.

Naive quark model $\Rightarrow \Delta u = -1/3$ and $\Delta d = 4/3$ (C.G. coefficients).

However, Naive quark model may not be sufficient as the contribution to nucleon spin from the strange quark (Δs) is non-vanishing.

$$d_q = \eta^E d_q^E + \eta^C \frac{e}{4\pi} d_q^C$$

$\eta^E = .61 \quad \eta^C = 3.4$ are QCD running factors.

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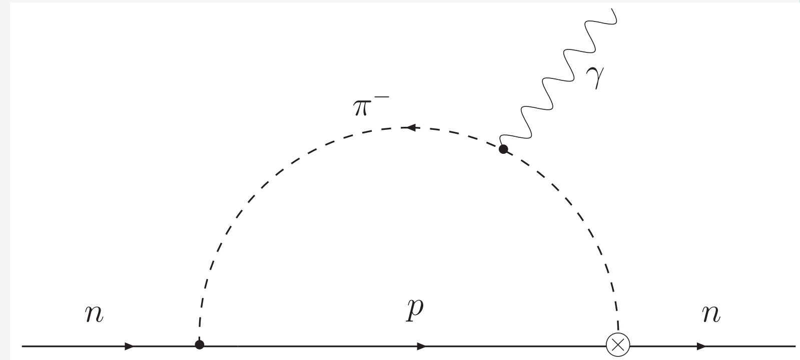
Chiral Techniques

First calculation

[Crewther, Veneziano, Witten PLB'79]

$$d_n = \frac{e}{\pi^2 M_n} g_{\pi NN} \bar{g}^0_{\pi NN} \ln \frac{\Lambda}{m_\pi}$$



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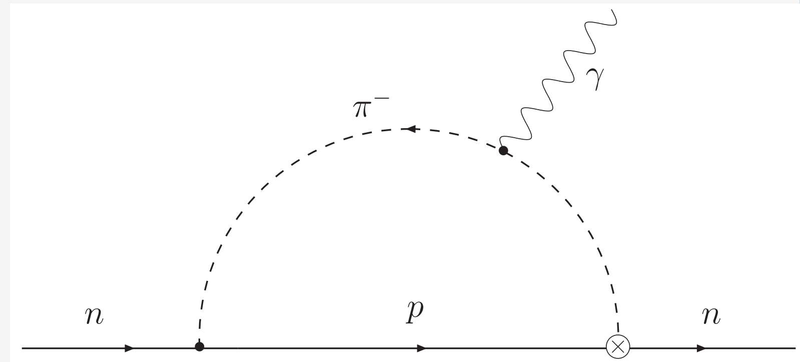

- For θ-term contribution, PCAC reduction of pion works well
  $\bar{g}^0_{\pi NN}(\theta_q) = \frac{\theta_q m_*}{f_\pi} \langle p|\bar{q}\tau^3 q|p\rangle \left(1 - \frac{m_\pi^2}{m_\eta^2}\right)$
  One can determine
  $\langle N|\bar{q}\tau^3 q|N\rangle$ from Lattice calculations or using global SU(3).

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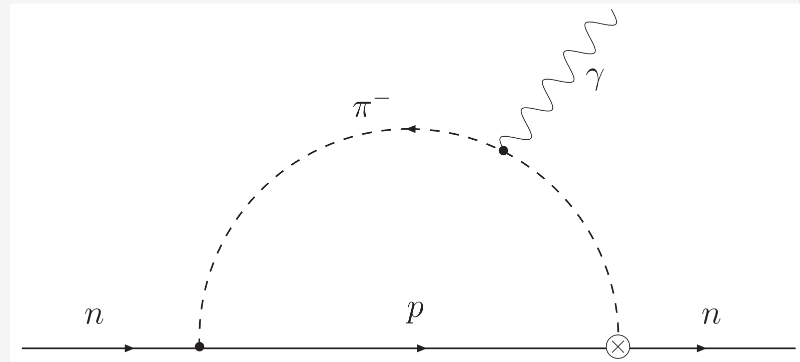

- Imposing $U(1)_{PQ}$ θ-term contribution vanishes
  However, the presence of CP-odd operators (CEDM) can shift the position of axion expectation value, leading to additional contributions $d_n(\theta_{\text{ind}})$ [Bigi, Uraltsev JETP'91]

- CEDM contribution is not calculable in Chiral Lagrangian method(?) Nevertheless, we have [Hisano and Shmizu PRD'2004]

$$d_n = -(1.6 \times d_u^C + 1.3 \times d_d^C + 0.26 \times d_s^C) \text{ e cm}$$

QCD Sum Rule

Pros –

- The only method that allows for systematic treatment of all CP violating sources
- Reduced uncertainly due to cancellation of light quark mass dependence

Cons –

- Sea quark and gluon dynamics difficult to incorporate
- Treatment of CPV operators upto dim=5

$$d_n^{PQ}(d_q^E, d_q^C) = (1 \pm 0.5 \frac{|\langle \bar{q}q \rangle|}{(225MeV)^3})[1.1e(d_d^C + 0.5 d_u^C) + 1.4(d_d^E - .25 d_u^E)]$$

QCD sum rule reproduces ratio of quark EDM contribution expected from non-relativistic SU(6) quark model !

