Realistic flavour models at the LHC

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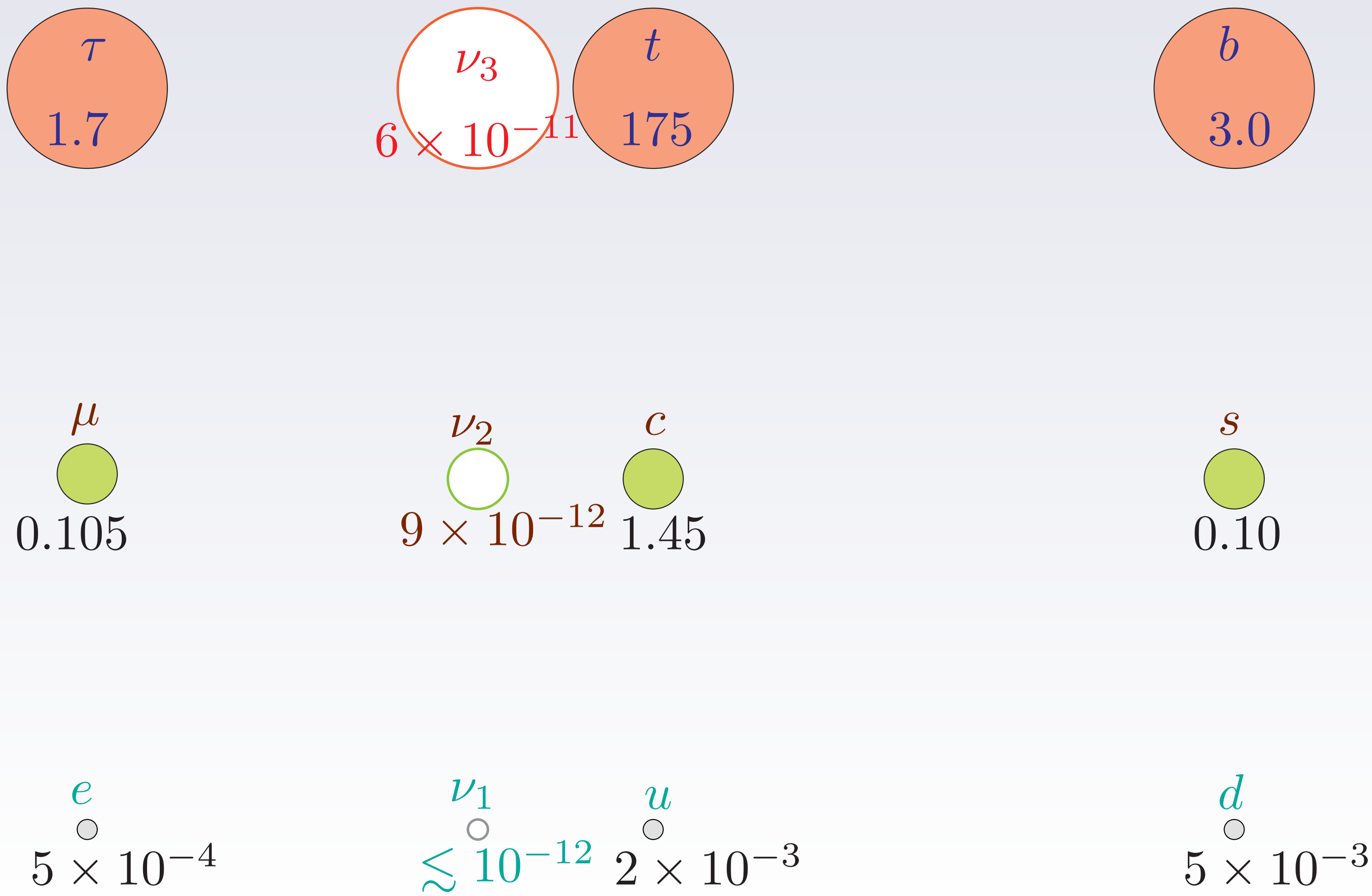

