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A Predictive Seesaw Scenario for EDMs

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hep-ph/0502022 with Masiero, Rossi, Vempati

Neutrino mass
seesawing to New Physics

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \Rightarrow \begin{pmatrix} -\frac{m_D^2}{M} & 0 \\ 0 & M \end{pmatrix}$$

$$m_\nu = \frac{m_D^2}{M} \sim 0.1 \text{ eV}$$

$$m_D \sim 100 \text{ GeV}$$
$$\rightarrow M \sim 10^{14} \text{ GeV}$$

- Question is if test such high scale physics.
- Possibly with many low-energy signatures featuring neutrino properties.

Supersymmetry: FCNC and CP problem

- Squark/slepton mixing leads to FCNC
- CP phase in soft terms leads to EDMs

$\mathrm{B}(\mu \to e\gamma) < 10^{-11}$ ⇒ $\delta_{12}^{LL} < 10^{-3}$

$d_e < 10^{-27} ecm$ ⇒ $\mathrm{Im}(A) < 10^{-2}$

$$\delta_{ij}^{LL} \equiv \frac{m^2_{\tilde{L}ij}}{m^2_{\tilde{L}}}$$

➢ Constraints today, discovery tomorrow…

FCNC & CPV as probes of Seesaw

- Neutrino sector provides new source of flavor violation and CP phase.
- Correlated pattern of LFV & EDM in relation to the neutrino data may then emerge to be tested:

  SUSY triplet (type II) seesaw model

Assumption: SUSY CP phase only in the neutrino sector.

Supersymmetric Seesaw Models

$$W_0 = \mathbf{Y}_e H_1 e^c L + \mathbf{Y}_d H_1 d^c Q + \mathbf{Y}_u H_2 u^c Q + \mu H_1 H_2$$

- Singlet Seesaw (Type I)

$$W_N = \mathbf{Y}_N N L H_2 + \frac{1}{2}\mathbf{M}_N N N$$

$$\mathbf{m}_D = \mathbf{Y}_N v_2 \qquad \mathbf{m}_\nu = v_2^2 \mathbf{Y}_N^T \mathbf{M}_N^{-1} \mathbf{Y}_N$$

$$\mathbf{m}_\nu = \mathbf{U}^* \mathbf{m}_\nu^D \mathbf{U}^\dagger .$$

- Triplet Seesaw (Type II)

$$W_T = \frac{1}{\sqrt{2}}(\mathbf{Y}_T L T L + \lambda_1 H_1 T H_1 + \lambda_2 H_2 \bar{T} H_2) + M_T T \bar{T}$$

$$T=(T^0,T^+,T^{++}),\ \bar{T}=(\bar{T}^0,\bar{T}^-,\bar{T}^{--}) \qquad \langle T \rangle = \frac{\lambda_2 v_2^2}{M_T} \qquad \mathbf{m}_\nu = \frac{v_2^2 \lambda_2}{M_T}\mathbf{Y}_T$$

Supersymmetric Seesaw Models

- Singlet Seesaw (Type I)

$$\mathbf{m}_\nu = v_2^2 \mathbf{Y}_N^T \mathbf{M}_N^{-1} \mathbf{Y}_N$$

15 ($\mathbf{Y}_N$) + 3 ($\mathbf{M}_N$) = 18 parameters

$$\mathbf{Y}_N = \frac{1}{v_2}\sqrt{\mathbf{M}_N} R \sqrt{\mathbf{m}_\nu^D} U^\dagger$$

R: complex orthogonal, $RR^T = R^T R = 1$

3 ($\mathbf{m}_\nu^D$) + 6 (U) + 6 (R) + 3 ($\mathbf{M}_N$) = 18

Unknown flavor structure in R and $\mathbf{M}_N$

- Triplet Seesaw (Type II)

$$\mathbf{m}_\nu = \frac{v_2^2 \lambda_2}{M_T} \mathbf{Y}_T$$

9 ($\mathbf{Y}_T$) + { 4 ($\lambda_{1,2}$) + 1 (M_T) } = 14

Same flavor structure for $\mathbf{m}_\nu$ and $\mathbf{Y}_T$.