Mercury and Deuteron EDM

Mercury EDM – Finite size nucleus gives rise to CPV $N - N$ interaction inducing Schiff moment $S(d^C, W, \theta)$ which generates CP-odd electrostatic potential $V_{\text{eff.}} = 4\pi S(\vec{I} \cdot \vec{\nabla})\delta(\vec{r})$ for electron and hence giving rise to atomic EDM. The QCD sum rule approach gives

$$d_{Hg} = -(d_d^C - d_u^C - 0.012 d_s^C) \times 3.2 \cdot 10^{-2} e.$$

The Chiral Lagrangian approach gives –

$$d_{Hg} = -8.7 \times 10^{-3} \times e(d_d^C - d_u^C - 0.0051 d_s^C).$$

For Deuteron EDM $d_D = d_n + d_p + d_D^{NN}$

$$d_D = -e(d_u^C - d_d^C) 5^{+11}_{-3}$$

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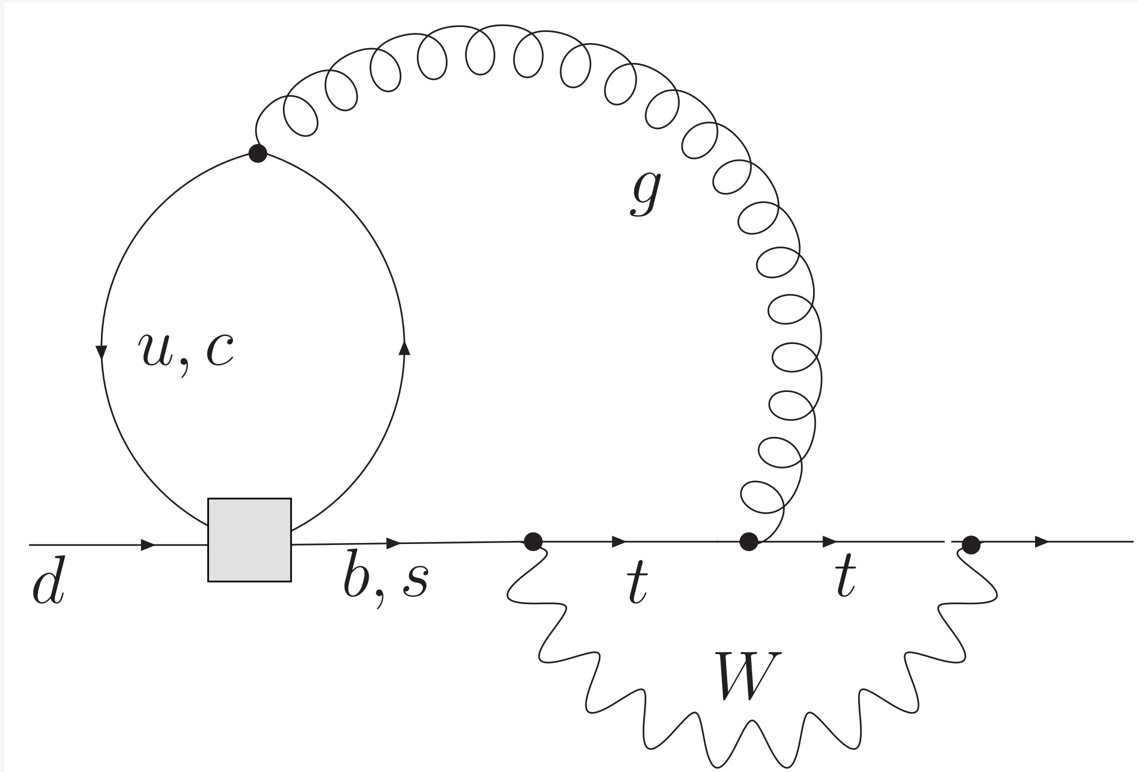
Neutron EDM in SM

KM phase contribution starts only at 3-loop



$$d_d^{KM} \approx 10^{-34}$$

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Supersymmetry w/o R-parity: Higgs identity crises

$\left(\hat{L}_i, \hat{H}_d\right)$ carry identical gauge quantum numbers

$\Rightarrow$ gauge int. respect an SU(4) symmetry in $\left(\hat{L}_i, \hat{H}_d\right)$ space

$\Rightarrow$ Yukawa int. break SU(4) symmetry

$\Rightarrow$ several choices before you write Superpotential W:

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Choice A: impose L and B conservation $\Rightarrow$ **MSSM**

$$W_{MSSM} = \mu_0 \hat{H}_u \hat{H}_d \; + \; h^u_{ij} \hat{Q}_i \hat{H}_u \hat{U}^c_j \; + \; h^d_i \hat{H}_d \hat{Q}_i \hat{D}^c_i \; + \; h^e_i \hat{H}_d \hat{L}_i \hat{E}^c_i$$

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Toward Choice B: Since L is accidental – forsake L conservation

$$W_{MSSM} = \mu_0 \hat{H}_u \underbrace{\hat{H}_d}_{\hat{L}_i} + h^u_{ij} \hat{Q}_i \hat{H}_u \hat{U}^c_j + h^d_i \underbrace{\hat{H}_d}_{\hat{L}_i} \hat{Q}_i \hat{D}^c_i + h^e_i \underbrace{\hat{H}_d}_{\hat{L}_i} \hat{L}_i \hat{E}^c_i$$

