Electric Dipole Moments from Spontaneous CP Violation in SU(3)-flavoured SUSY

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Outline

- Motivation
- SU(3) Flavour Models
- Observables (eEDM, LFV)
- Conclusions

Flavour Problems

- SUSY Flavour Problem: Arbitrary choice of parameters in Soft-Mass matrices give a wrong (too large) contribution to non-observed processes.

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We do not understand flavour.

CP Problem

- SUSY CP Problem

Large phases in flavour-independent parameters give too large contributions to EDMs.

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Maybe we don't understand CP Violation either?

Our Goal

- Devise a mechanism with which to generate the Yukawa textures and phases.
- Extend this mechanism into SUSY models, and predict its implications on the non-observed low energy phenomena.

Yukawa Textures

What we want:

$$Y_u \propto \begin{pmatrix} 0 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix} \qquad Y_d \propto \begin{pmatrix} 0 & \bar{\varepsilon}^3 & \bar{\varepsilon}^3 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1 \end{pmatrix}$$

$$\varepsilon = 0.05 \qquad \bar{\varepsilon} = 0.15$$

R. G. Roberts, A. Romanino, G. G. Ross, L. Velasco-Sevilla (hep-ph/0104088)

SU(3) Flavour Model

Relevant Symmetries:

- MSSM: $SU(3)_C\ SU(2)_L\ U(1)_Y\ Z_R$
- SU(3) in flavour sector.
- Exact CP
- Additional U(1)s: avoid particular terms.

S. F. King, G. G. Ross (hep-ph/0307190)

G. G. Ross, L. Velasco-Sevilla, O. Vives (hep-ph/0401064)

SU(3) Flavour Model

Effective Superpotential:

$$W = H_d Q_\alpha d^c_\beta \left[\frac{\theta_3^\alpha \theta_3^\beta}{M_d^2} + \frac{\theta_{23}^\alpha \theta_{23}^\beta (\theta_3 \overline{\theta}_3)}{M_d^4} + \varepsilon^{\alpha\mu\nu} \frac{\overline{\theta}_{23\mu} \overline{\theta}_{3\nu} \theta_{23}^\beta (\theta_{23} \overline{\theta}_3)}{M_d^5} \right.$$

$$\left. + \varepsilon^{\alpha\beta\mu} \frac{\overline{\theta}_{23\mu} (\theta_{23} \overline{\theta}_3)^2}{M_d^5} + \varepsilon^{\alpha\beta\mu} \frac{\overline{\theta}_{3\mu} (\theta_{23} \overline{\theta}_3)(\theta_{23} \overline{\theta}_{23})}{M_d^5} + \ldots \right]$$

SU(3) Flavour Model

Flavons acquire the following vevs:

$$\langle \theta_3 \rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u & 0 \\ 0 & a_3^d e^{i\chi} \end{pmatrix} \qquad \langle \overline{\theta}_3 \rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u e^{i\alpha_u} & 0 \\ 0 & a_3^d e^{i\alpha_d} \end{pmatrix}$$

Spontaneous breaking of CP symmetry

SU(3) Flavour Model

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$$\langle \theta_{23} \rangle = \begin{pmatrix} 0 \\ b_{23} \\ b_{23} e^{i\beta_3} \end{pmatrix} \qquad \langle \bar{\theta}_{23} \rangle = \begin{pmatrix} 0 \\ b_{23} e^{i\beta_2} \\ b_{23} e^{i(\beta_2 - \beta_3)} \end{pmatrix}$$

$$\frac{a_3^u}{M_u} = y_t \quad \frac{a_3^d}{M_d} = y_b \quad \frac{b_{23}}{M_u} = \varepsilon \quad \frac{b_{23}}{M_d} = \bar{\varepsilon}$$

SU(3) Flavour Model

Yukawa Textures:

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We omit ϑ (1) constants

Works the same way for up sector.

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$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} y_b$$

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Flavour Models in SUSY

- SUSY provides new flavour contributions to low-energy processes.

$$L_{Soft} = -\tilde{Q}^* m_Q^2 \tilde{Q} - \tilde{L}^* m_L^2 \tilde{L}$$
$$-\tilde{u}^{c^*} m_{u^c}^2 \tilde{u}^c - \tilde{d}^{c^*} m_{d^c}^2 \tilde{d}^c - \tilde{e}^{c^*} m_{e^c}^2 \tilde{e}^c$$
$$-\tilde{Q} A_u \tilde{u}^c H_u - \tilde{Q} A_d \tilde{d}^c H_d - \tilde{L} A_e \tilde{e}^c H_d$$

SU(3) Flavour Model

Soft Mass Matrices:

$$K = \tilde{\psi}_{\alpha}^{+}\tilde{\psi}_{\beta}.\Big\{\delta^{\alpha\beta} + \frac{1}{M_{\psi}^{2}}\Big[\theta_{3}^{\alpha^{+}}\theta_{3}^{\beta} + \theta_{23}^{\alpha^{+}}\theta_{23}^{\beta}\Big]$$

$$+ \frac{1}{M_{\psi}^{4}}\Big(\varepsilon^{\alpha\mu\nu}\,\overline{\theta}_{3\mu}\overline{\theta}_{23\nu}\Big)^{+}\Big(\varepsilon^{\alpha\rho\sigma}\,\overline{\theta}_{3\rho}\overline{\theta}_{23\sigma}\Big)\Big\}$$

SU(3) Flavour Model

Soft Mass Matrices:

$$m_{\tilde{e}^c}^2 = \left(\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} \varepsilon^2 y_b & 0 & 0 \\ 0 & \varepsilon^2 & \varepsilon^2 \\ 0 & \varepsilon^2 & y_b \end{pmatrix} \right) m_0^2$$

$$m_{\tilde{L}}^2 = \left(\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} \varepsilon^2 y_t & 0 & 0 \\ 0 & \varepsilon^2 & \varepsilon^2 \\ 0 & \varepsilon^2 & y_t \end{pmatrix} \right) m_0^2$$

SU(3) Flavour Model

SCKM Basis:

$$\left(m^2_{\tilde{L}}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon^2\bar{\varepsilon} & \bar{\varepsilon}^3 \\ & & \bar{\varepsilon}^2 \\ & & \end{pmatrix} m_0^2$$

RVV1

$$\left(m^2_{\tilde{e}^c}\right)^{SCKM} \approx \begin{pmatrix} & \bar{\varepsilon}^3 & \bar{\varepsilon}^3 \\ & & \bar{\varepsilon}^2 \\ & & \end{pmatrix} m_0^2$$

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$$\left(m^2_{\tilde{L}}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon^2\bar{\varepsilon} & \varepsilon\bar{\varepsilon}y_t^{0.5} \\ & & \bar{\varepsilon}y_t^{0.5} \\ & & \end{pmatrix} m_0^2$$

RVV2

$$+\bar{\theta}_{23}\theta_3$$

$$\left(m^2_{\tilde{e}^c}\right)^{SCKM} \approx \begin{pmatrix} & \bar{\varepsilon}^3 & \bar{\varepsilon}^2 y_b^{0.5} \\ & & \bar{\varepsilon}y_b^{0.5} \\ & & \end{pmatrix} m_0^2$$

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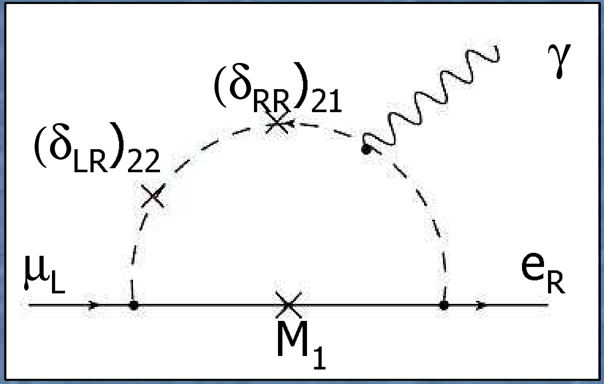
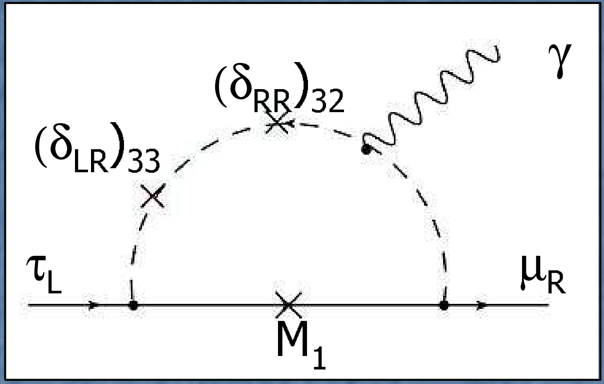
$$\left(m^2_{\tilde{L}}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon^2\varepsilon & \varepsilon^3 \\ & & \varepsilon^2 \\ & & \end{pmatrix} m_0^2 \qquad \text{RVV1} \qquad \left(m^2_{\tilde{e}^c}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon^3 & \varepsilon^3 \\ & & \varepsilon^2 \\ & & \end{pmatrix} m_0^2$$