Low Energy Signatures of Supersymmetric Seesaw Model

Neutrino Yukawa couplings induces

$$\mathbf{Y}_N,\ \mathbf{Y}_T$$

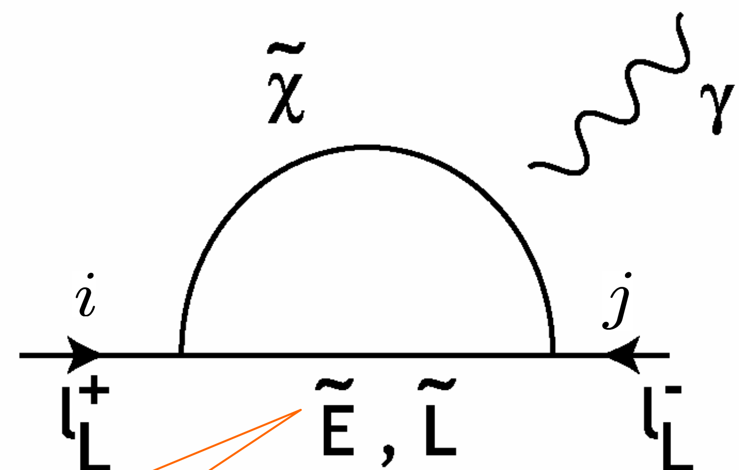
- LFV rare decays

$$\mu \to e\gamma$$

$$\tau \to \mu/e\,\gamma$$

- CP phase/Fermion EDMs

$$d_{e,\mu,\tau}\ \ d_{u,d}$$



slepton mixing $(\mathbf{Y}^\dagger\mathbf{Y})_{ij}$

Lepton Flavor Violation

$$B(l_i \to l_j \gamma) \approx 10^{-5} \frac{M_W^4}{m_{\tilde{L}}^4} \tan^2\beta \, |\delta_{ij}^{LL}|^2 \, B(l_i \to l_j \bar{\nu}_j \nu_i)$$

$$\delta_{ij}^{LL} \equiv \frac{m_{\tilde{L}ij}^2}{m_{\tilde{L}}^2}$$

Fermion EDMs

$$\frac{d_l}{e\,cm} \sim 10^{-25} \sin\varphi_A \left(\frac{m_l}{0.5\ \text{MeV}}\right) \left(\frac{300\ \text{GeV}}{\tilde{m}}\right)^2$$

$$\frac{(d_e)_i}{e} \approx \frac{-\alpha}{4\pi c_W^2} m_{e_i} \frac{M_1 \text{Im}(\delta\hat{\mathbf{A}}_e)_{ii}}{m_{\tilde{L}}^4} F(x_1),$$

$$\frac{(d_d)_i}{e} \approx \frac{-2\alpha_s}{9\pi} m_{d_i} \frac{M_3 \text{Im}(\delta\hat{\mathbf{A}}_d)_{ii}}{m_{\tilde{Q}}^4} F(x_3),$$

$$\frac{(d_u)_i}{e} \approx \frac{4\alpha_s}{9\pi} m_{u_i} \frac{M_3 \text{Im}(\delta\hat{\mathbf{A}}_u)_{ii}}{m_{\tilde{Q}}^4} F(x_3),$$

Tree or one−loop

Flavor Violation due to Neutrino Yukawas (Type I)

Ellis,Hisano,Raidal,Shimizu, hep-ph/0206110

- RG-induced soft masses

  $M_G \to Q_k = M_{N_k}$

  at Y_N^2

$$(\delta m^2_{\tilde L})_{ij} \simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)H_{ij}\,, \quad H_{ij} = \sum_k \left[\mathbf{Y}_N^\dagger(Q_k) \ln\frac{M_G}{Q_k}\mathbf{Y}_N(Q_k)\right]_{ij}$$

$$(\delta A_e)_{ij} \simeq -\frac{1}{8\pi^2}A_0 Y_{e_i} H_{ij}\,, \qquad RR^T = R^T R = 1$$

$$H = \frac{1}{v_2^2} U\sqrt{\mathbf{m}_\nu^D} R^\dagger \overline{M_N} R \sqrt{\mathbf{m}_\nu^D} U^\dagger$$