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Choice B: L violation $\Rightarrow \hat{H}_d \to \hat{L}_\alpha = (\underbrace{\hat{L}_0}_{\hat{H}_d}, \hat{L}_i)$

$$h_i^d \to \lambda'_{\alpha jk} = (\underbrace{\lambda'_{0ii}}_{h_i^d}, \lambda'_{ijk})$$

$$h_i^e \to \lambda_{\alpha\beta k} = (\underbrace{\lambda_{0ii}}_{h_i^e}, \lambda_{ijk})$$

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$$W_{MSSM+LV} = \mu_\alpha \hat{H}_u \hat{L}_\alpha + h^u_{ik} \hat{Q}_i \hat{H}_u \hat{U}^c_k + \lambda'_{\alpha jk} \hat{L}_\alpha \hat{Q}_j \hat{D}^c_k + \frac{1}{2} \lambda_{\alpha\beta k} \hat{L}_\alpha \hat{L}_\beta \hat{E}^c_k$$

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$$W_{MSSM+LV} \quad = \quad \mu_\alpha \hat{H}_u \hat{L}_\alpha \ + \ h^u_{ik} \hat{Q}_i \hat{H}_u \hat{U}^c_k \ + \ \lambda'_{\alpha jk} \hat{L}_\alpha \hat{Q}_j \hat{D}^c_k \ + \ \tfrac{1}{2} \lambda_{\alpha\beta k} \hat{L}_\alpha \hat{L}_\beta \hat{E}^c_k$$

Choice C: **R-parity violation** $\Rightarrow \ W_{MSSM+LV} + \frac{1}{2} \lambda''_{ijk} \hat{U}^c_i \hat{D}^c_j \hat{D}^c_k$

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Freedom of SU(4) Rotation: use and misuse

RPV Framework: though Yukawa break SU(4), LV implies a freedom of SU(4) rotation in $\left(\hat{L}_i, \hat{H}_d\right)$

Two popular choices:

- ⇒ single μ parametrization (SMP): all $\mu_i = 0$ for $i = 1, 2, 3$
- ⇒ single VEV parametrization (SVP): all $\tilde{\nu}_i = 0$ for $i = 1, 2, 3$

Which one is the best ?

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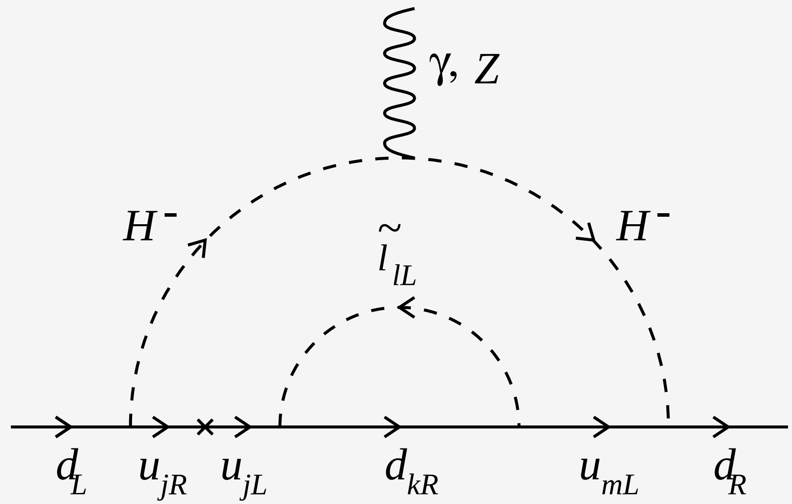
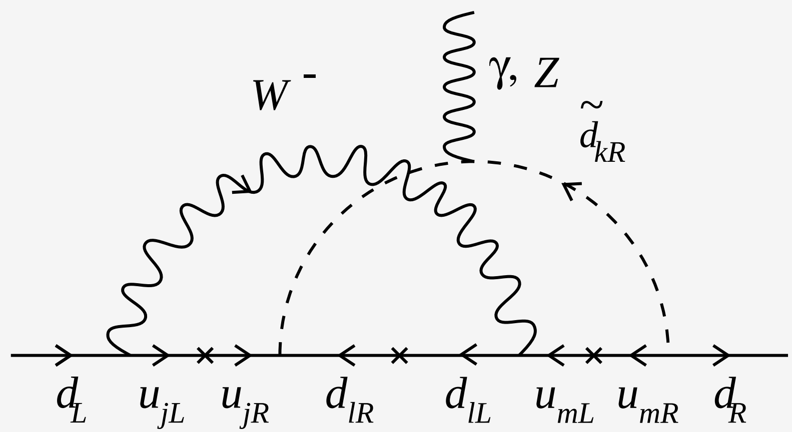
Which one is the best ? Depends on who you ask ? In practise –

- ⇒ both choices present their own complications
  [principle of conservation of difficulty]
- ⇒ it is important to specify a basis choice and work consistently
- ⇒ we shall work in SVP.