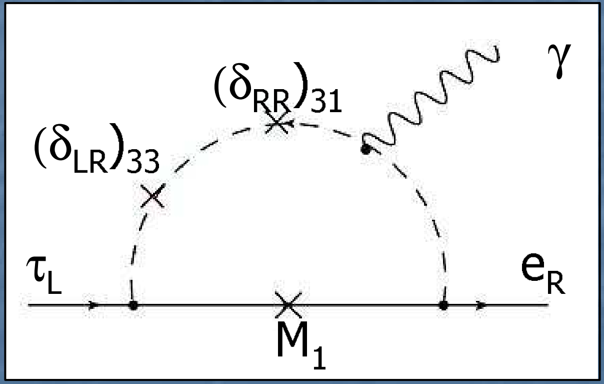
$$\left(m^2_{\tilde{L}}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon^2\varepsilon & \varepsilon\varepsilon y_t^{0.5} \\ & & \varepsilon y_t^{0.5} \\ & & \end{pmatrix} m_0^2 \qquad \text{RVV2} + \bar{\theta}_{23}\theta_3 \qquad \left(m^2_{\tilde{e}^c}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon^3 & \varepsilon^2 y_b^{0.5} \\ & & \varepsilon y_b^{0.5} \\ & & \end{pmatrix} m_0^2$$

$$\left(m^2_{\tilde{L}}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon\varepsilon^2 & \varepsilon y_t \\ & & \varepsilon^2 \\ & & \end{pmatrix} m_0^2 \qquad \text{RVV3} + \left(\varepsilon\theta_3\theta_{23}\right)\theta_3 \qquad \left(m^2_{\tilde{e}^c}\right)^{SCKM} \approx \begin{pmatrix} & \varepsilon^3 & \varepsilon y_b \\ & & \varepsilon^2 \\ & & \end{pmatrix} m_0^2$$

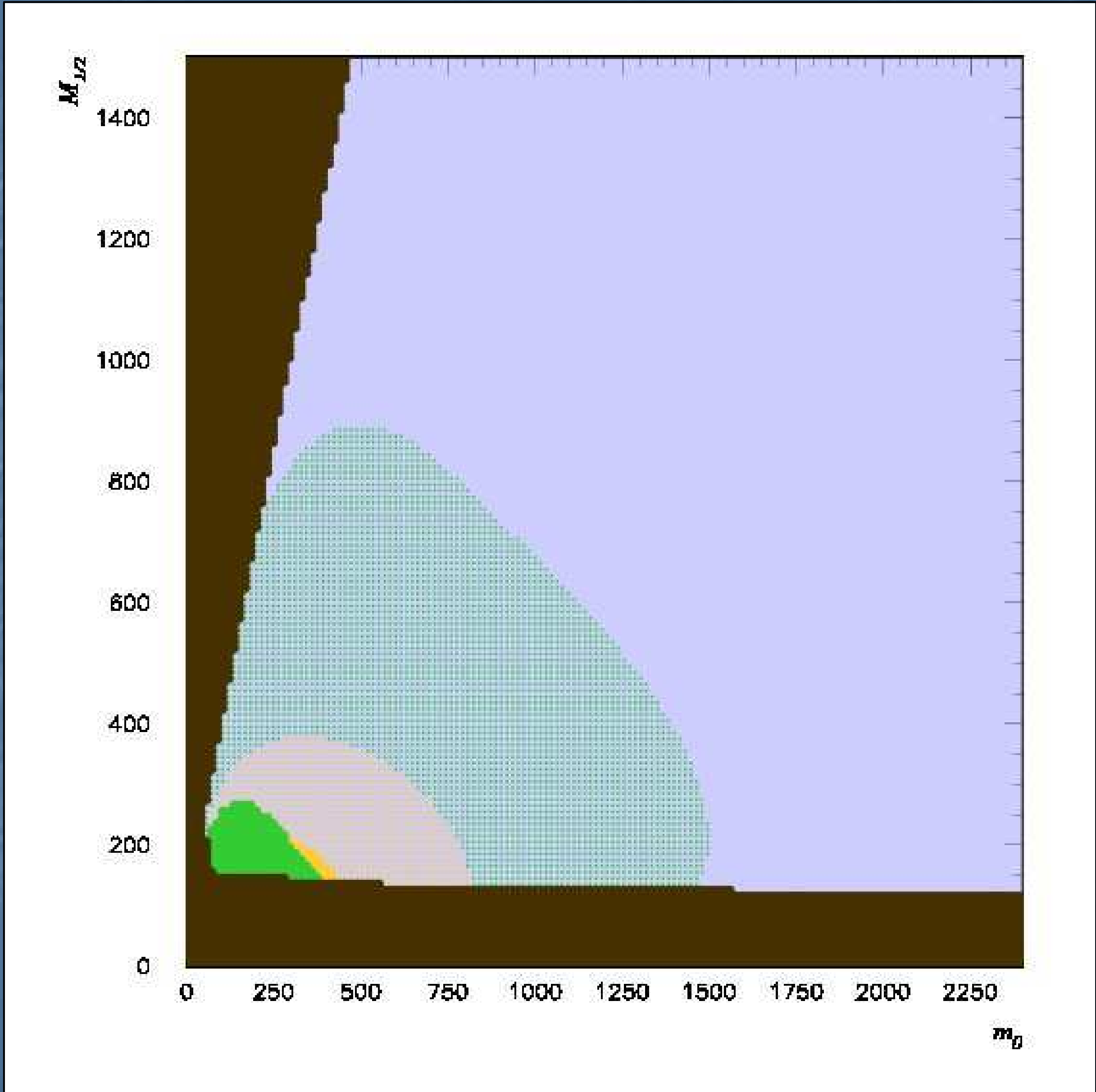
Lepton Flavour Violation







RVV1 ($\tan\beta=10$, $a_0=0$)