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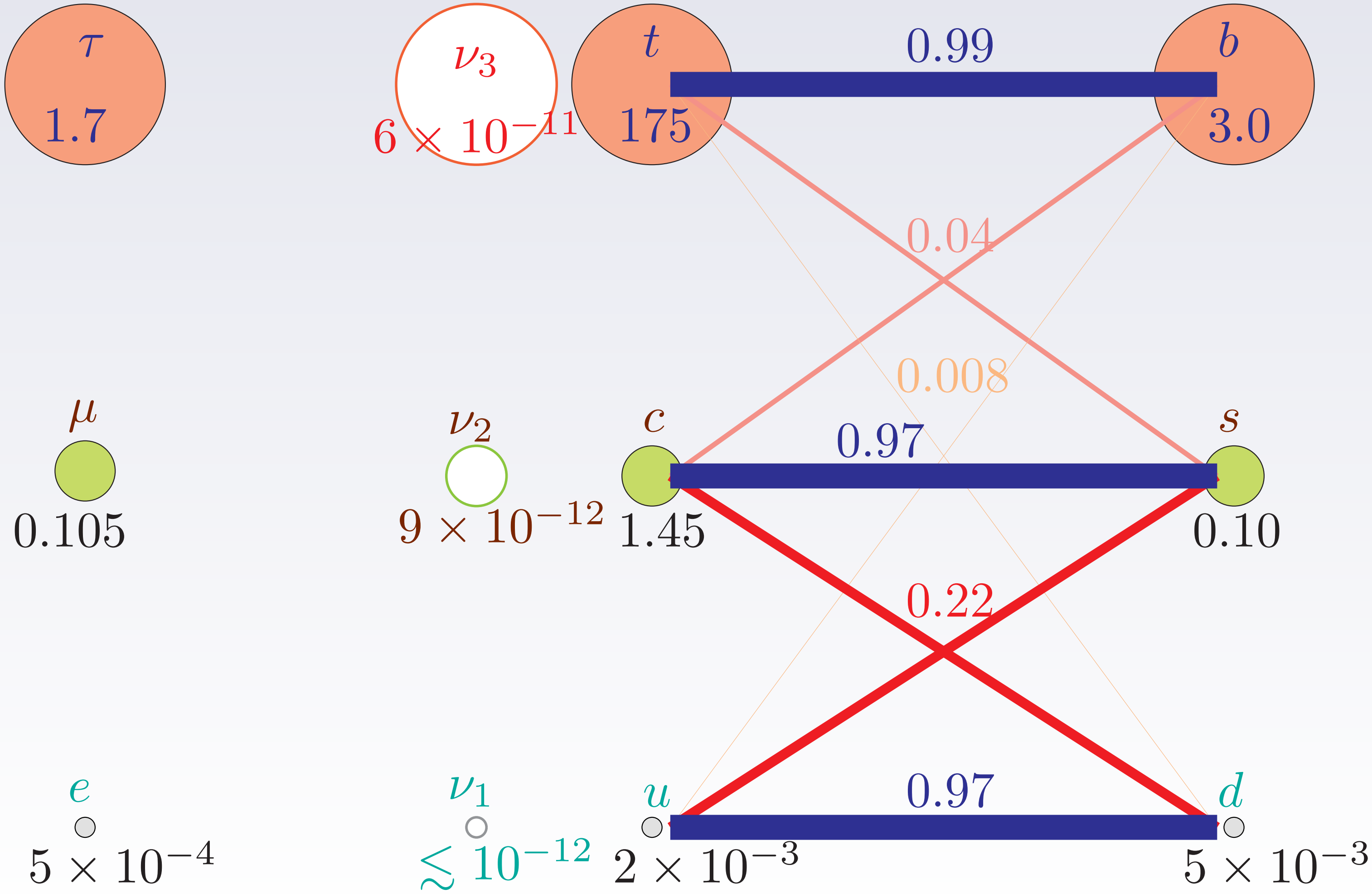