EDM from R-parity Violation

2-loop contribution [Godbole, Pakvasa, Rindani, Tata PRD'2000]





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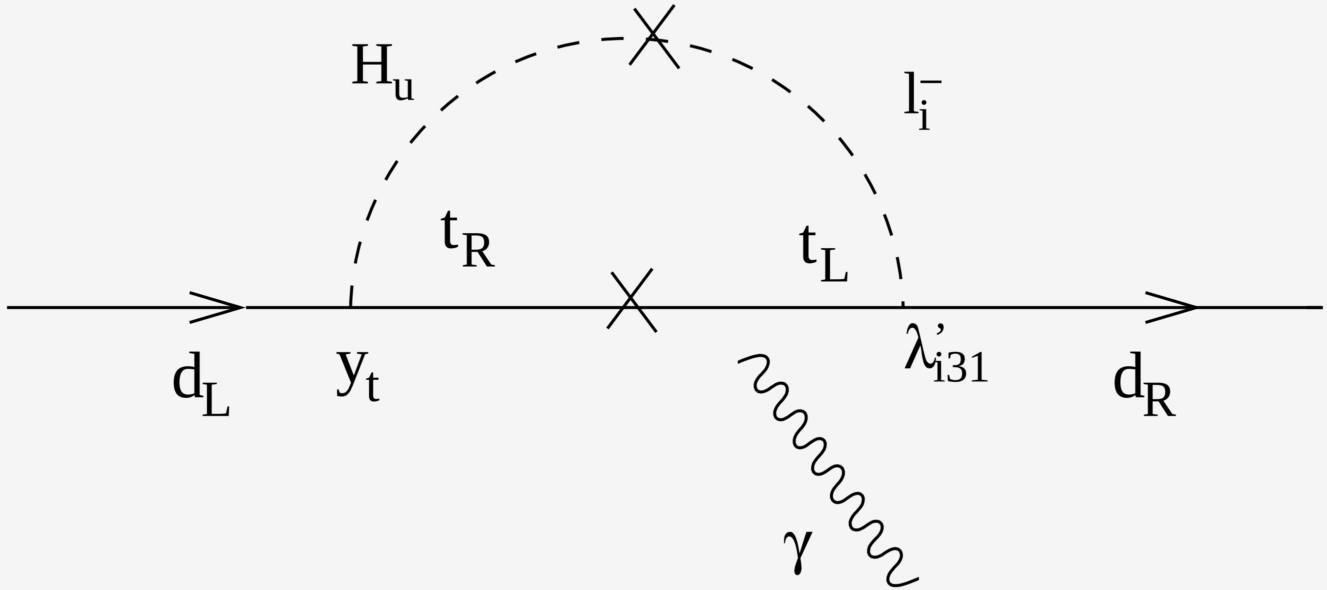
1-loop EDMs from R-parity Violation



The interacton Lagrangian defines the coefficients $\widetilde{\mathcal{C}}^{L,R}_{nmi}$.

$$\mathcal{L}^d = g_2 \overline{\Psi}(u_n)\Phi(\phi^-_m)\left[\widetilde{\mathcal{C}}^L_{nmi}\frac{1-\gamma_5}{2} + \widetilde{\mathcal{C}}^R_{nmi}\frac{1+\gamma_5}{2}\right]\Psi(d_i) \ + \text{h.c.}$$

$$\widetilde{\mathcal{C}}^{L*}_{nmi} = \frac{y_{u_n}}{g_2} V^{ni^*}_{\text{CKM}}\mathcal{D}^l_{1m} \ ,$$

$$\widetilde{\mathcal{C}}^{R*}_{nmi} = \frac{y_{d_i}}{g_2} V^{ni^*}_{\text{CKM}}\mathcal{D}^l_{2m} + \frac{\lambda'_{jki}}{g_2} V^{nk^*}_{\text{CKM}}\mathcal{D}^l_{(j+2)m} \ .$$

And similarly for the up-quark EDM.

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quark EDM is given as:

$$\left(\frac{d_f}{e}\right)_{\phi^-} = -\frac{\alpha_{\rm em}}{4\pi\,\sin^2\theta_W} \sum_m{}' \sum_{n=1}^{3} \mathrm{Im}(\widetilde{\mathcal{C}}^L_{nmi}\widetilde{\mathcal{C}}^{R*}_{nmi}) \frac{M_{f'_n}}{M^2_{\tilde{\ell}_m}} \left[(\mathcal{Q}_f - \mathcal{Q}_{f'})\, F_4\left(\frac{M^2_{f'_n}}{M^2_{\tilde{\ell}_m}}\right) - \mathcal{Q}_{f'}\, F_3\left(\frac{M^2_{f'_n}}{M^2_{\tilde{\ell}_m}}\right)\right],$$

and for the chromo-electric dipole form factor,

$$\left(d^C_f\right)_{\phi^-} = \frac{g_s\,\alpha_{\rm em}}{4\pi\,\sin^2\theta_W} \sum_m{}' \sum_{n=1}^{3} \mathrm{Im}(\widetilde{\mathcal{C}}^L_{nmi}\widetilde{\mathcal{C}}^{R*}_{nmi}) \frac{M_{f'_n}}{M^2_{\tilde{\ell}_m}}\, \mathcal{Q}_{f'}\, F_3\left(\frac{M^2_{f'_n}}{M^2_{\tilde{\ell}_m}}\right).$$

Analytical Expression

Focussing on RPV part of $\text{Im}(\widetilde{\mathcal{C}}^{L}_{nmi}\widetilde{\mathcal{C}}^{R*}_{nmi})$:

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Focussing on RPV part of $\mathrm{Im}(\widetilde{\mathcal{C}}^{L}_{nmi}\widetilde{\mathcal{C}}^{R*}_{nmi})$:

For d-quark EDM,

$$\mathrm{Im}(\widetilde{\mathcal{C}}^{L}_{nm1}\widetilde{\mathcal{C}}^{R*}_{nm1})_{RPV} = \mathrm{Im}\left[(y_{u_n} V^{n1}_{\mathrm{CKM}} \mathcal{D}^{l*}_{1m}) \times (\lambda'_{jk1} V^{nk*}_{\mathrm{CKM}} \mathcal{D}^{l}_{(j+2)m})\right].$$

For the u-quark dipole, we have

$$\mathrm{Im}(\widetilde{\mathcal{C}}^{L}_{nm1}\widetilde{\mathcal{C}}^{R*}_{nm1})_{RPV} = \mathrm{Im}\left[(\lambda'_{jkn} V^{1k*}_{\mathrm{CKM}} \mathcal{D}^{l}_{(j+2)m}) \times (y_{u} V^{1n}_{\mathrm{CKM}} \mathcal{D}^{l*}_{1m})\right].$$

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$m = 1$ Goldstone mode, $m = 2-5$ 1st order in perturbation, $m = 6-8$ 2nd order effects.

To 1st order: $\mathcal{D}^{l}_{(j+2)2}\,\mathcal{D}^{l*}_{12} \sim \frac{B^*_j}{M^2_s} \times \mathbf{O}(1)$

What about μ_i ?

Term involving μ_i is given as:

$$\mathcal{D}^{l}_{(j+2)(j+5)}\,\mathcal{D}^{l*}_{1(j+5)} \sim \frac{\mu_j^* m_j}{M_s^2} \times \left[\frac{(A_e^* - \mu_0 \tan\beta) m_j}{M_s^2} - \frac{\sqrt{2} M_W \sin\beta (\mu_k \lambda^*_{kjj})}{g_2 M_s^2}\right]$$

μ_i contribution is suppressed because:

- contributes at 2nd order in perturbation expansion
- proportionality to lepton mass
- in principle λ_{kjj} can also contribute but they have to be present in addition to μ_i and λ'_{ijk} making it 4th order in RPV.

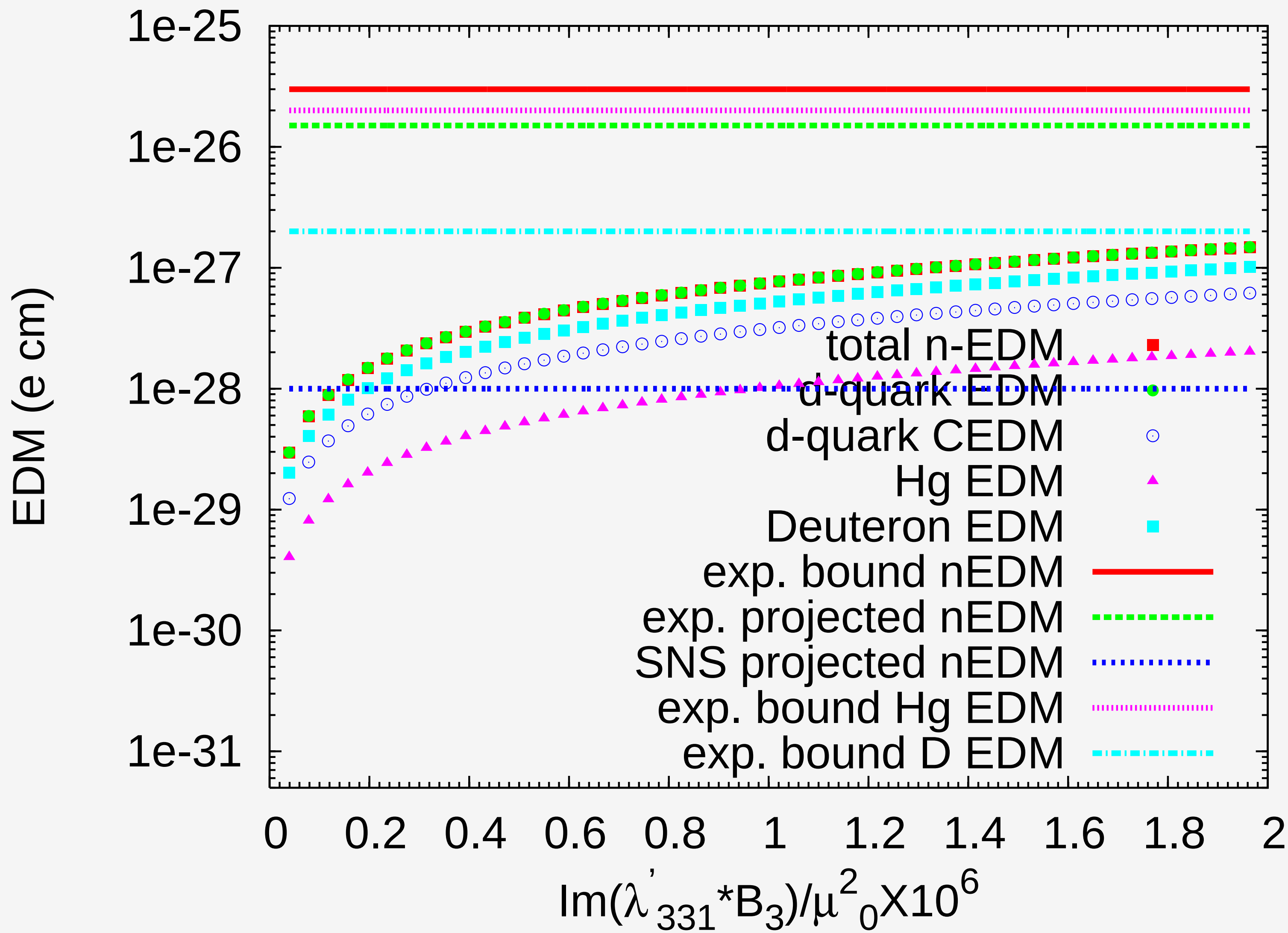
So we will concentrate on $B_i \lambda'$ kind of contributions.