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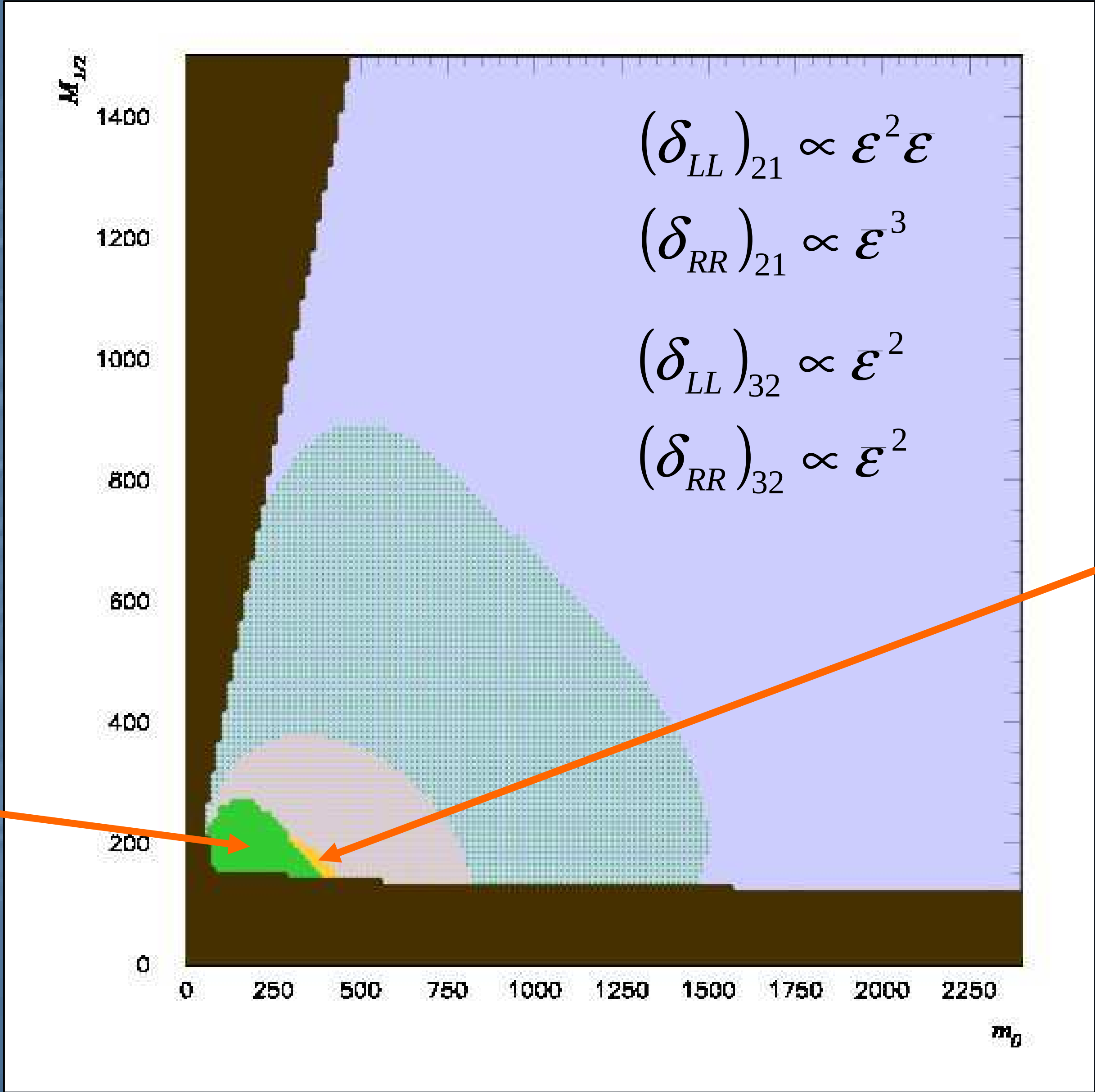
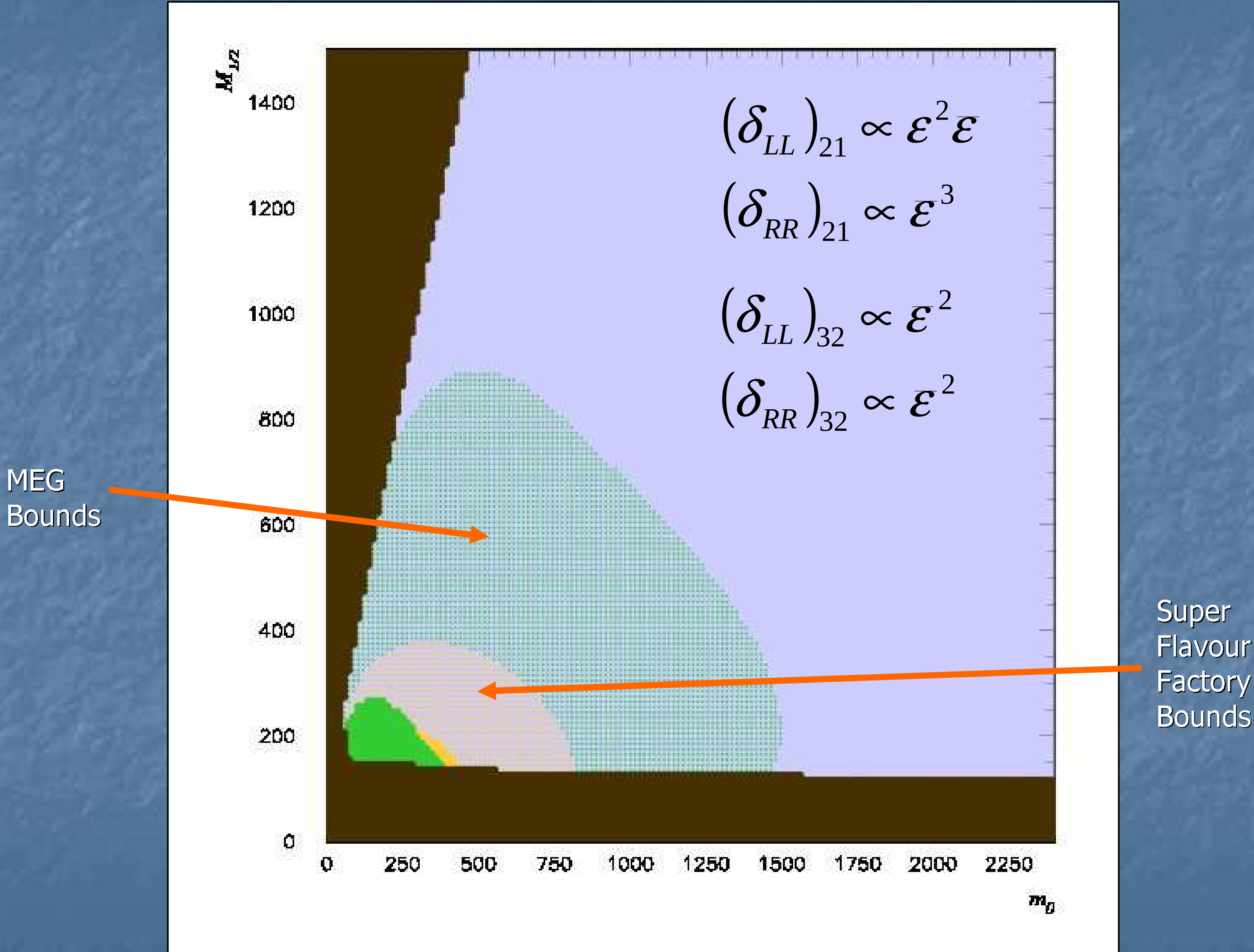


