Flavour symmetries and SUSY soft-breaking in the LHC era

Oscar Vives

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- Strong hierarchy between generations.
- Small quark, large lepton mixing angles.

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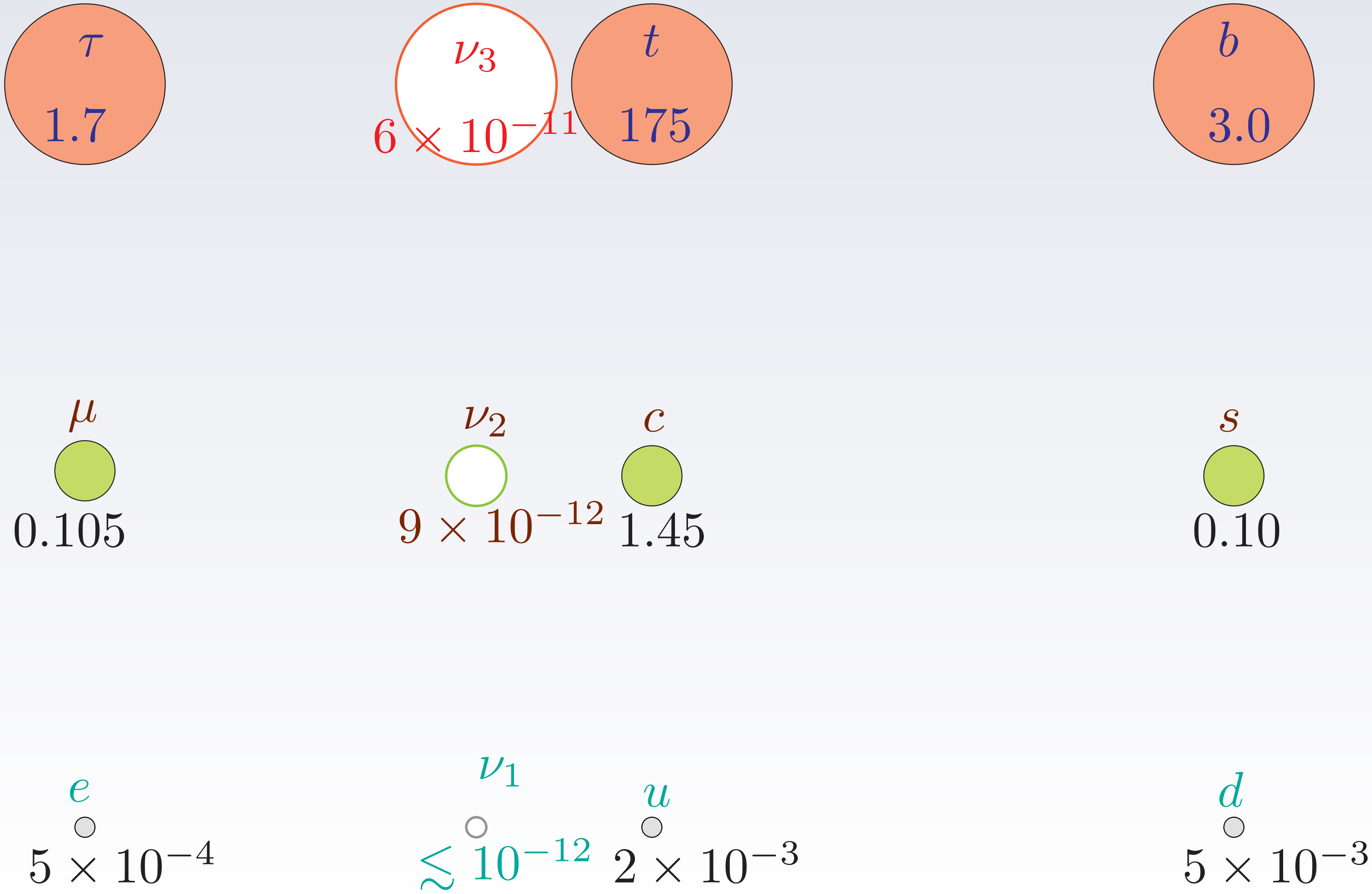