Numerical Results

Parameter Specifications:

- Keep a pair(a bilinear B_i and a trilinear λ') of RPV couplings non-zero at a time
- All sleptons and H_d to be 100 GeV, $\mu_0 = -300$ GeV
- up-type Higgs and B_0 determined from EW symmetry breaking condition
- $\tan\beta = 3$ (very little sensitivity to $\tan\beta$
- CKM phase + relative phase of $\pi/4$ in RPV couplings

Nemerics: the top loop conribution



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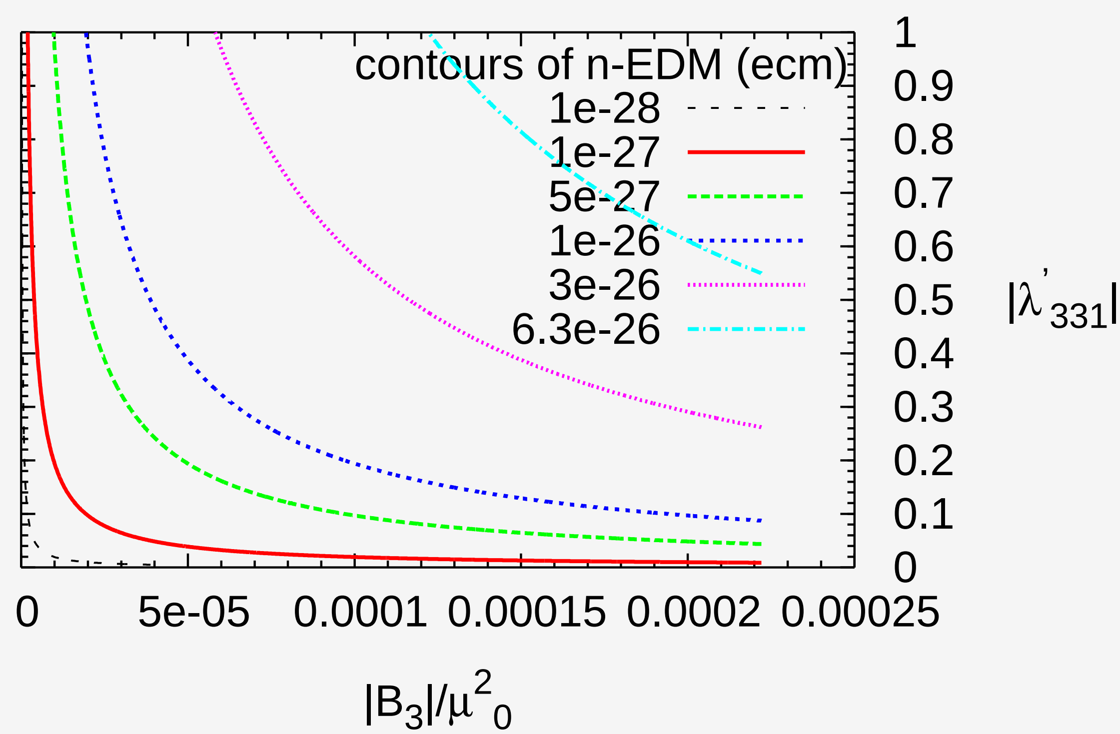
contours of n-EDM (ecm)
1e-28
1e-27
5e-27
1e-26
3e-26
6.3e-26
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$|\lambda'_{331}|$
0
5e-05
0.0001
0.00015
0.0002
0.00025
$|B_3|/\mu^2_0$