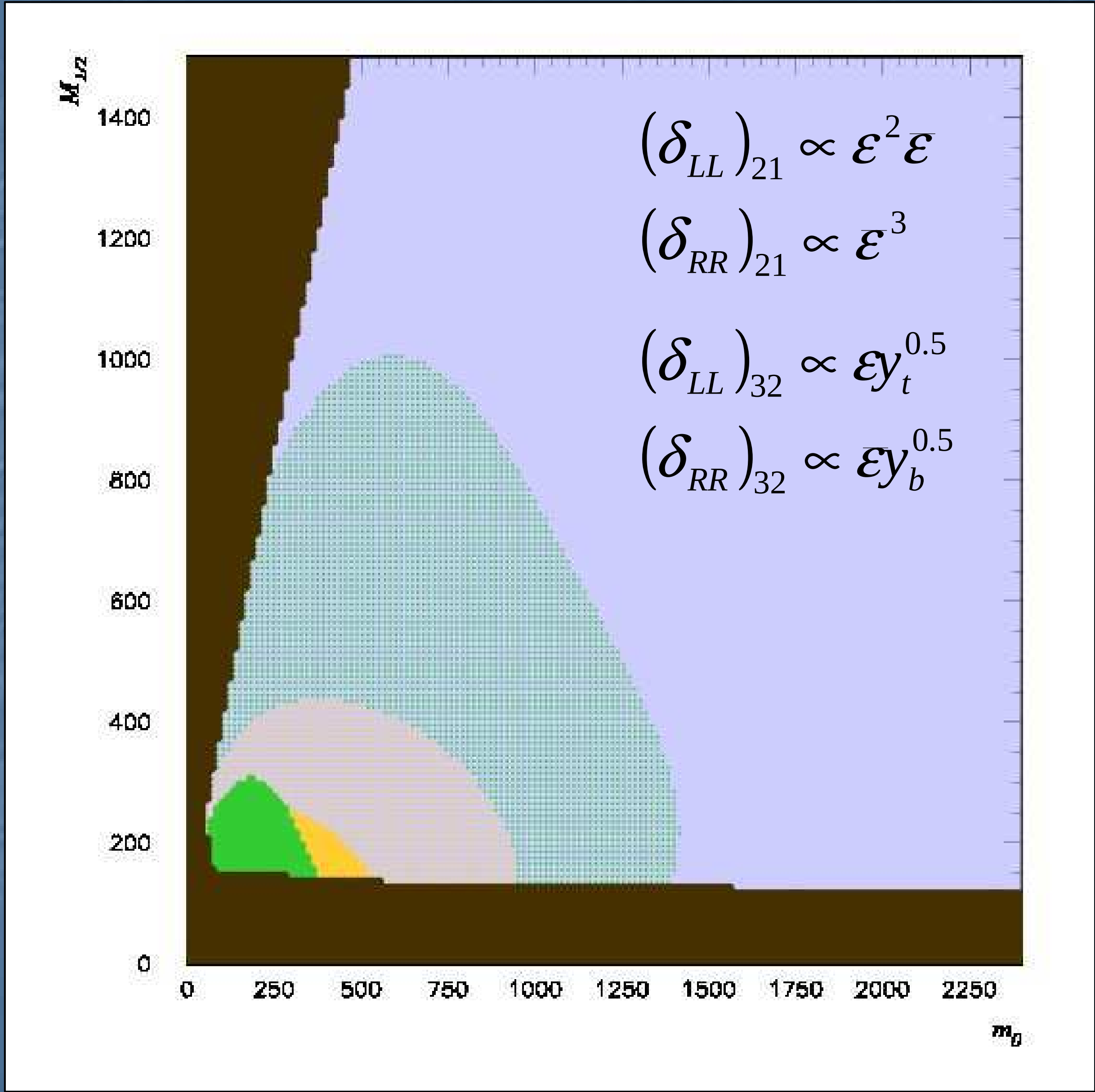
MEGA Bounds

BABAR + BELLE Bounds

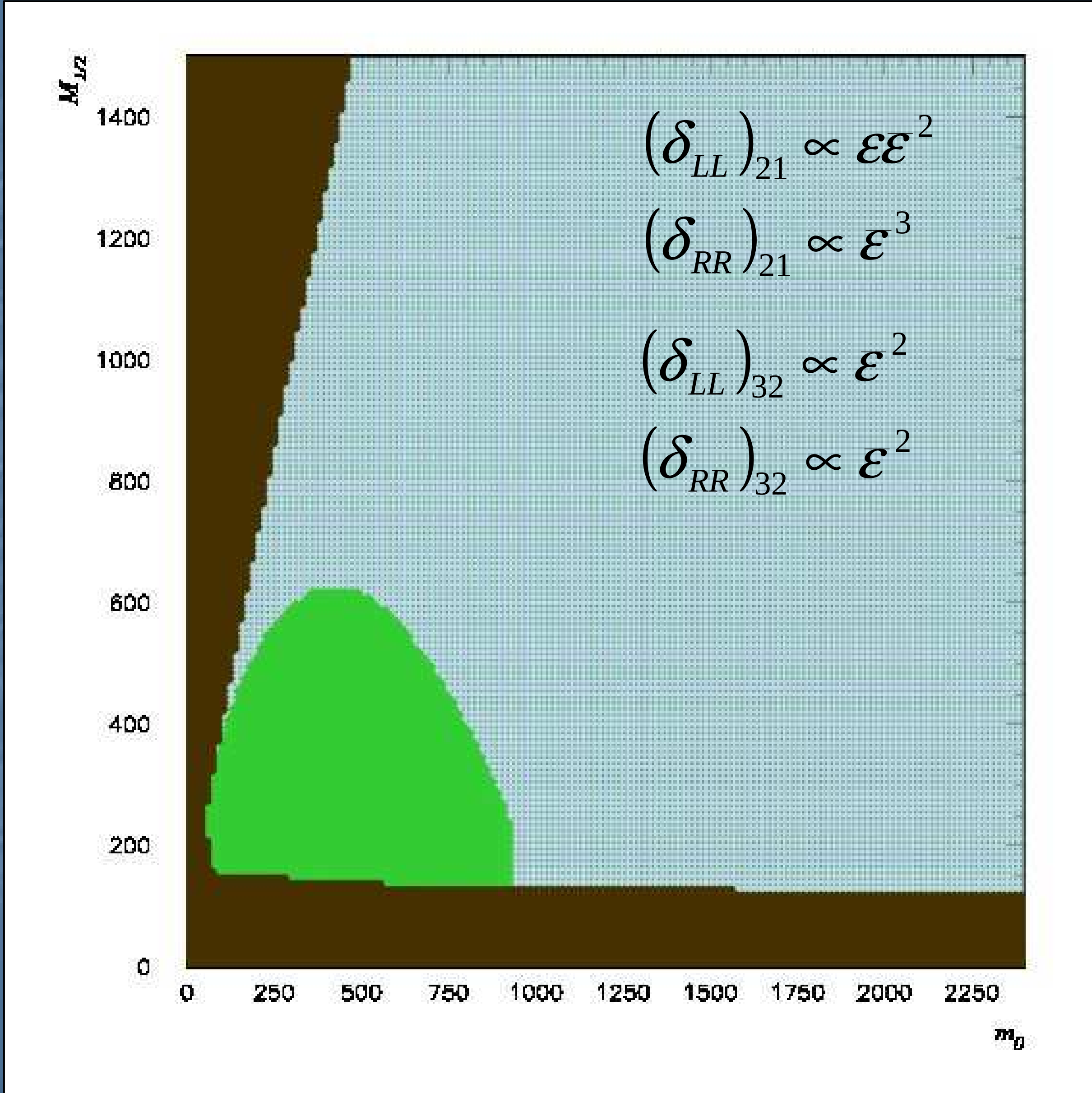
RVV1 ($\tan\beta=10$, $a_0=0$)



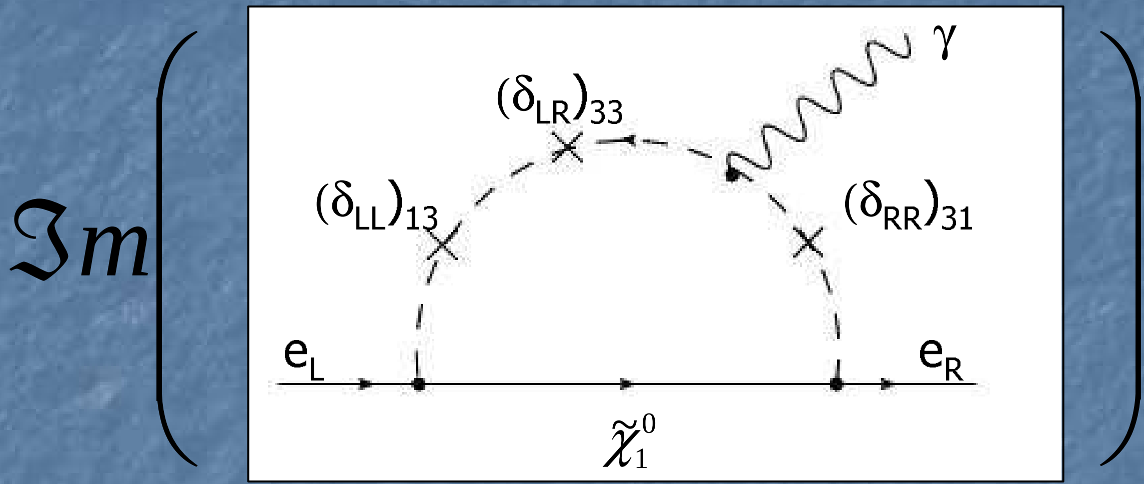
RVV2 (tanβ=10, a_0=0)