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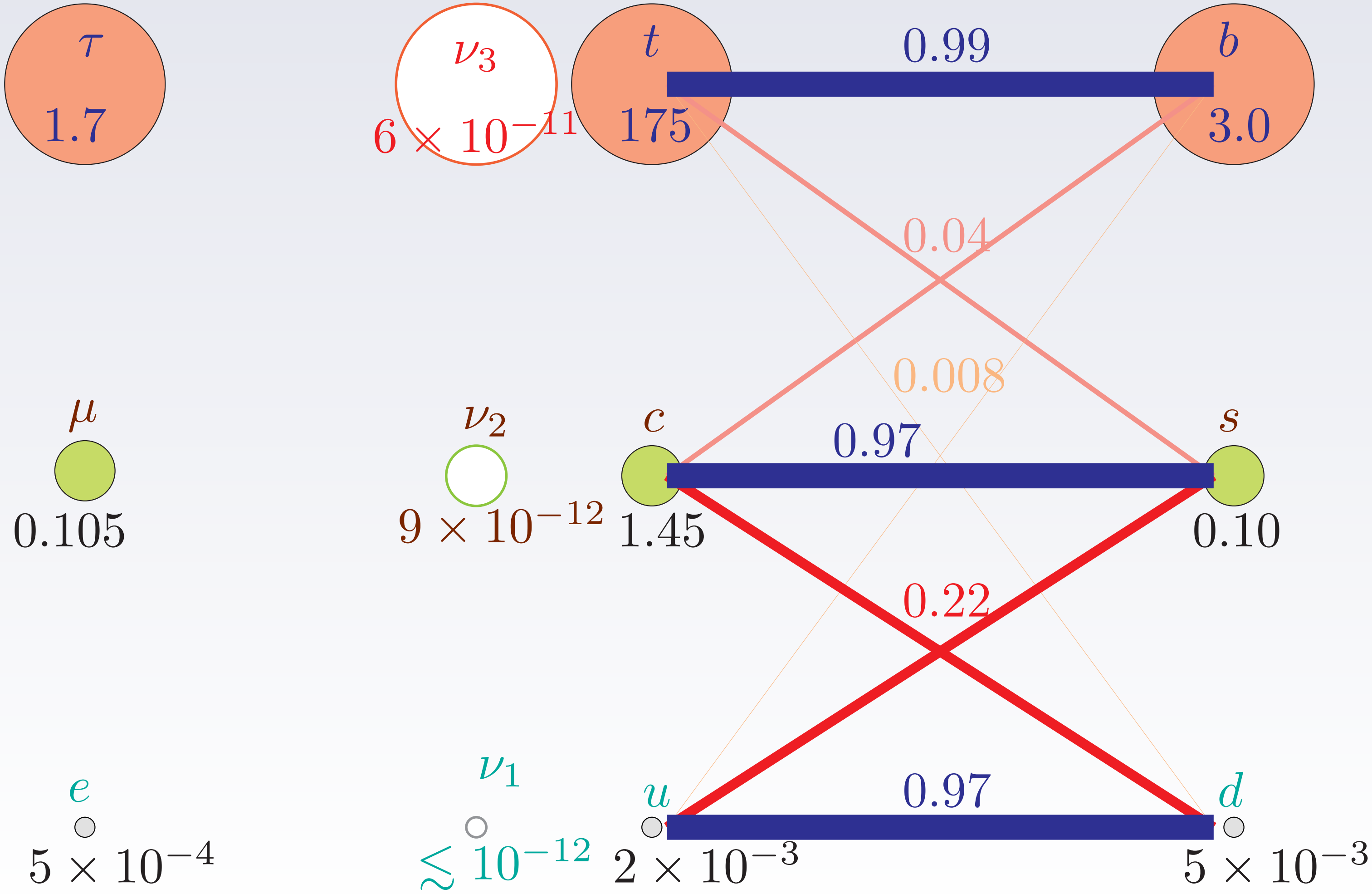

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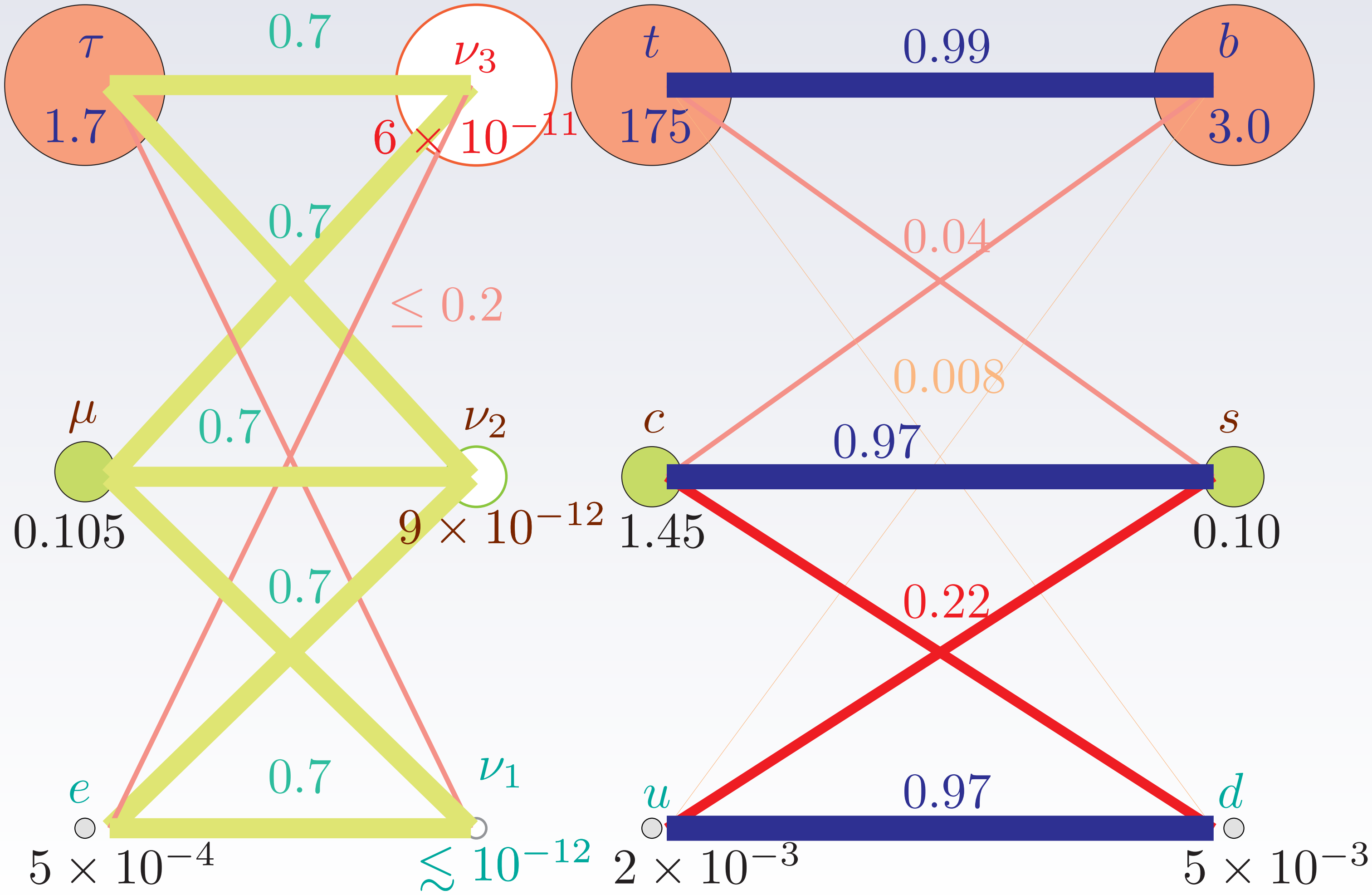