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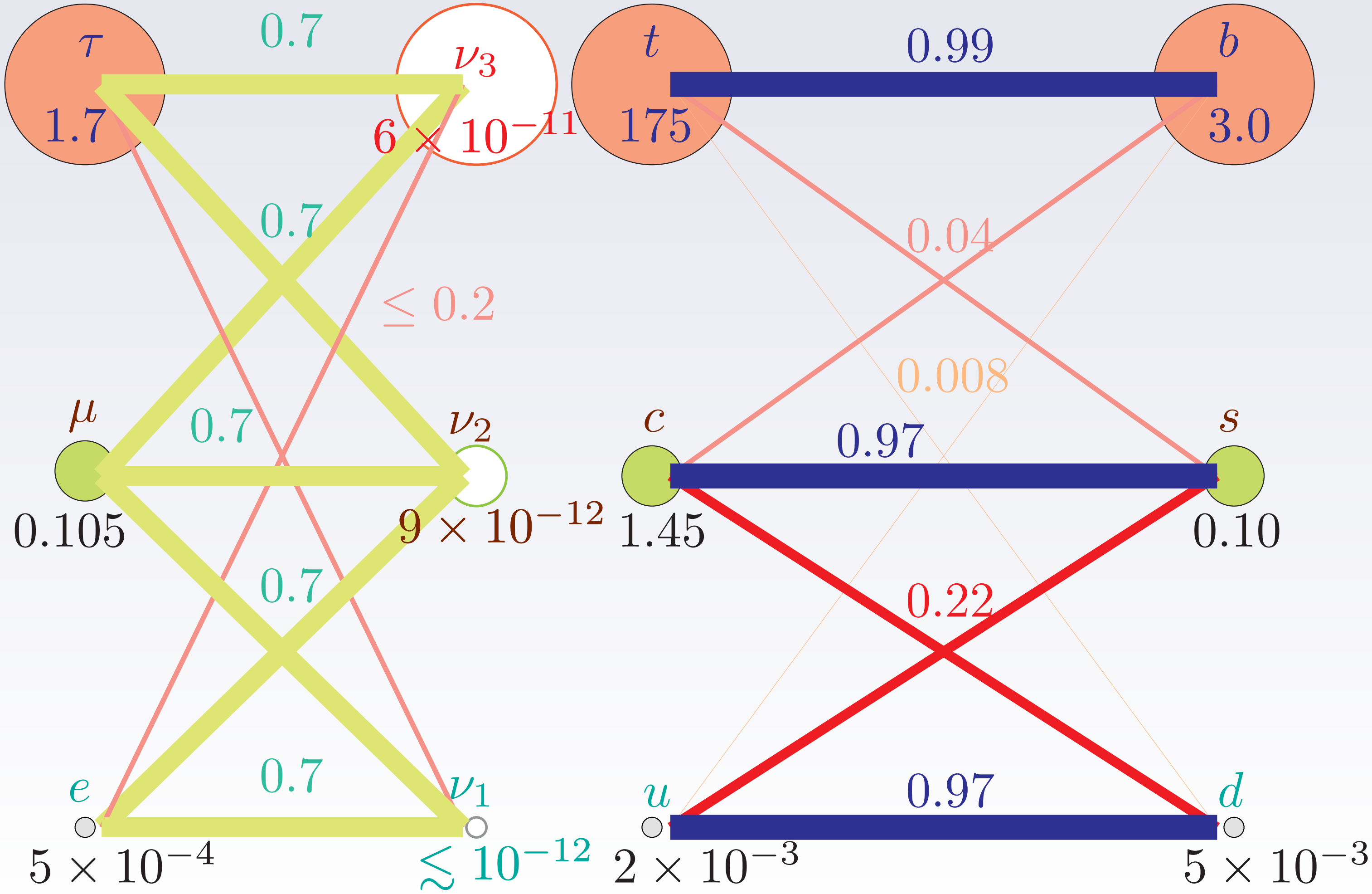
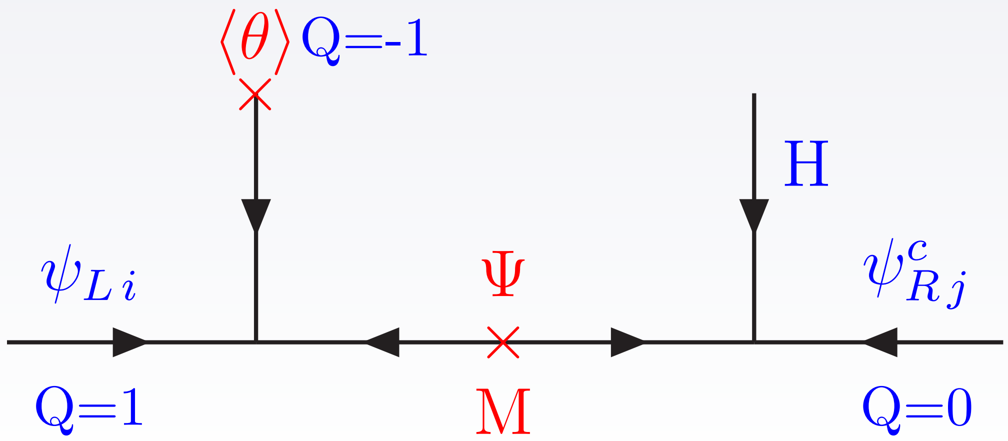


Flavour symmetries in SUSY

- 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, quarks:

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

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

Lepton textures:

- Large leptonic mixings . . .

$$U_{PMNS} \simeq \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\frac{\sin\theta_{12}}{\sqrt{2}} & \frac{\cos\theta_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\theta_{12}}{\sqrt{2}} & -\frac{\cos\theta_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \qquad \sin\theta_{12} \simeq \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{3}}$$

- Charged-lepton similar to down-quark masses

$\Rightarrow$ Quark/lepton unification a la Georgi-Jarlskog ??

- Neutrinos are (can be...) Majorana particles.

$$m_{\nu_L} = v_2^2 \, Y_\nu \cdot \frac{1}{M_R} \cdot Y_\nu^T$$

Symmetric texture

- Non-Abelian flavour symmetries.

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

- 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:

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

Asymmetric texture

- Abelian flavour symmetries.