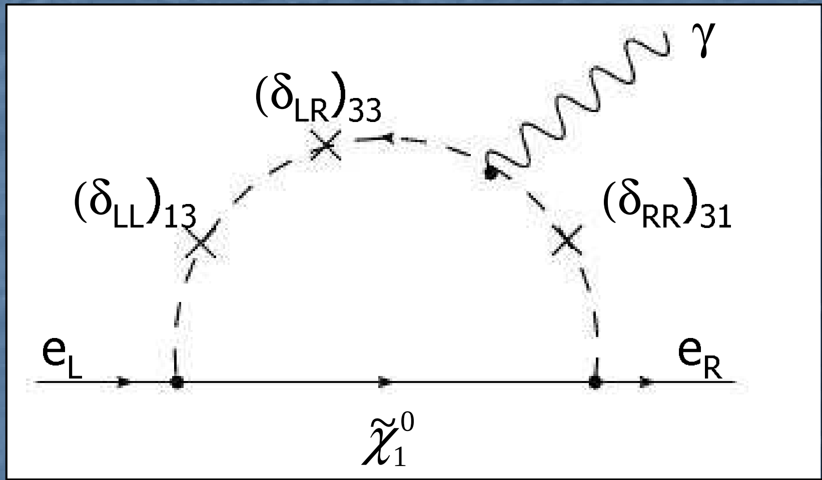
RVV3 (tanβ=10, a_0=0)



Electric Dipole Moments



Electric Dipole Moments

$\Im m \Bigg($ 

$\Bigg)$

RVV1 $\left(\delta^{e}_{RR}\right)_{13}\left(\delta^{e}_{LL}\right)_{31} \approx \varepsilon^{6}\left(\tfrac{1}{3} - y_b e^{2i(\chi-\beta_3)}\right)\left(y_t - \left(\varepsilon/\varepsilon\right)^{2} e^{2i(\chi-\beta_3)}\right)$

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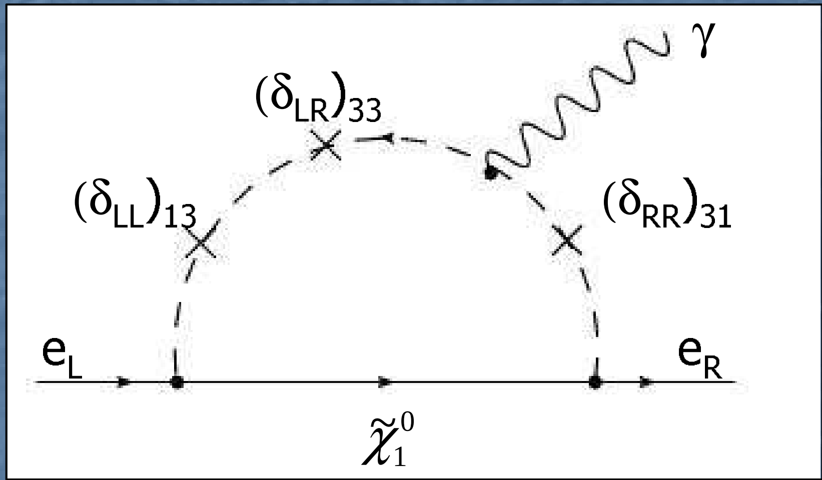
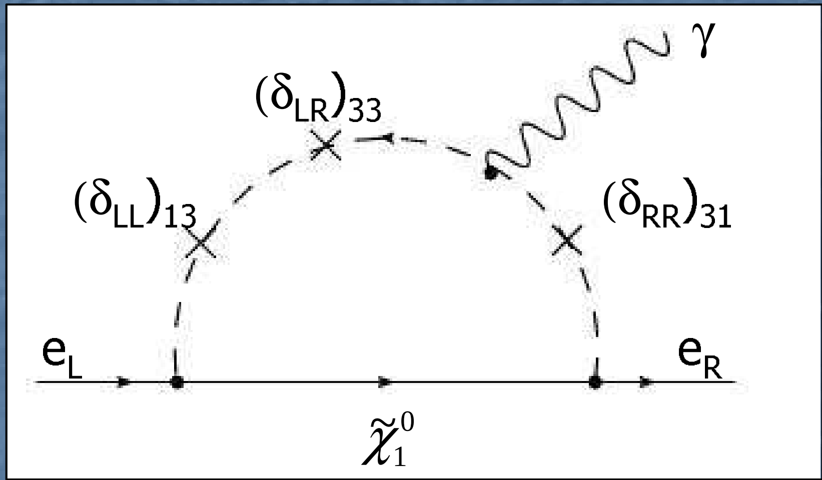
$\Im m \Bigg($  $\Bigg)$

RVV1 $\quad (\delta^e_{RR})_{13}(\delta^e_{LL})_{31} \approx \varepsilon^6 \left(1/3 - y_b e^{2i(\chi-\beta_3)} \right)\left(y_t - (\varepsilon/\varepsilon)^2 e^{2i(\chi-\beta_3)} \right)$

RVV2 $\quad (\delta^e_{RR})_{13}(\delta^e_{LL})_{31} \approx \frac{\varepsilon\varepsilon^3}{9}(y_b y_t)^{1/2} e^{-i(\chi-2\beta_2)}$