Standard Model

All flavour physics originate in Yukawa couplings:

$$\mathcal{L}_Y = H \, \bar{Q}_i \, Y^d_{ij} \, d_j + H^* \, \bar{Q}_i \, Y^u_{ij} \, u_j$$

In absence of Yukawas, $\mathcal{L}_{SM}$ invariant under global $(U(3))^5$

$\Longrightarrow$ quark masses and CKM mixings only observables in SM

Not enough information to determine the full Yukawa matrices

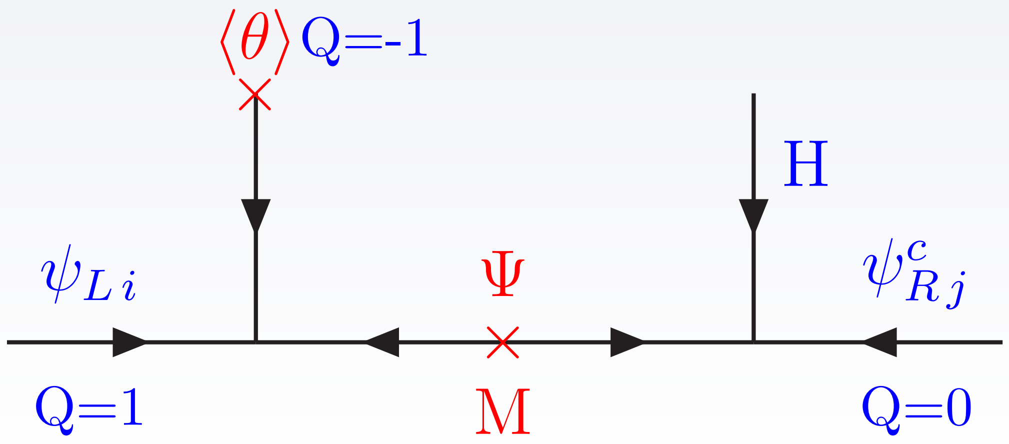
Supersymmetry

New flavour dependent interactions (sfermions/gauginos)

$\Longrightarrow$ new experimental information on flavour (urgently needed)!!

Flavour symmetries in SUSY

- Very different elements in Yukawa matrices: $y_t \simeq 1$, $y_u \simeq 10^{-5}$
- Expect couplings in a “fundamental” theory $\mathcal{O}(1)$
- Small couplings generated at higher order or function of small vevs.
- Froggatt-Nielsen mechanism and flavour symmetry to understand small Yukawa elements. Example: $U(1)_{fl}$



$$\Rightarrow Y_{ij} = \left(\frac{\langle\theta\rangle}{M}\right) \ll 1$$

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$\Downarrow$

We can relate the structure in Yukawa matrices to the nonuniversality in Soft Breaking masses !!!

Yukawa textures

- Masses and mixings in terms of a few fundamental parameters.
- Small mixing due to smallness of offdiagonal vs diagonal entries.
- Approximate texture zeros (GST) $\Rightarrow$ relate masses and mixings

Phenomenological fits:

$$Y_d \propto \begin{pmatrix} \leq \bar{\varepsilon}^5 & a\, \bar{\varepsilon}^3 & b\, \bar{\varepsilon}^3 \\ a\, \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & c\, \bar{\varepsilon}^2 \\ \leq \bar{\varepsilon} & \leq 1 & 1 \end{pmatrix}, \qquad Y_u \propto \begin{pmatrix} \leq \varepsilon^4 & \varepsilon^3 & \mathcal{O}(\varepsilon^3) \\ \leq \varepsilon^3 & \varepsilon^2 & \mathcal{O}(\varepsilon^2) \\ \leq \varepsilon & \leq 1 & 1 \end{pmatrix}$$

with $\varepsilon \simeq 0.05$ and $\bar{\varepsilon} \simeq 0.15$

Symmetric texture

- Non-Abelian flavour symmetries.

$$Y^d = \begin{pmatrix} 0 & 1.5\,\varepsilon^3 & 0.4\,\varepsilon^3 \\ 1.5\,\varepsilon^3 & \varepsilon^2 & 1.3\,\varepsilon^2 \\ 0.4\,\varepsilon^3 & 1.3\,\varepsilon^2 & 1 \end{pmatrix} y_b$$

- Universal sfermion masses in in unbroken limit:

$$\mathcal{L}_{m^2} = m_0^2 \Phi^\dagger \Phi = m_0^2 \left(\phi_1\ \phi_2\ \phi_3\right)^* \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

- After symmetry breaking:

$$M^2_{\tilde{D}_R} \simeq \begin{pmatrix} 1+\bar{\varepsilon}^3 & \bar{\varepsilon}^3 & 0 \\ \bar{\varepsilon}^3 & 1+\bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ 0 & \bar{\varepsilon}^2 & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

Asymmetric texture

- Abelian flavour symmetries.

$$Y^d = \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & 1 & 1 \end{pmatrix} y_b$$

- In principle nonuniversal masses in unbroken symmetry:

$$\mathcal{L}_{m^2} = m_1^2\ \phi_1^*\phi_1 + m_2^2\ \phi_2^*\phi_2 + m_3^2\ \phi_3^*\phi_3$$

- After symmetry breaking:

$$M^2_{\tilde{D}_R} \simeq \begin{pmatrix} 1 & \bar{\varepsilon} & \bar{\varepsilon} \\ \bar{\varepsilon} & c & b \\ \bar{\varepsilon} & b & a \end{pmatrix} m_0^2$$

FCNC constraints

- Large offdiagonal entries in sfermion mass matrices generally overproduce FCNC and CP Violation transitions

$\Longrightarrow$ SUSY flavour problem

- Strong phenomenological bounds on Mass Insertions

$$\left(\delta^f_A\right)_{ij} = \frac{(m^2_{\tilde{f}_A})_{ij}}{m^2_{\tilde{f}}}$$

