BSM and Flavour in the Lepton Sector

Plan of talk:

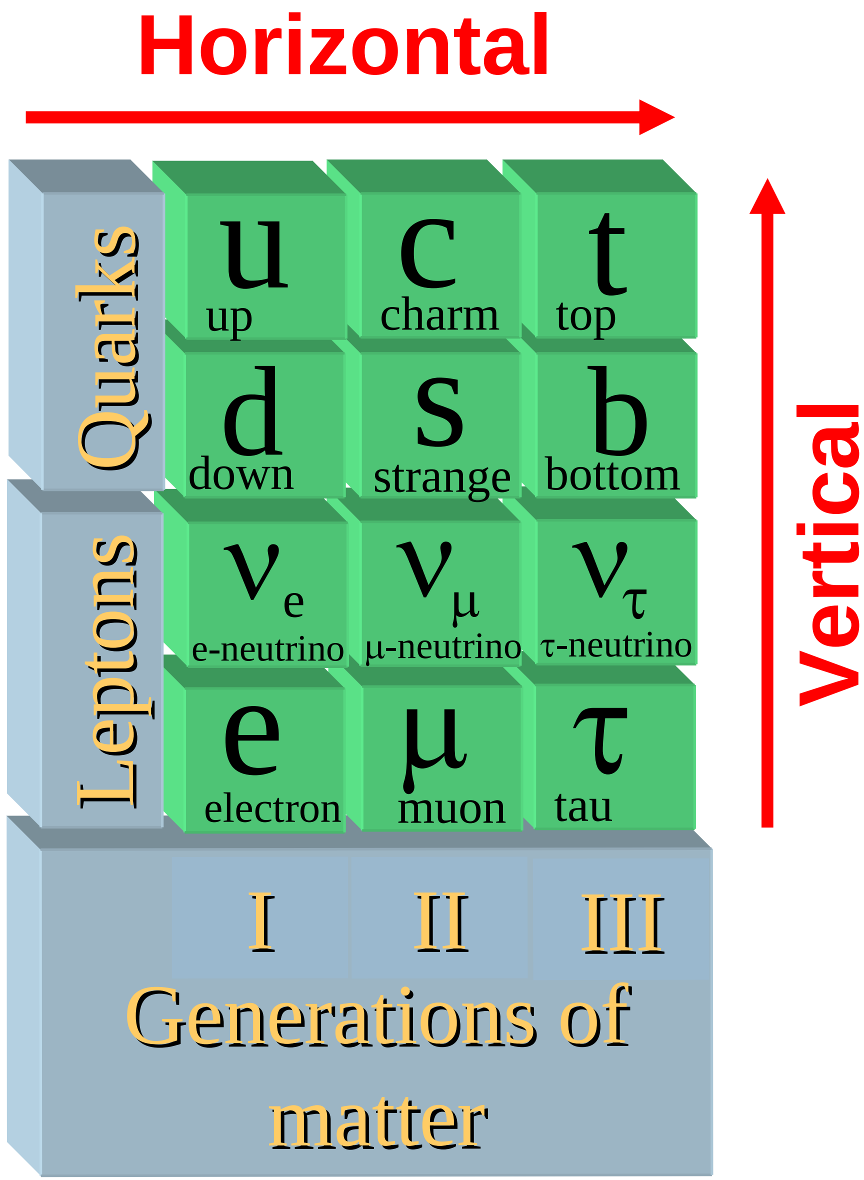
I. The Flavour Problem

II. The SUSY Flavour Problem

III. Flavour Dependent Leptogenesis

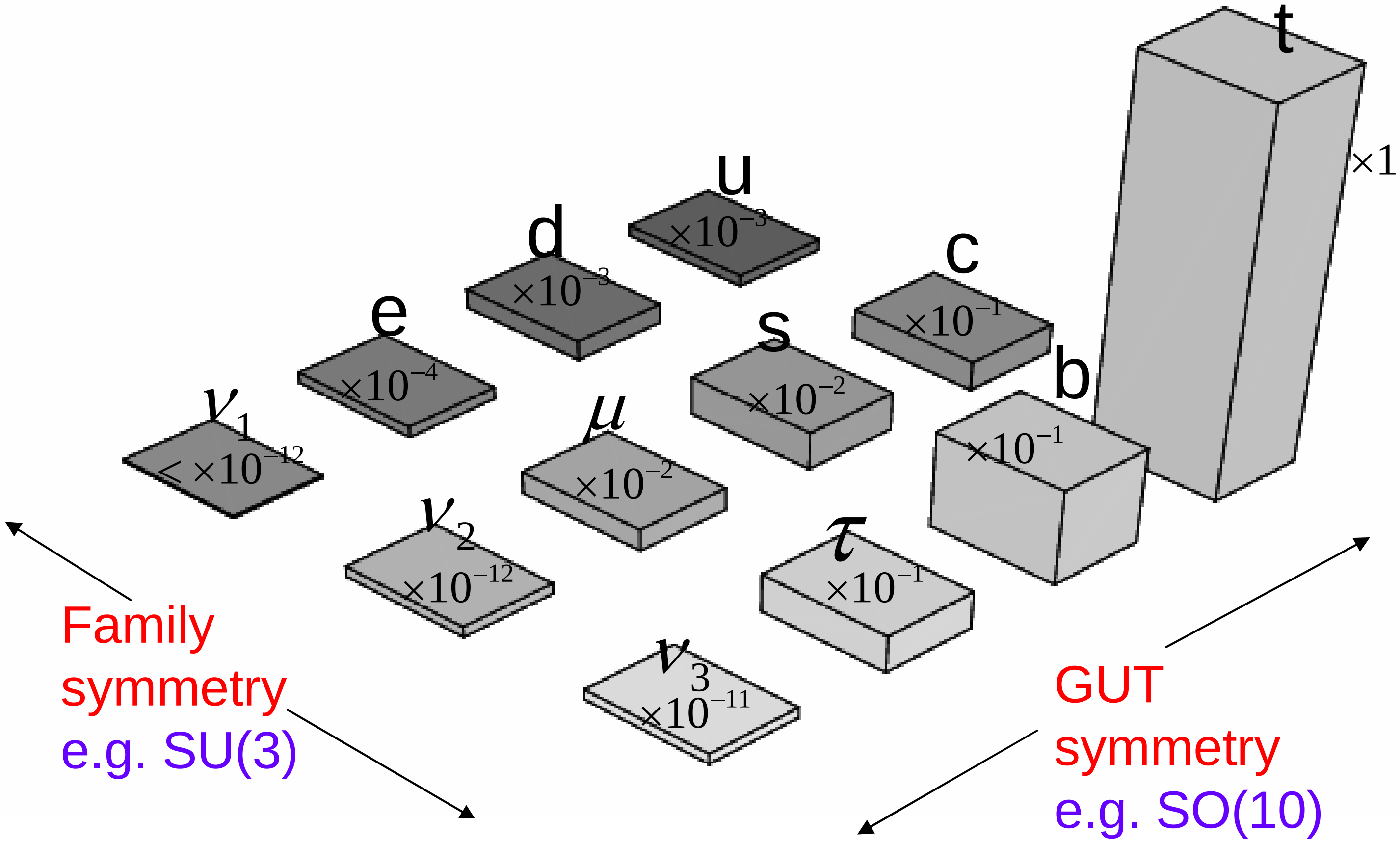
The Flavour Problem