$$\overline{M_{N_i}} \equiv M_{N_i}\log(M_G/M_{N_i})$$

Nontrivial flavor structure

- CP phase from higher-order $\mathrm{Im}(\delta \mathbf{A}) \neq 0$

  at Y_N^4

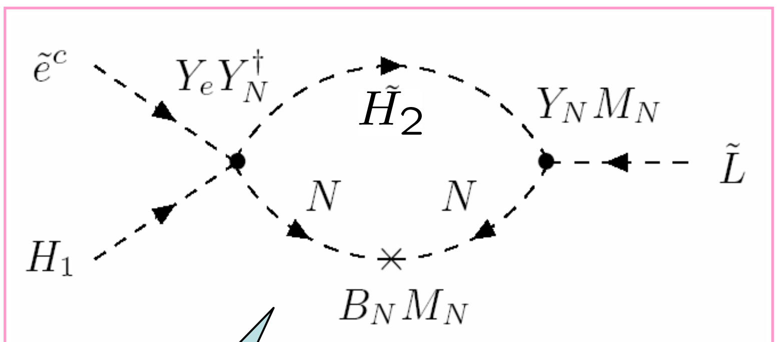
$$(\delta' \mathbf{A}_e)_{ii} \approx \frac{4}{(4\pi)^4} A_0 (\mathbf{Y}_e)_i \left[\sum_{k<l} [X_k, X_l] \ln\frac{M_{N_l}}{M_{N_k}}\right]_{ii} \ln\frac{M_G}{M_N}$$

where $X_k \equiv \mathbf{Y}_N^\dagger(Q_k)\mathbf{Y}_N(Q_k)$

Vanishes for degenerate RHN

Flavor Violation due to Neutrino Yukawas (Type I)

New contribution
from B term
at Y_N^2



finite

CP phase of Im(B)

$$\delta \mathbf{A}_e = -\frac{1}{16\pi^2} \mathbf{Y}_e (\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)$$

Farzan, hep−ph/0310055

$$\delta \mathbf{A}_u = -\frac{1}{16\pi^2} \mathbf{Y}_u \,\mathrm{tr}(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)$$

CMRV, hep−ph/0502022

LFV, EDM ratios in Type I

Conventional contribution

Depend on unknowns in Y_N & M_k

$$\frac{B(\mu\to e\gamma)}{B(\tau\to\mu\gamma)} \propto \frac{H_{12}}{H_{23}}$$

$$H_{ij} = \sum_k \left[\mathbf{Y}_N^\dagger(Q_k) \ln \frac{M_G}{Q_k} \mathbf{Y}_N(Q_k)\right]_{ij}$$

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \frac{\left[\sum [X_k, X_l] \ln \frac{M_{N_l}}{M_{N_k}}\right]_{22}}{\left[\sum [X_k, X_l] \ln \frac{M_{N_l}}{M_{N_k}}\right]_{11}}$$

$$X_k = \sum_k \mathbf{Y}_N^\dagger(Q_k) \mathbf{Y}_N(Q_k)$$

New contribution inducing also quark EDM

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \frac{(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)_{22}}{(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)_{11}}, \qquad \frac{d_u}{d_e} \approx C \frac{m_u}{m_e} \frac{\mathrm{tr}(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)}{(\mathbf{Y}_N^\dagger \mathbf{B}_N \mathbf{Y}_N)_{11}},$$

CMRV, hep-ph/0502022

Flavor Violation due to Neutrino Yukawas (Type II)

- RGE of soft masses

$$\mathbf{m}^2_{\tilde{L}} \approx \frac{-1}{8\pi^2}(9m_0^2 + 3A_0^2)(\mathbf{Y}_T^\dagger \mathbf{Y}_T) \log\frac{M_G}{M_T}$$

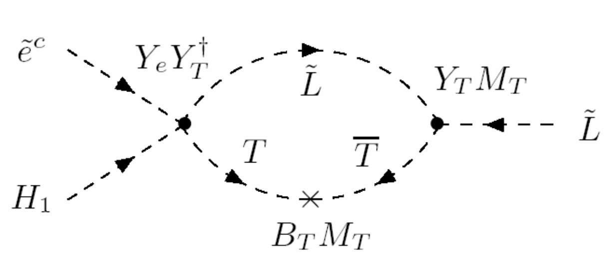
$$\mathbf{A}_e \approx \frac{-9}{16\pi^2} A_0(\mathbf{Y}_e \mathbf{Y}_T^\dagger \mathbf{Y}_T) \log\frac{M_G}{M_T}$$