Electric Dipole Moments

$\Im m\Bigg($  $\Bigg)$

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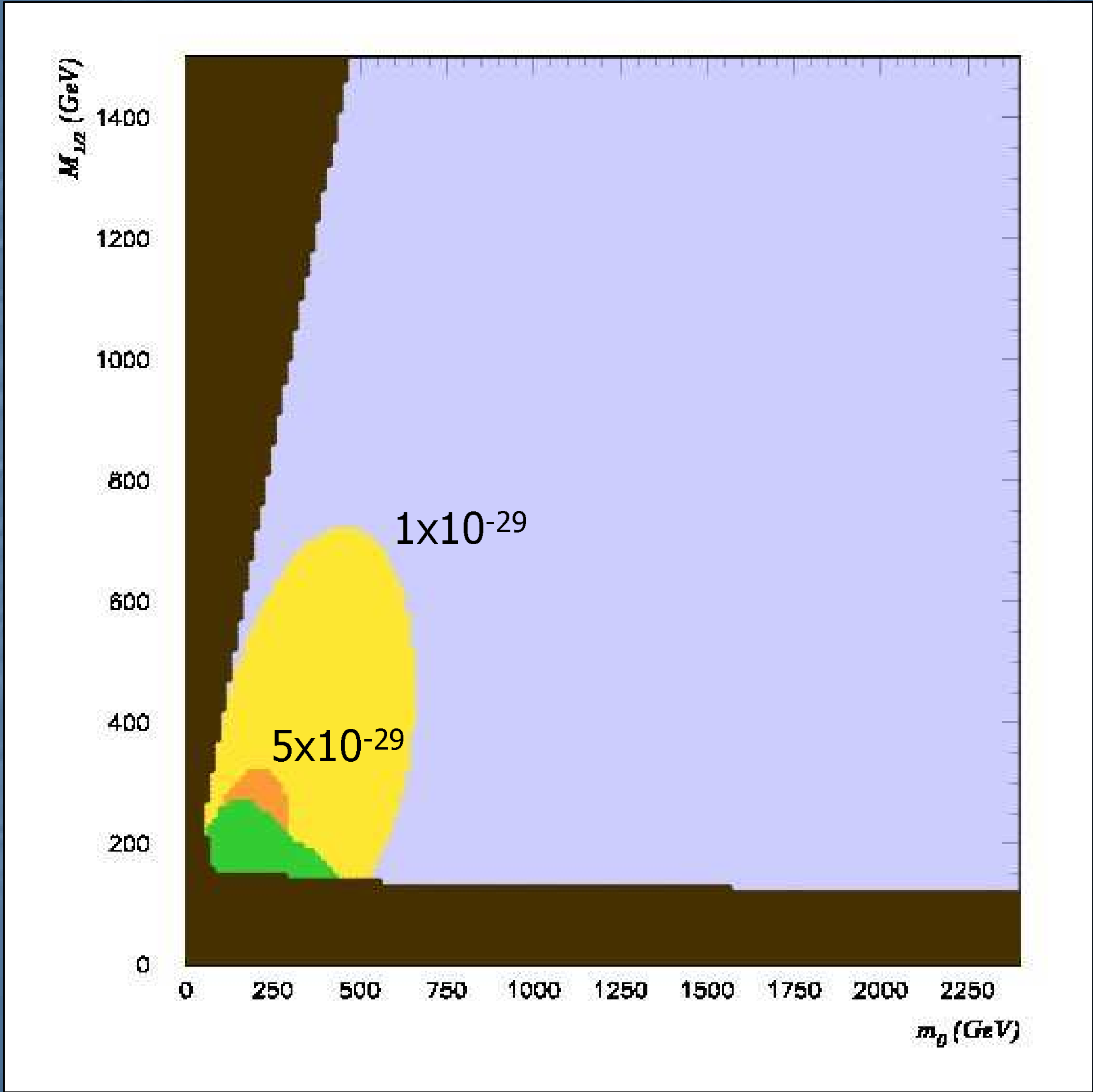
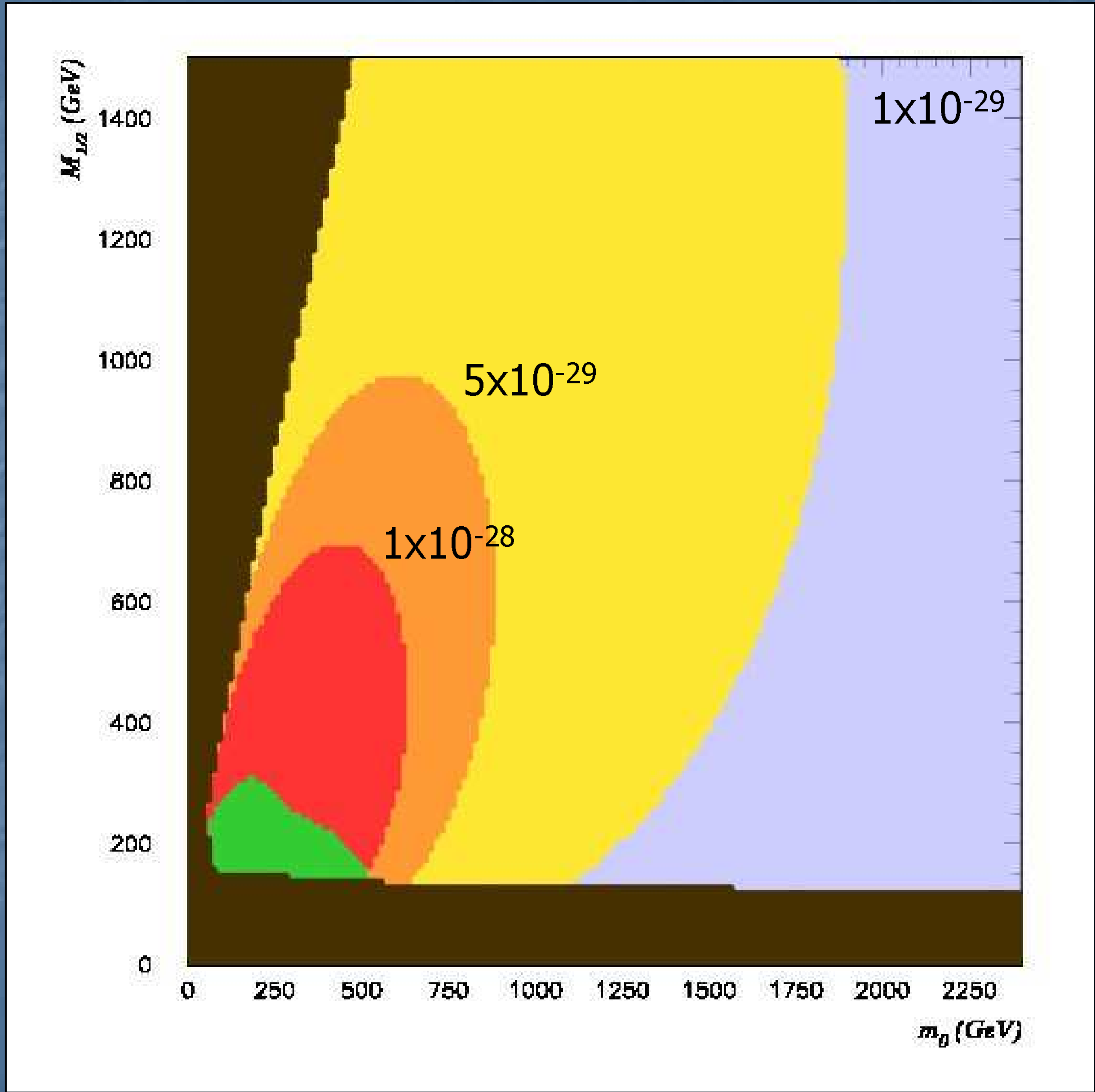
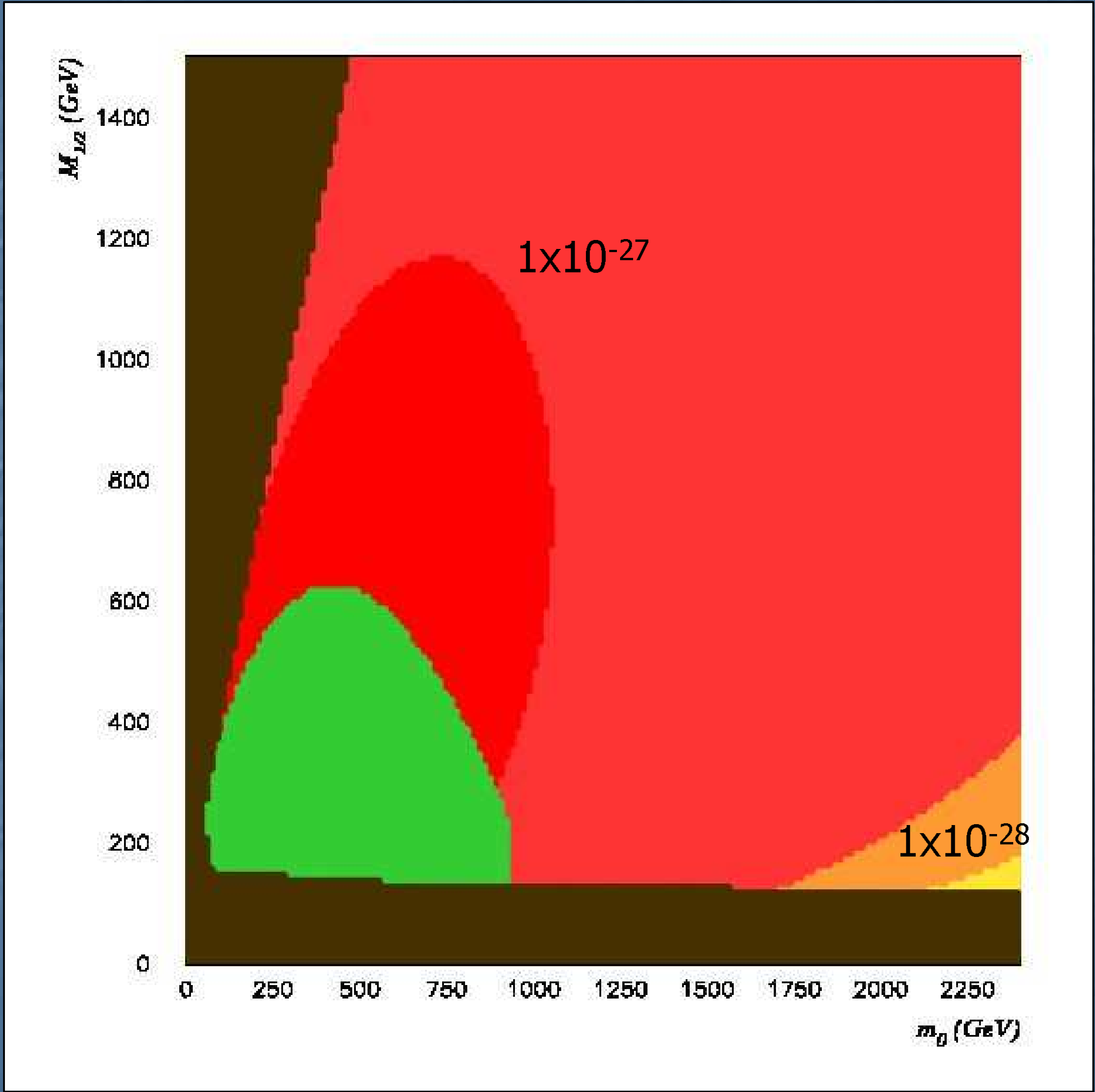
RVV1 ($\tan\beta=10$, $a_0=0$)



RVV2 ($\tan\beta=10$, $a_0=0$)



RVV3 ($\tan\beta=10$, $a_0=0$)



Conclusions

- Family symmetries are useful for generating textures in SUSY-breaking terms.
- Such textures imply LFV processes, which are likely to be observed if SUSY is accesible at the LHC.