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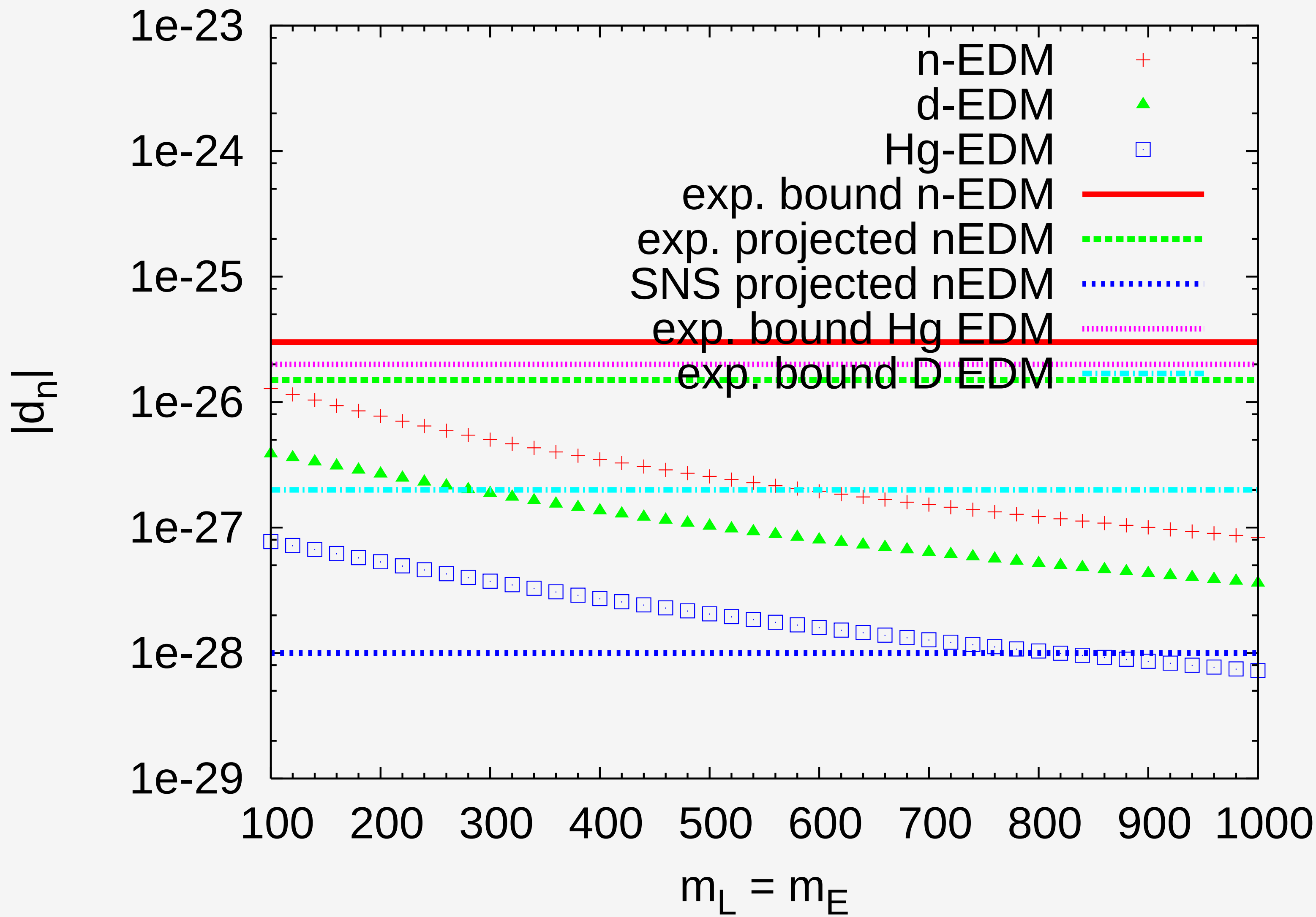

n-EDM
d-EDM
Hg-EDM
exp. bound n-EDM
exp. projected nEDM
SNS projected nEDM
exp. bound Hg EDM
exp. bound D EDM
|d_n|
1e-23
1e-24
1e-25
1e-26
1e-27
1e-28
1e-29
100 200 300 400 500 600 700 800 900 1000
m_L = m_E

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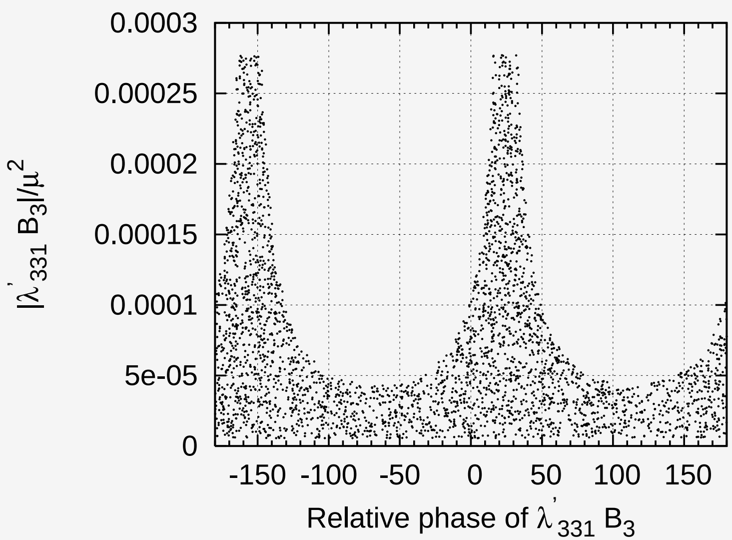
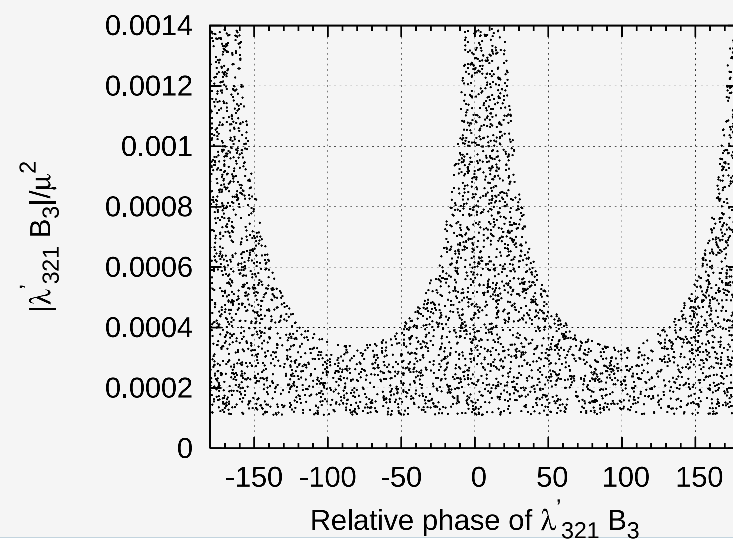
Table of bounds