- Very stringent bounds on $d \longrightarrow s$ transitions from ΔM_k and ε_k:

$$\text{Re}\{\left(\delta^d_R\right)_{12}\} \leq 4 \times 10^{-2}, \qquad \text{Im}\{\left(\delta^d_R\right)_{12}\} \leq 3.2 \times 10^{-3}$$

- Less stringent bounds from $b \longrightarrow d$ and $b \longrightarrow s$ transitions

$$\text{Re}\{\left(\delta^d_R\right)_{13}\},\ \text{Im}\{\left(\delta^d_R\right)_{13}\} \leq 0.1$$

($\Rightarrow$ Simple abelian models not allowed by ΔM_k and ε_k)

$SU(3)$ Flavour model

- $Q, L \sim \mathbf{3}$ and $d^c, u^c, e^c \sim \mathbf{3}$; flavon fields: $\theta_3, \theta_{23} \sim \overline{\mathbf{3}}$, $\overline{\theta}_3, \overline{\theta}_{23} \sim \mathbf{3}$
- Family Symmetry breaking: $SU(3) \xrightarrow{\langle\theta_3\rangle} SU(2) \xrightarrow{\langle\theta_{23}\rangle} \emptyset$

$$\theta_3, \overline{\theta}_3 = \begin{pmatrix} 0 \\ 0 \\ a_3 \end{pmatrix}, \quad \theta_{23}, \overline{\theta}_{23} = \begin{pmatrix} 0 \\ b \\ b \end{pmatrix} \text{with} \quad \left(\frac{a_3}{M}\right) \sim \mathcal{O}(1), \left(\frac{b}{M_u}\right) \simeq \left(\frac{b}{M_d}\right)^2 = \varepsilon \sim 0.05.$$

- Yukawa superpotential: $W_Y = H\psi_i\psi_j^c\left[\theta_3^i\theta_3^j + \theta_{23}^i\theta_{23}^j\Sigma + \epsilon^{ikl}\overline{\theta}_{23,k}\overline{\theta}_{3,l}\theta_{23}^j\left(\theta_{23}\overline{\theta_3}\right)\right]$

$$Y^f = \begin{pmatrix} 0 & a\ \varepsilon^3 & b\ \varepsilon^3 \\ a\ \varepsilon^3 & \varepsilon^2\dfrac{\Sigma}{|a_3|^2} & c\ \varepsilon^2\dfrac{\Sigma}{|a_3|^2} \\ b\ \varepsilon^3 & c\ \varepsilon^2\dfrac{\Sigma}{|a_3|^2} & 1 \end{pmatrix}\frac{|a_3|^2}{M^2},$$

- Soft mass coupling $\Phi^\dagger\Phi$ invariant $\Longrightarrow$ common soft mass for the triplet
- Universality guaranteed in the exact symmetry limit.
- After symmetry breaking offdiagonal entries proportional to flavon vevs

$$M^2_{ij} = m_0^2 \left(\delta^{ij} + \frac{1}{M^2}[\theta_3^{i\dagger}\theta_3^j + \theta_{23}^{i\dagger}\theta_{23}^j] + \frac{1}{M^4}[(\epsilon^{ikl}\overline{\theta}_{3,k}\overline{\theta}_{23,l})^\dagger(\epsilon^{jmn}\overline{\theta}_{3,m}\overline{\theta}_{23,n})]\right)$$

$$M^2_{\tilde{D}_R}{}^{\rm SCKM} \simeq 6\ M^2_{1/2}\ \mathbb{1}\ + \begin{pmatrix} 1+\bar{\varepsilon}^3 & \bar{\varepsilon}^3 & \bar{\varepsilon}^3 \\ \bar{\varepsilon}^3 & 1+\bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

(with $\bar{\varepsilon} \simeq 0.15, \varepsilon \simeq 0.05$)

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$$M^2_{\tilde{D}_R}{}^{\mathrm{SCKM}} \simeq 6\ M^2_{1/2}\ \mathbb{1}\ + \begin{pmatrix} 1 & 0.003 & 0.003 \\ 0.003 & 1 & 0.02 \\ 0.003 & 0.02 & 1 \end{pmatrix} m_0^2$$

(with $\bar{\varepsilon} \simeq 0.15$, $\varepsilon \simeq 0.05$)

At M_W in the SCKM basis:

$$M^2_{\tilde{D}_L} \simeq 6\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1+\varepsilon^3 & \varepsilon^2\bar{\varepsilon} & \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 \\ \varepsilon^2\bar{\varepsilon} & 1+\varepsilon^2 & \varepsilon^2 + c_{\rm run}\ \bar{\varepsilon}^2 \\ \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 & \varepsilon^2 + c_{\rm run}\ \bar{\varepsilon}^2 & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

$$M^2_{\tilde{E}_R} \simeq 0.15\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1+\bar{\varepsilon}^3 & \frac{\bar{\varepsilon}^3}{3} & \bar{\varepsilon}^3 \\ \frac{\bar{\varepsilon}^3}{3} & 1+\bar{\varepsilon}^2 & \bar{\varepsilon}^2 \\ \bar{\varepsilon}^3 & \bar{\varepsilon}^2 & 1+\bar{\varepsilon} \end{pmatrix} m_0^2$$

$$M^2_{\tilde{E}_L} \simeq 0.5\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1+\varepsilon^3 & \frac{\varepsilon^2\bar{\varepsilon}}{3} & \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 \\ \frac{\varepsilon^2\bar{\varepsilon}}{3} & 1+\varepsilon^2 & \varepsilon^2 + 3\ c_{\rm run}\ \bar{\varepsilon}^2 \\ \varepsilon^2\bar{\varepsilon} + c_{\rm run}\ \bar{\varepsilon}^3 & \varepsilon^2 + 3\ c_{\rm run}\ \bar{\varepsilon}^2 & 1+\varepsilon \end{pmatrix} m_0^2$$

At M_W in the SCKM basis:

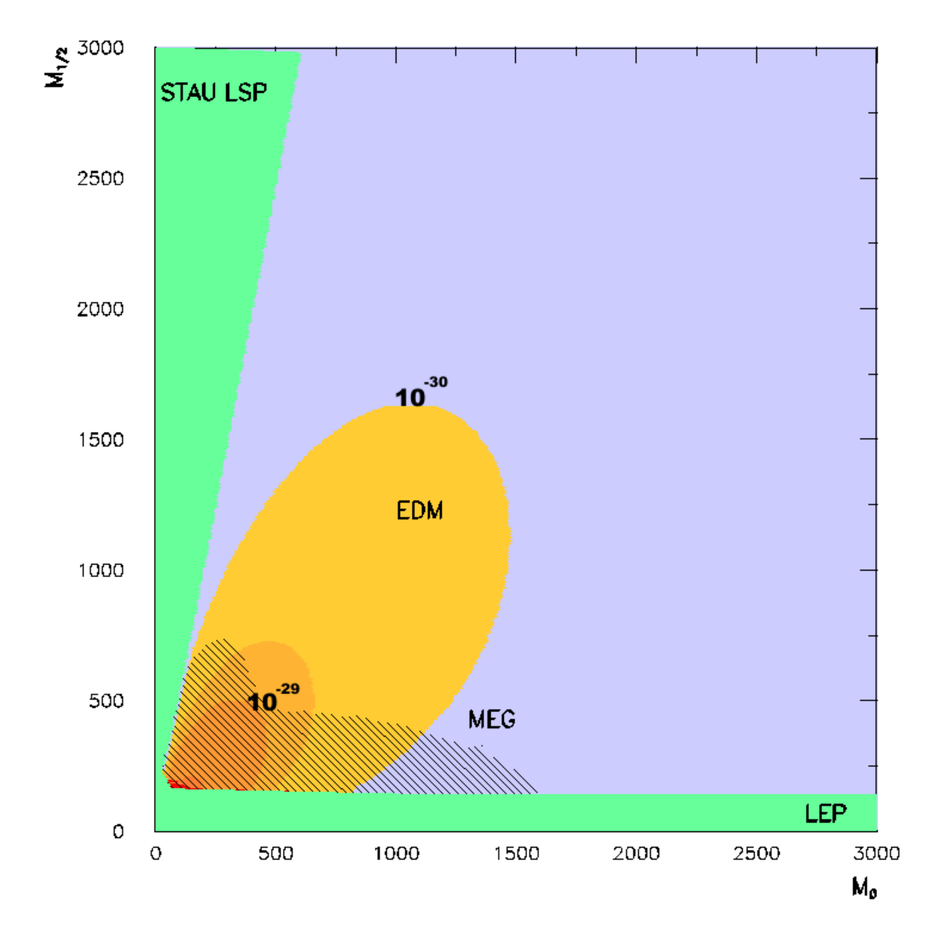
$$M^2_{\tilde{D}_L} \simeq 6\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1 & 4\times10^{-4} & 7\times10^{-4} \\ 4\times10^{-4} & 1 & 4\times10^{-3} \\ 7\times10^{-4} & 4\times10^{-3} & 1 \end{pmatrix} m_0^2$$

$$M^2_{\tilde{E}_R} \simeq 0.15\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1 & 0.001 & 0.003 \\ 0.001 & 1 & 0.02 \\ 0.003 & 0.02 & 1 \end{pmatrix} m_0^2$$

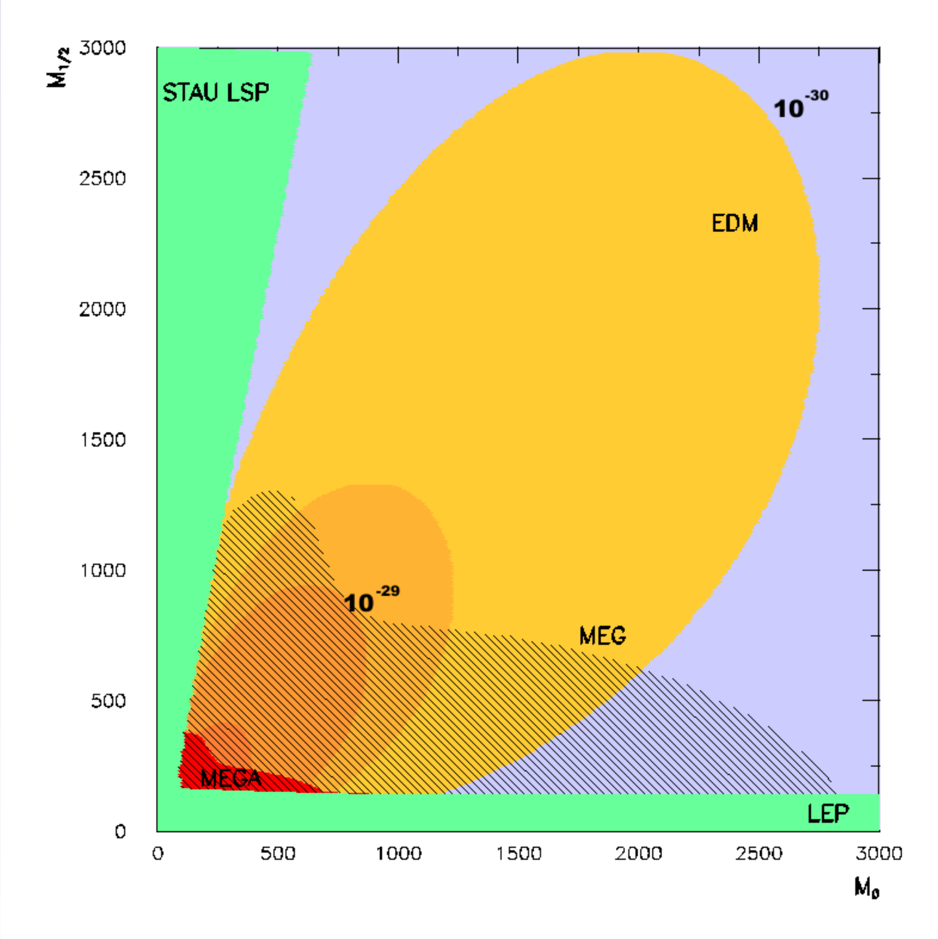
$$M^2_{\tilde{E}_L} \simeq 0.5\, M^2_{1/2}\, \mathbb{1} + \begin{pmatrix} 1 & 1\times10^{-4} & 7\times10^{-4} \\ 1\times10^{-4} & 1 & 1\times10^{-2} \\ 7\times10^{-4} & 1\times10^{-2} & 1 \end{pmatrix} m_0^2$$