- New contribution from B term

$$\delta\mathbf{A}_e = -\frac{3}{16\pi^2}\mathbf{Y}_e\left(\mathbf{Y}_T^\dagger \mathbf{Y}_T + |\lambda_1|^2\right) B_T,$$

$$\delta\mathbf{A}_d = -\frac{3}{16\pi^2}\mathbf{Y}_d|\lambda_1|^2 B_T,$$

$$\delta\mathbf{A}_u = -\frac{3}{16\pi^2}\mathbf{Y}_u|\lambda_2|^2 B_T.$$



CPV in Type II

- Conventional contribution from higher–loops suppressed at Y_T^6

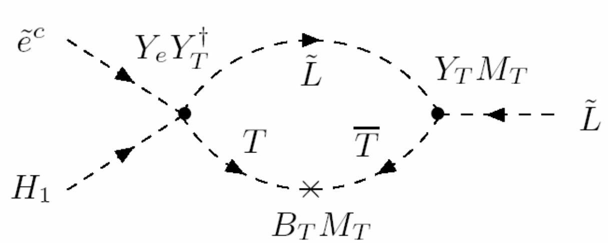
$$Y_e Y_\tau^2 \,\mathrm{Im}[(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{12}(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{23}(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{31}] = Y_e Y_\tau^2 |Y_N|^6 \sin^2\theta_{13} \sin 2\delta$$

Dirac phase in V

- Leading B–term contribution at Y_T^2

$$\delta \mathbf{A}_e = -\frac{3}{16\pi^2}\mathbf{Y}_e\left(\mathbf{Y}_T^\dagger \mathbf{Y}_T + |\lambda_1|^2\right) B_T,$$

$$\mathbf{Y}_T^\dagger \mathbf{Y}_T = \mathbf{V}(\mathbf{m}_\nu^D)^2 \mathbf{V}^\dagger \left(\frac{M_T}{\lambda_2 v_2^2}\right)^2$$



made assumption $(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{ii} \gg |\lambda_1|^2$

LFV in Type II

Rossi, hep-ph/0207006

EJC,Park, hep-ph/0306069

The ratio of branching ratios depends only on neutrino parameters

$$(\mathbf{m}^2_{\tilde{L}})_{12} : (\mathbf{m}^2_{\tilde{L}})_{13} : (\mathbf{m}^2_{\tilde{L}})_{23} = 1 : \tan\theta_{23} : \rho \frac{\sin 2\theta_{23}}{\cos\theta_{23} \sin 2\theta_{12}}$$

$$\rho \equiv \frac{\Delta m^2_{31}}{\Delta m^2_{21}} \approx 25$$

for $s_{13} < \rho^{-1} c_{12} s_{12} \sim 0.02$

$$B(\mu \to e\gamma) : B(\tau \to e\gamma) : B(\tau \to \mu\gamma) \approx 1 : 0.1 : 300$$

Lepton EDMs in Type II

CMRV, hep-ph/0502235

- Ratio of Lepton EDMs

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e}\frac{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{22}}{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{11}}, \qquad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu}\frac{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{33}}{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{22}}$$

Depending on the neutrino mass patterns

(HI) $m_3 \gg m_2 > m_1$
(IH) $m_2 \sim m_1 \gg m_3$
(DG) $m_3 \approx m_2 \approx m_1$

$$\rho \equiv \frac{\Delta m^2_{31}}{\Delta m^2_{21}} \approx 25$$

$$[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{11} : [\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{22} : [\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{33}$$
$$= \begin{cases} c^2_{13}s^2_{12} + \rho s^2_{13} : \rho c^2_{13}s^2_{23} : \rho c^2_{13}c^2_{23} & \text{(HI)} \\ c^2_{13} : c^2_{23} : s^2_{23} & \text{(IH)} \\ 1:1:1 & \text{(DG)} \end{cases}$$

Lepton EDMs in Type II

CMRV, hep-ph/0502235

- Ratio of Lepton EDMs

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \frac{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{22}}{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{11}}, \qquad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu} \frac{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{33}}{[\mathbf{V}(\mathbf{m}^D)^2_\nu \mathbf{V}^\dagger]_{22}}$$

(HI) $m_3 \gg m_2 > m_1$
(IH) $m_2 \sim m_1 \gg m_3$
(DG) $m_3 \approx m_2 \approx m_1$

for $s_{13} < 1/2\rho \sim 0.02$

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e}\frac{\rho s_{23}^2}{s_{12}^2} \sim 10^4, \qquad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu}\frac{s_{23}^2}{c_{23}^2} \sim 17, \quad \text{(HI)}$$