Conclusions

- Family symmetries can spontaneously break CP, and provide textures with a phase structure.
- Phase structure can be probed with the electron EDM, which could be observed if phases are of O(1).

Backup Slides

Renormalizable Superpotential

$$W_1 = u^c U_1 \theta_3 + \overline{U}_1 U_2 \theta_3 + \overline{U}_2 Q H_u$$

$$+ d^c D_1 \theta_3 + \overline{D}_1 D_2 \theta_3 + \overline{D}_2 Q H_d$$

$$+ M_u \left(U_1 \overline{U}_1 + U_2 \overline{U}_2 \right)$$

$$+ M_d \left(D_1 \overline{D}_1 + D_2 \overline{D}_2 \right)$$

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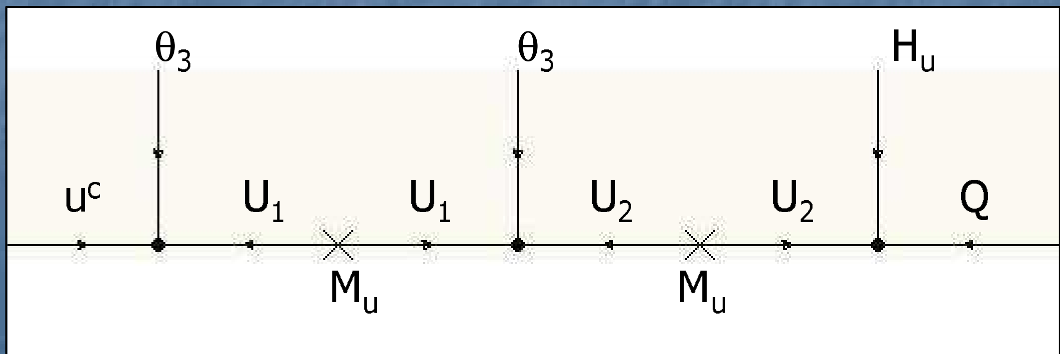

Renormalizable Superpotential

$$W_1 = u^c U_1 \theta_3 + \bar{U}_1 U_2 \theta_3 + \bar{U}_2 Q H_u$$

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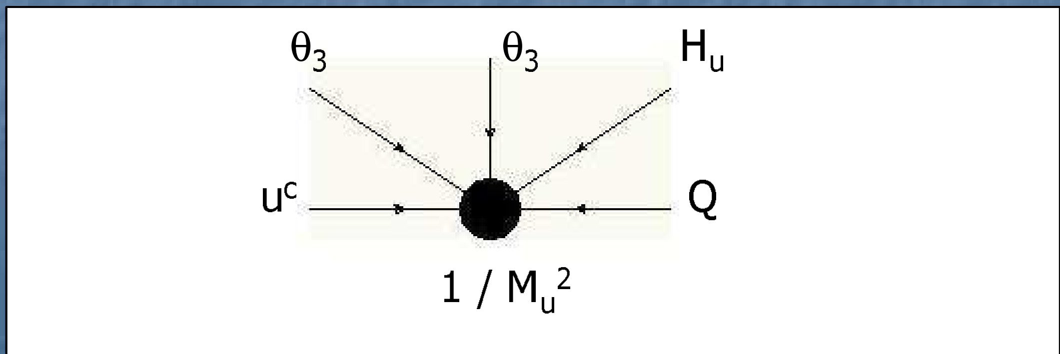
$$H_u Q u^c \frac{\theta_3 \theta_3}{M_u^2}$$



Vacuum Alignment

$$W = P\left(\theta_3\bar{\theta}_3 + T\right) + U\left(\theta_{23}\bar{\theta}_{23} + S^2\right) + V\left(\left(\theta_3\bar{\theta}_3\right)^4 + S\bar{S}\right)$$
$$+ Y\left(\theta_3\bar{\theta}_2\right) + Z\left(\left(\theta_{23}\bar{\theta}_3\right)\left(\theta_{23}\bar{\theta}_2\right) + \bar{S}^2\right)$$

G. G. Ross, L. Velasco-Sevilla, O. Vives (hep-ph/0401064)

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$$\left\langle \theta_3\bar{\theta}_3 \right\rangle = -\left\langle T \right\rangle$$

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$$\left\langle \theta_3\bar{\theta}_3 \right\rangle = -\left\langle T \right\rangle \qquad \left\langle S\bar{S} \right\rangle = -\left\langle \left(\theta_3\bar{\theta}_3\right)^4 \right\rangle$$

$$\left\langle \left(\theta_{23}\bar{\theta}_{23}\right) \right\rangle = -\left\langle S^2 \right\rangle$$

Vacuum Alignment

$$W = P\left(\theta_3\bar{\theta}_3 + T\right) + U\left(\theta_{23}\bar{\theta}_{23} + S^2\right) + V\left(\left(\theta_3\bar{\theta}_3\right)^4 + S\bar{S}\right)$$
$$+ Y\left(\theta_3\bar{\theta}_2\right) + Z\left(\left(\theta_{23}\bar{\theta}_3\right)\left(\theta_{23}\bar{\theta}_2\right) + \bar{S}^2\right)$$

$$\left\langle \theta_3 \right\rangle = \left\langle \bar{\theta}_3 \right\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u & 0 \\ 0 & a_3^d \end{pmatrix}$$

$$\left\langle S\bar{S} \right\rangle = -\left\langle \left(\theta_3\bar{\theta}_3\right)^4 \right\rangle$$

$$\left\langle \left(\theta_{23}\bar{\theta}_{23}\right) \right\rangle = -\left\langle S^2 \right\rangle$$

Vacuum Alignment

$$W = P\left(\theta_3\bar{\theta}_3 + T\right) + U\left(\theta_{23}\bar{\theta}_{23} + S^2\right) + V\left(\left(\theta_3\bar{\theta}_3\right)^4 + S\bar{S}\right)$$
$$+ Y\left(\theta_3\bar{\theta}_2\right) + Z\left(\left(\theta_{23}\bar{\theta}_3\right)\left(\theta_{23}\bar{\theta}_2\right) + \bar{S}^2\right)$$

$$\langle\theta_3\rangle = \langle\bar{\theta}_3\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u & 0 \\ 0 & a_3^d \end{pmatrix}$$

$$\langle S\bar{S}\rangle = -\left\langle \left(\theta_3\bar{\theta}_3\right)^4 \right\rangle$$

$$\left\langle \left(\theta_{23}\bar{\theta}_{23}\right) \right\rangle = -\left\langle S^2 \right\rangle$$

$$\langle\bar{\theta}_2\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} a_2^u & 0 \\ 0 & a_2^d \end{pmatrix}$$

Vacuum Alignment

$$W = P\left(\theta_3\bar{\theta}_3 + T\right) + U\left(\theta_{23}\bar{\theta}_{23} + S^2\right) + V\left(\left(\theta_3\bar{\theta}_3\right)^4 + S\bar{S}\right)$$
$$+ Y\left(\theta_3\bar{\theta}_2\right) + Z\left(\left(\theta_{23}\bar{\theta}_3\right)\left(\theta_{23}\bar{\theta}_2\right) + \bar{S}^2\right)$$

$$\langle\theta_3\rangle = \langle\bar{\theta}_3\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u & 0 \\ 0 & a_3^d \end{pmatrix} \qquad \langle S\bar{S}\rangle = -\left\langle\left(\theta_3\bar{\theta}_3\right)^4\right\rangle$$

$$\langle\theta_{23}\rangle = \langle\bar{\theta}_{23}\rangle = \begin{pmatrix} 0 \\ b_{23} \\ b_{23} \end{pmatrix} \qquad \langle\bar{\theta}_2\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} a_2^u & 0 \\ 0 & a_2^d \end{pmatrix}$$

Vacuum Alignment

$$W = P\left(\theta_3\bar{\theta}_3 + T\right) + U\left(\theta_{23}\bar{\theta}_{23} + S^2\right) + V\left(\left(\theta_3\bar{\theta}_3\right)^4 + S\bar{S}\right)$$
$$+ Y\left(\theta_3\bar{\theta}_2\right) + Z\left(\left(\theta_{23}\bar{\theta}_3\right)\left(\theta_{23}\bar{\theta}_2\right) + \bar{S}^2\right)$$

$$\langle\theta_3\rangle = \langle\bar{\theta}_3\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \otimes \begin{pmatrix} a_3^u & 0 \\ 0 & a_3^d \end{pmatrix}$$

$$\langle\theta_{23}\rangle = \langle\bar{\theta}_{23}\rangle = \begin{pmatrix} 0 \\ b_{23} \\ b_{23} \end{pmatrix}$$

SM Masses

At mZ (GeV):

	1	2	3
m_u	1.4E-3	0.63	170
m_d	3.0E-3	5.6E-2	2.89
m_e	5.0E-4	0.10	1.75

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	1	2	3
m_u	1.3E-3	0.66	168
m_d	3.6E-3	5.7E-2	2.78
m_e	5.9E-4	0.12	1.74

Ours.