LFV, EDMs & b–s transitions (Preliminary)

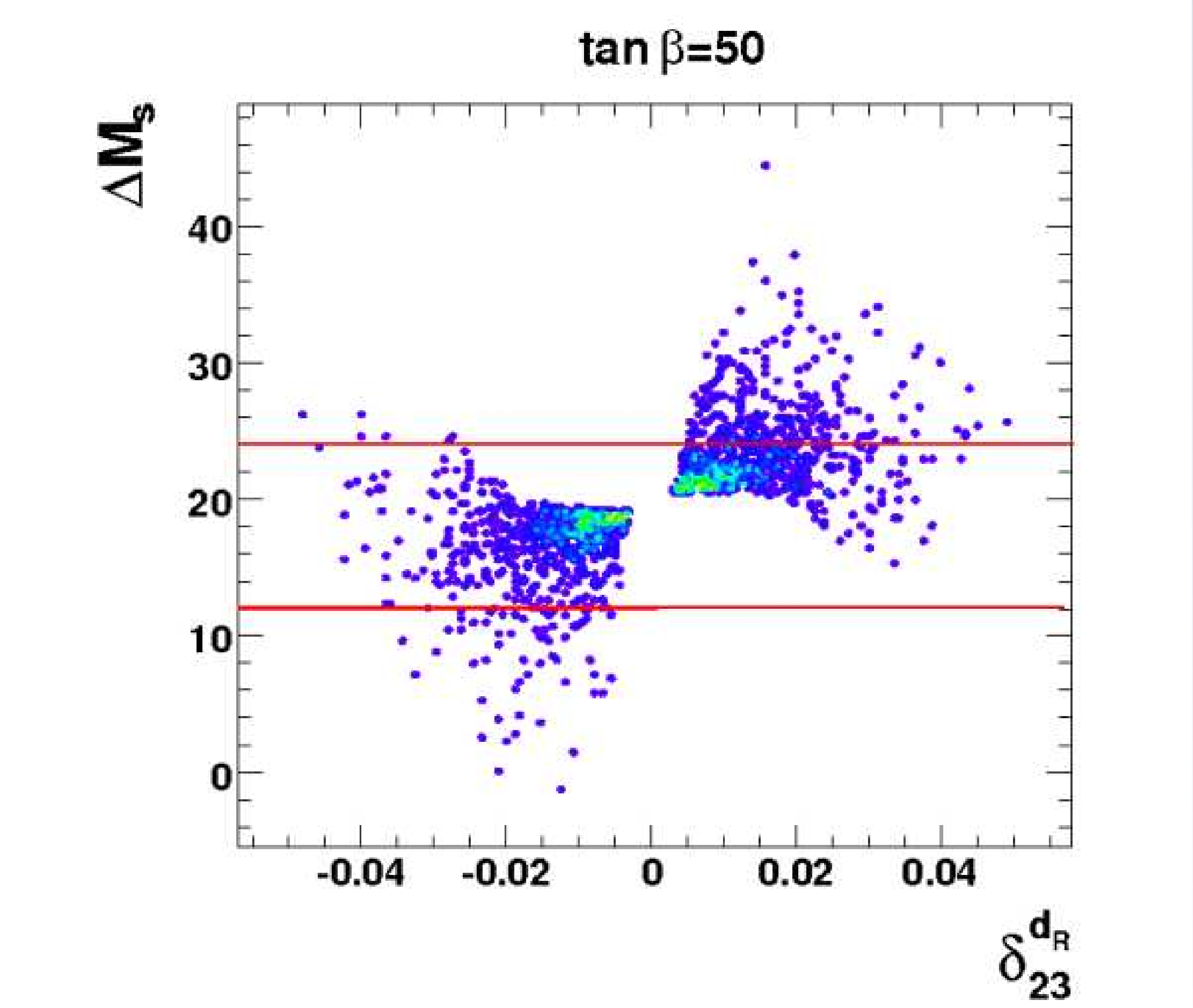
$\tan\beta = 10,\ A_0 = 0$



$\tan\beta = 30,\ A_0 = 0$



$$d_e \propto m_\tau \mu \tan\beta \cdot \mathrm{Im}\left[\delta_{13}^{e_R} \cdot \delta_{31}^{e_L}\right]$$