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} c_{23}^2 \sim 10^2, \qquad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu}\frac{s_{23}^2}{c_{23}^2} \sim 17, \quad \text{(IH)}$$

$$\frac{d_\mu}{d_e} \approx \frac{m_\mu}{m_e} \sim 2 \times 10^2, \qquad \frac{d_\tau}{d_\mu} \approx \frac{m_\tau}{m_\mu} \sim 17, \quad \text{(DG)}.$$

Lepton EDMs in Type II

CMRV, hep-ph/0502235

- Electron EDM

$$\frac{d_e}{e} \sim 10^{-30} \left(\frac{M_T}{10^{11}\ \mathrm{GeV}} \cdot \frac{10^{-3}}{\lambda_2} \right)^2 \left(\frac{200\ \mathrm{GeV}}{\tilde{m}} \right)^2 \ \mathrm{cm}$$

- Muon and Tau EDMs

$$d_\mu \sim 1 \times 10^{-26} \quad , \quad d_\tau \sim 1.7 \times 10^{-25} \quad \text{(HI)}$$
$$d_\mu \sim 1 \times 10^{-28} \quad , \quad d_\tau \sim 1.7 \times 10^{-27} \quad \text{(IH)}$$
$$d_\mu \sim 2 \times 10^{-28} \quad , \quad d_\tau \sim 3.4 \times 10^{-27} \quad \text{(DG)}$$

Constraint from μ -> eγ

$$\delta^{LL}_{12} = \frac{18}{8\pi^2}(1+\frac{a_0^2}{3})(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{12} \log\frac{M_G}{M_T} < 10^{-3}$$

$$d_e < 3\times 10^{-30} \left(\frac{(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{11}}{(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{12}}\right) \left(\frac{3}{\tan\beta}\right) \left(\frac{\log 10^2}{\log M_G/M_T}\right) \left(\frac{\mathrm{Im}(B)}{\mu}\right)\, ecm$$

Triplet in SU(5) GUT : 15=(T,S,Z)

$$W = \mathbf{Y}_{15}\bar{5}15\bar{5} = \mathbf{Y}_T\,(LTL + d^c S d^c + d^c Z L)$$

quark EDM correlated with lepton EDM

$$\frac{d_d}{d_e} \approx \frac{4\alpha_s}{9\alpha}\,\frac{M_3}{M_1}\,\frac{m^2_{\tilde{l}}}{m^2_{\tilde{q}}}\,\frac{m_d}{m_e}$$

Probing triplet seesaw

Optimistic possibility with
hierarchical neutrino mass pattern

$$\mathrm{B}(\mu \to e\gamma) = 10^{-11}, \quad \mathrm{B}(\tau \to \mu\gamma) = 4 \times 10^{-9}$$

$$d_e = 3 \times 10^{-30}\, ecm, \quad d_\mu = 2 \times 10^{-26}\, ecm$$

$$\text{and} \quad d_n \approx 10^{-28}\, ecm$$

(*) Detailed RGE analysis for the deviation of three Yukawas from Y_T is needed.

Current limit and future discovery(?) of LFV and EDM

LFV	Present limits	Future limits	
$B(\mu \to e\gamma)$	1.2×10^{-11}	$\sim 10^{-14}$	
$B(\tau \to \mu\gamma)$	2.7×10^{-6}	$\sim 10^{-8}$	$300\ B(\mu \to e\gamma)$
$B(\tau \to e\gamma)$	0.1×10^{-6}	$\sim 10^{-8}$	$0.1\ B(\mu \to e\gamma)$

EDM	Present limits	Future limits	
d_e	7×10^{-28} [13]	10^{-32} [14]	10^{-30}
d_μ	3.7×10^{-19} [13]	$10^{-24} - 5 \times 10^{-26}$ [15]	$10^{-26;28}$
$\mathrm{Re}(d_\tau)$	4.5×10^{-17} [13]	$10^{-17} - 10^{-18}$	$10^{-25;27}$
d_n	3.1×10^{-26} [13]	$d_{n,D} \sim 10^{-28}$	$\sim 10^{-28}$

Summary

- Supersymmetric seesaw model may lead to observable LFV and EDM.
- Prediction of Singlet Seesaw involves extra flavor structure in RH sector.
- Neutrino flavor structure is reflected directly in low-energy observables of Triplet Seesaw.
- Soft B-term of heavy mass can induce sizable (finite) contributions to quark and lepton EDM.
- EDM and LFV ratios are predicted only in terms of neutrino parameters in Triplet Seesaw.