SU(3) Flavour Model

Lepton Yukawas:

$$W = H_d L_\alpha e^c_\beta \left[\frac{\theta_3^\alpha \theta_3^\beta}{M_d^2} + \frac{\theta_{23}^\alpha \theta_{23}^\beta \left(\theta_3 \bar{\theta}_3\right)}{M_d^5} \Sigma + \varepsilon^{\alpha\mu\nu} \frac{\bar{\theta}_{23\mu} \bar{\theta}_{3\nu} \theta_{23}^\beta \left(\theta_{23} \bar{\theta}_3\right)}{M_d^5} \right.$$

$$\left. + \varepsilon^{\alpha\beta\mu} \frac{\bar{\theta}_{23\mu} \left(\theta_{23} \bar{\theta}_3\right)^2}{M_d^5} + \varepsilon^{\alpha\beta\mu} \frac{\bar{\theta}_{3\mu} \left(\theta_{23} \bar{\theta}_3\right)\left(\theta_{23} \bar{\theta}_{23}\right)}{M_d^5} + \ldots \right]$$

$$\langle \Sigma \rangle = \left(B - L + 2T_3^R \right)$$

Neutrino Mixing

- We use a see-saw mechanism and introduce sneutrino antitriplets λ, with vevs.

$$W_M = \frac{\nu^c_\alpha \nu^c_\beta}{M}\Big[\lambda^\alpha \lambda^\beta + \theta_3^\alpha \theta_{23}^\beta (\lambda\bar{\theta}_3)^2 (\theta_3\bar{\theta}_3)^2$$

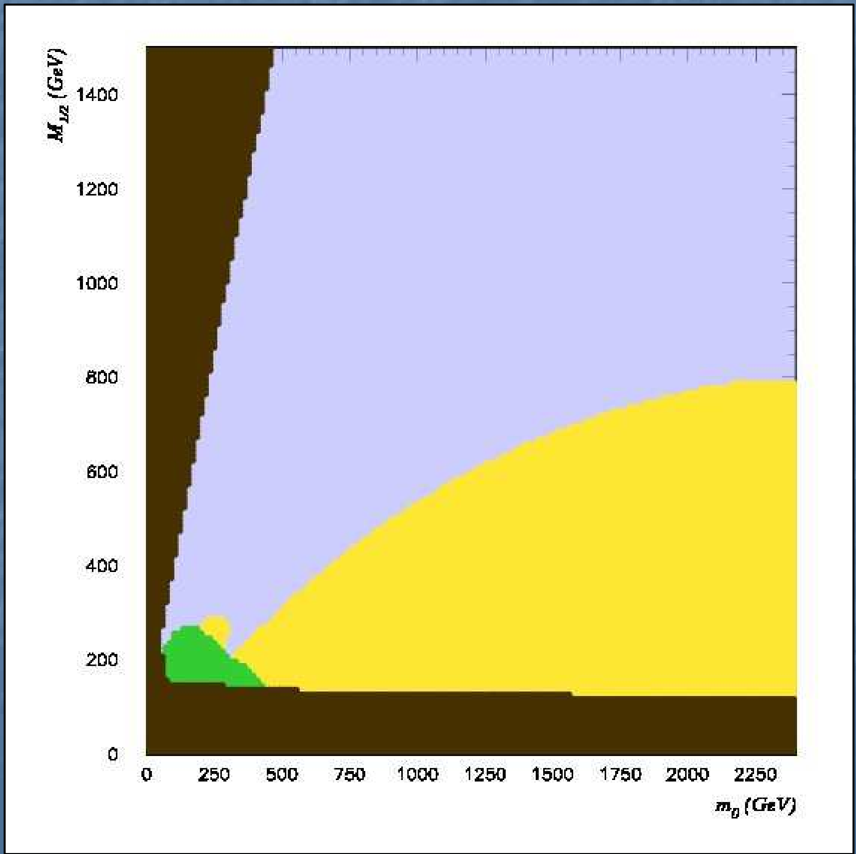
$$+\theta_{23}^\alpha \theta_{23}^\beta (\lambda\bar{\theta}_3)^2 (\theta_3\bar{\theta}_3)^6$$

$$+\varepsilon^{\alpha\mu\nu}\bar{\theta}_{23\mu}\bar{\theta}_{3\nu}\theta_3^\beta (\lambda\bar{\theta}_3)^2 (\theta_3\bar{\theta}_3)^6$$

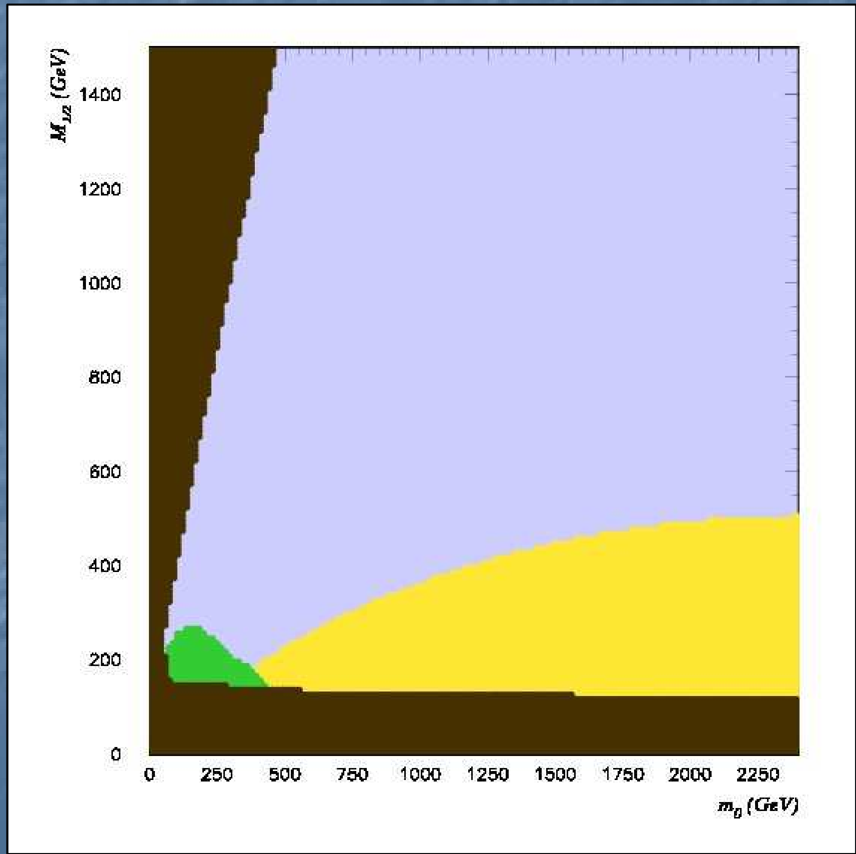
$$+\varepsilon^{\alpha\mu\nu}\bar{\theta}_{23\mu}\bar{\theta}_{3\nu}\theta_{23}^\beta (\lambda\bar{\theta}_3)^2 (\theta_3\bar{\theta}_3)(\theta_{23}\bar{\theta}_3)^2\Big]$$

Neutron EDM – RVV1 Preliminary Results

Quark-Parton Model



Chiral Quark Model



ε_K – RVV1
Preliminary Results