tan β=50
ΔM_s
40
30
20
10
0
-0.04
-0.02
0
0.02
0.04
$\delta_{23}^{d_R}$

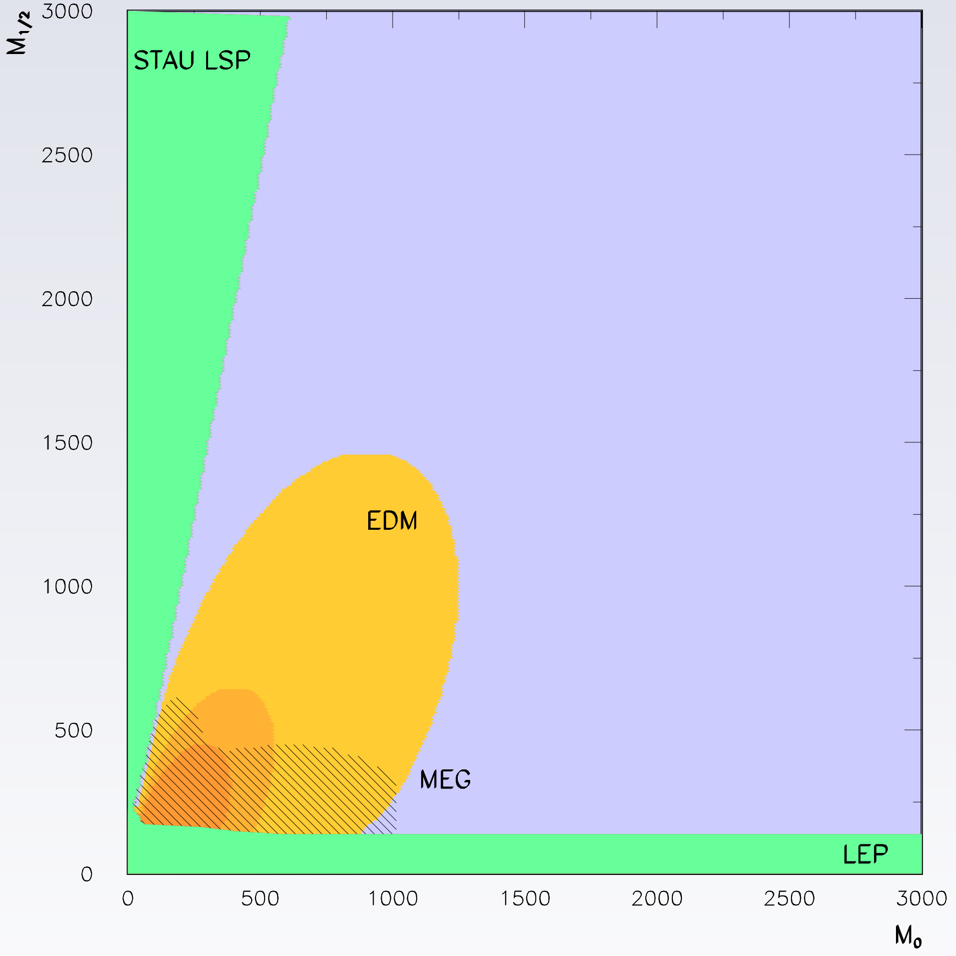
LHC and FCNC measurements

Measure of sfermion mass matrices can help to distinguish different flavour models !!

$\Downarrow$

- Combination of direct and indirect measurements provide MSSM masses and mixings.
- $b \to s$ FCNC processes are key measurements to understand flavour.
- LFV and EDMs can explore large areas of flavour MSSM in near future.