Parameter values	μ_0 (GeV)	$\tilde{m}_L$ (GeV)	m_{H_d} (GeV)	RPV phase	$\frac{\Im(B_i^* \cdot \lambda'_{i31})}{(100\ \text{GeV})^2}$ I	II	III
(a)	-100	100	100	$\pi/4$	1.5×10^{-4}	5.0×10^{-7}	1.5×10^{-5}
(b)[a]	-100	100	100	0	8.0×10^{-5}	2.5×10^{-7}	2.0×10^{-5}
(c)	-400	100	100	$\pi/4$	5.5×10^{-4}	2.6×10^{-6}	5.2×10^{-5}
(d)	-800	100	100	$\pi/4$	1.7×10^{-3}	5.5×10^{-5}	1.5×10^{-4}
(e)	-100	400	100	$\pi/4$	6.3×10^{-4}	2.1×10^{-6}	5.6×10^{-5}
(f)	-100	800	100	$\pi/4$	1.9×10^{-3}	6.4×10^{-6}	1.6×10^{-4}
(g)	-100	100	300	$\pi/4$	3.8×10^{-4}	1.2×10^{-6}	3.6×10^{-5}
(h)	-100	100	600	$\pi/4$	1.0×10^{-3}	3.5×10^{-6}	9.2×10^{-5}


0.0003
0.00025
0.0002
0.00015
0.0001
5e-05
0
-150 -100 -50 0 50 100 150
Relative phase of λ'331 B3
|λ'331 B3|/μ2


0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
-150 -100 -50 0 50 100 150
Relative phase of λ'321 B3
|λ'321 B3|/μ2

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Thanks !

How do I experimentally detect a Permanant neutron EDM ?

- Ultracold neutrons (UCN) trapped in uniform $\vec{E}$ and $\vec{B}$ fields.
- $H = H_0 - \mu_n.\vec{B} - d_n.\vec{E}$
- Larmor frequencies are given by
  $h\nu_{\uparrow\uparrow} = |2\mu_n B + 2d_n E|$ for $\vec{s}_n \uparrow\uparrow$ to $\vec{B}, \vec{E}$
  $h\nu_{\uparrow\downarrow} = |2\mu_n B - 2d_n E|$ for $\vec{s}_n \uparrow\uparrow$ to $\vec{B}$ and $\uparrow\downarrow$ $\vec{E}$
- Now measure any shift in the transition frequency ν as an applied field $\vec{E}$ alternated between being parallel and then anti-parallel to $\vec{B}$

The electric field technique explains the focus on the neutral particles for EDM measurement

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‘Permanant’ EDM of Polar Molecules (Ammonia and Water)

- H_2O and NH_3 have pair of nearly degenerate states with opposite parities $|+\rangle, |-\rangle$

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'Permanant' EDM of Polar Molecules (Ammonia and Water)

- In presence of external $\vec{E}$
  $|r\rangle = \frac{(|+\rangle + |-\rangle)}{\sqrt{2}}$
  $|l\rangle = \frac{(|+\rangle - |-\rangle)}{\sqrt{2}}$
  $E_{r,l} = \frac{1}{2}(E_+ + E_-) \pm \left[\frac{1}{4}(E_+ - E_-)^2 + (e\langle\vec{x}\rangle.\vec{E})^2\right]^{\frac{1}{2}}$
- Because $E_\pm$ are almost degenerate $e\langle\vec{x}\rangle.\vec{E}$ dominates
  $E_{r,l} = \frac{1}{2}(E_+ + E_-) \pm e\langle\vec{x}\rangle.\vec{E}$
- Energy shift is linear in $\vec{E}$ and the proportionality constant is called permanant EDM of this molecule
- If measurement were carried out infinitesimally weak $\vec{E}$ at very low temp. the shift would be quadratic

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These are induced EDMs and DO NOT violate P, T

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Summary

- A combination of bilinear and trilinear RPV is the only way RPV parameters can contribute at one loop level. With top mass and top yukawa it gives large contribution.
- In our numerical exercise we have obtained robust bounds on the combinations $\frac{|B_i^* \cdot \lambda'_{ij1}|}{(100\ \text{GeV})^2}$ for $i, j = 1, 2, 3$ that have not been reported before.
- These contributions are not much sensitive to $\tan\beta$ and even with slepton mass at TeV scale it predicts EDM for neutron that is order of magnitude larger than sensitivity of Los Alamos expriment.
- Even if the RPV couplings are real, they could still contribute to neutron EDM via CKM phase. For some cases CKM phase induced contribution is as strong as that due to an explicit complex phase in the RPV couplings.

- There also exist contributions involving $\mu_i^* \lambda'_{ijk}$. However these are higher order effects which are further suppressed by proportionality to charged lepton mass. Since μ_i are expected to be very small (of order 10^{-3} GeV) for sub-eV neutrino masses, such contributions are highly suppressed.

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Thank you very much !