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

- 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:

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

FCNC constraints

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

$\Longrightarrow$ SUSY flavour problem

- Stringent bounds on $d \to s$ and $\mu \to e$ MI ($m_{\tilde{q}} = 500$ GeV)

$$\mathrm{Re}\{(\delta^d_R)_{12}\} \le 4 \times 10^{-2}, \quad \mathrm{Im}\{(\delta^d_R)_{12}\} \le 3.2 \times 10^{-3}, \quad |(\delta^e_L)_{12}| \le 0.001 \, \frac{10}{\tan\beta}$$

- Less stringent bounds from $b \to s, d$ and $\tau \to \mu, e$ transitions

$$\mathrm{Re}\{(\delta^d_R)_{13}\}, \; \mathrm{Im}\{(\delta^d_R)_{13}\}, \; |(\delta^e_L)_{13}|, \; \le \; 0.1 \; \left(\frac{10}{\tan\beta}\right)$$

($\Rightarrow$ Simple Abelian models not allowed by ΔM_k, ε_k and $\mu \to e\gamma$)

Abelian Flavour symmetry

- "Realistic" model with two Abelian groups $U(1)_1 \times U(1)_2$
- Charges under $(U(1)_1, U(1)_2)$:

$Q_1 \sim (0,1)$, $Q_2 \sim (1,0)$, $Q_3 \sim (0,0)$, $\phi_1 \sim (-1,0)$ with $\langle \phi_1 \rangle / M = \lambda_c^2$

$d_1^c \sim (3,-1)$, $d_2^c \sim (1,0)$, $d_3^c \sim (1,0)$, (flavons)

$u_1^c \sim (0,1)$, $u_2^c \sim (-1,1)$, $u_3^c \sim (0,0)$ $\phi_2 \sim (0,-1)$ with $\langle \phi_2 \rangle / M = \lambda_c^3$

- Yukawa couplings proportional to: $Y_{ij} = \left(\frac{\langle \phi_1 \rangle}{M} \right)^{(q_1^i + q_1^j)} \left(\frac{\langle \phi_2 \rangle}{M} \right)^{(q_2^i + q_2^j)}$

$$M^{d,e} = \langle H_1 \rangle \, \lambda^2 \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ 0 & \lambda^2 & \lambda^2 \\ 0 & 1 & 1 \end{pmatrix}, \qquad M^u = \langle H_2 \rangle \begin{pmatrix} \lambda^6 & 0 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & 0 & 1 \end{pmatrix}.$$

- Soft mass coupling $\phi_i^\dagger \phi_i$ invariant under all symmetries

  $\Rightarrow$ flavour diagonal soft masses allowed by flavour symmetry

- Diagonal masses required to be equal by phenomenology

- After symmetry breaking offdiagonal entries proportional to flavon vevs

$$M_{ij}^2 = m_0^2 \left(\frac{\langle \phi_1 \rangle}{M} \right)^{|q_1^i - q_1^j|} \left(\frac{\langle \phi_2 \rangle}{M} \right)^{|q_2^i - q_2^j|}$$

$$M_{\tilde{D}_R, \tilde{E}_L}^2 \sim m_0^2 \begin{pmatrix} 1 & \lambda^7 & \lambda^7 \\ \lambda^7 & 1 & 1 \\ \lambda^7 & 1 & 1 \end{pmatrix}, \qquad M_{\tilde{U}_R}^2 \sim m_0^2 \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda^5 \\ \lambda^3 & \lambda^5 & 1 \end{pmatrix},$$

$$M_{\tilde{D}_L}^2 = M_{\tilde{U}_L}^2 \sim m_0^2 \begin{pmatrix} 1 & \lambda^5 & \lambda^3 \\ \lambda^5 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}.$$

$SU(3)$ 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: $W_Y = H \psi_i \psi_j^c \left[\theta_3^i \theta_3^j + \theta_{23}^i \theta_{23}^j \Sigma + \epsilon^{ikl} \overline{\theta}_{23,k} \overline{\theta}_{3,l} \theta_{23}^j \left(\theta_{23} \overline{\theta}_3\right)\right]$

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

- 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

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

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

LHC & FCNC measurements

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

$\Downarrow$

- Are squark and slepton mass matrices related by GUT?
  $\Rightarrow$ Grand Unification of FCNCs.
- $\tilde{b}_R$, $\tilde{\tau}_L$ and $\tilde{s}_R$, $\tilde{\mu}_L$ masses and $(\delta^d_R)_{23}$, $(\delta^e_L)_{23}$ very different in symmetric and asymmetric textures.
- $b \to s$ and $\tau \to \mu$ FCNC processes are key measurements to understand flavour.

You can help us !!!!

- B_s oscillations $\Rightarrow B_s \to D_s \pi$
- $b \to s$ penguin $\Rightarrow B_d \to \phi K_s,\ B_s \to \phi\phi$
- Lepton Flavour violation $\Rightarrow \mu \to e\gamma,\ \tau \to \mu\gamma \ldots$
- Electric Dipole Moments, ...

Backup: FCNC Grand unification.