$\tan\beta = 10,\ A_0 = 2m_0$



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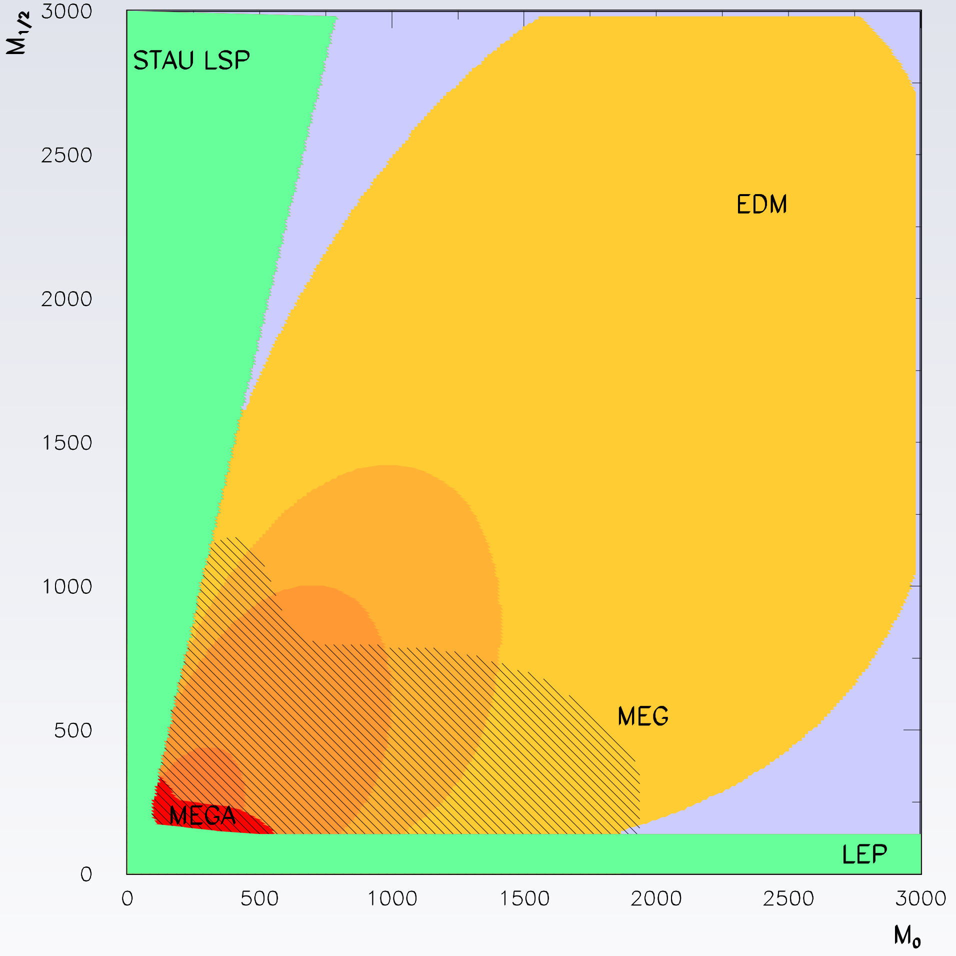
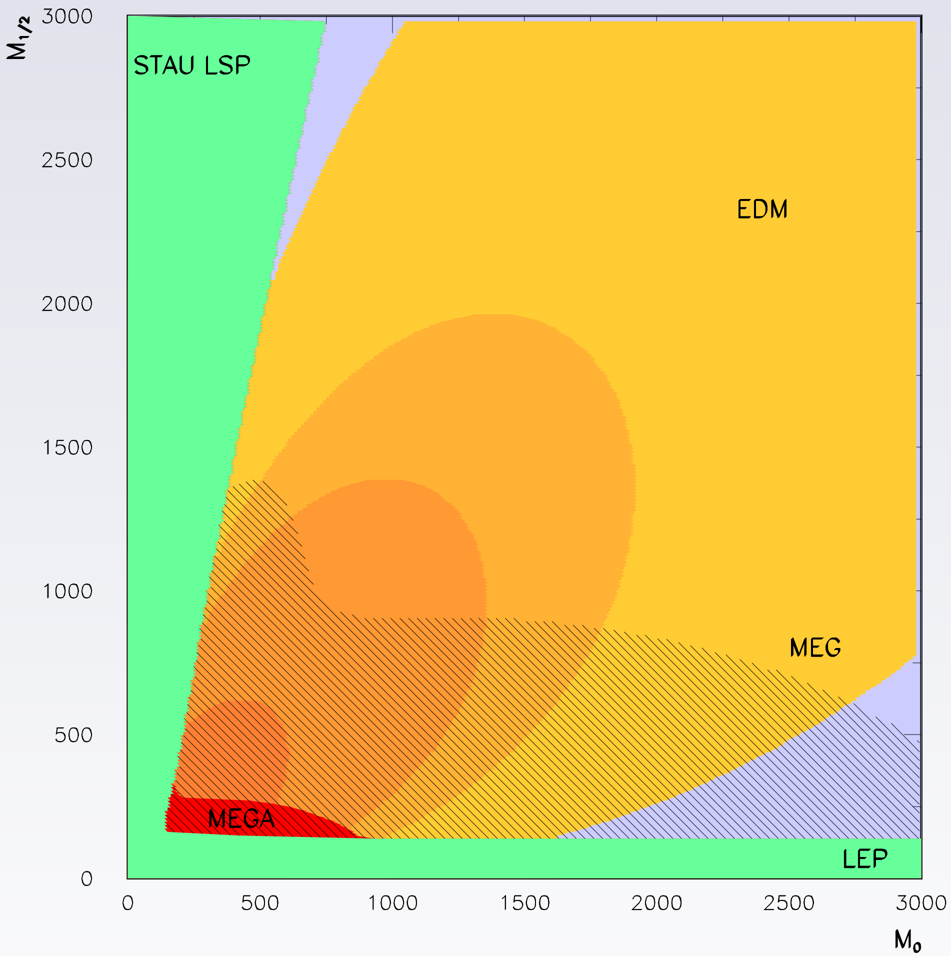
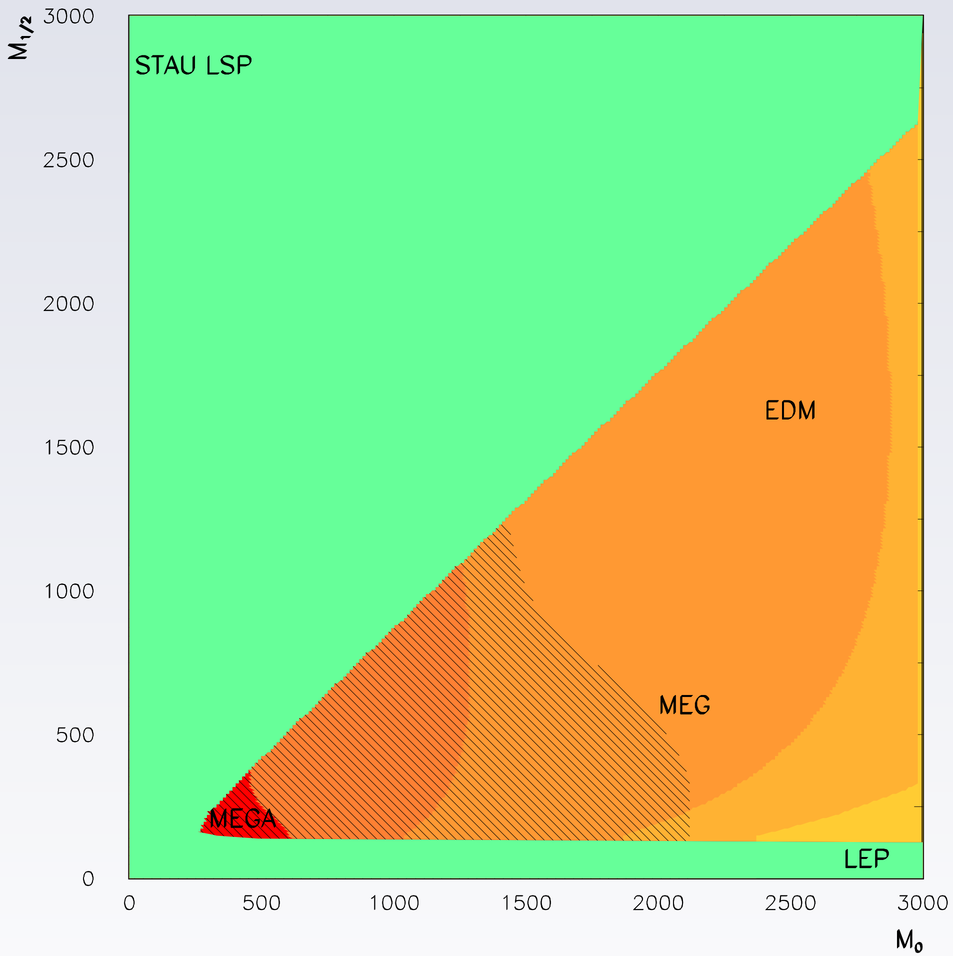


$$d_e \propto m_\tau \mu \tan\beta \cdot \mathrm{Im}\left[\delta^{e_R}_{13} \cdot \delta^{e_L}_{31}\right]$$

$\tan\beta = 50,\ A_0 = 0$



$\tan\beta = 50,\ A_0 = 2m_0$



$$d_e \propto m_\tau \mu \tan\beta \cdot \mathrm{Im}\left[\delta^{e_R}_{13} \cdot \delta^{e_L}_{31}\right]$$