I. Why are there three families of quarks and leptons?



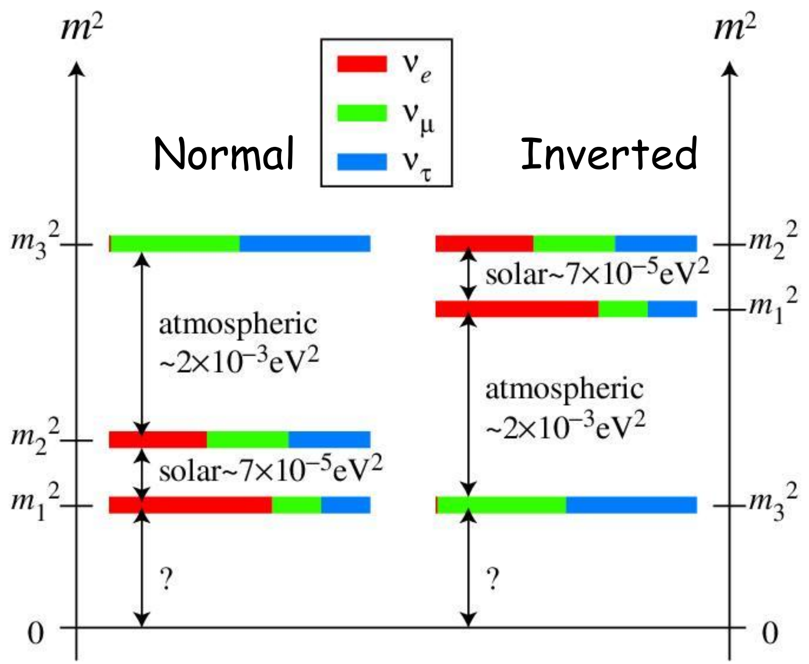
The Flavour Problem

II. Why are quark and charged lepton masses so peculiar?



The Flavour Problem

III. Why are neutrino masses so small?

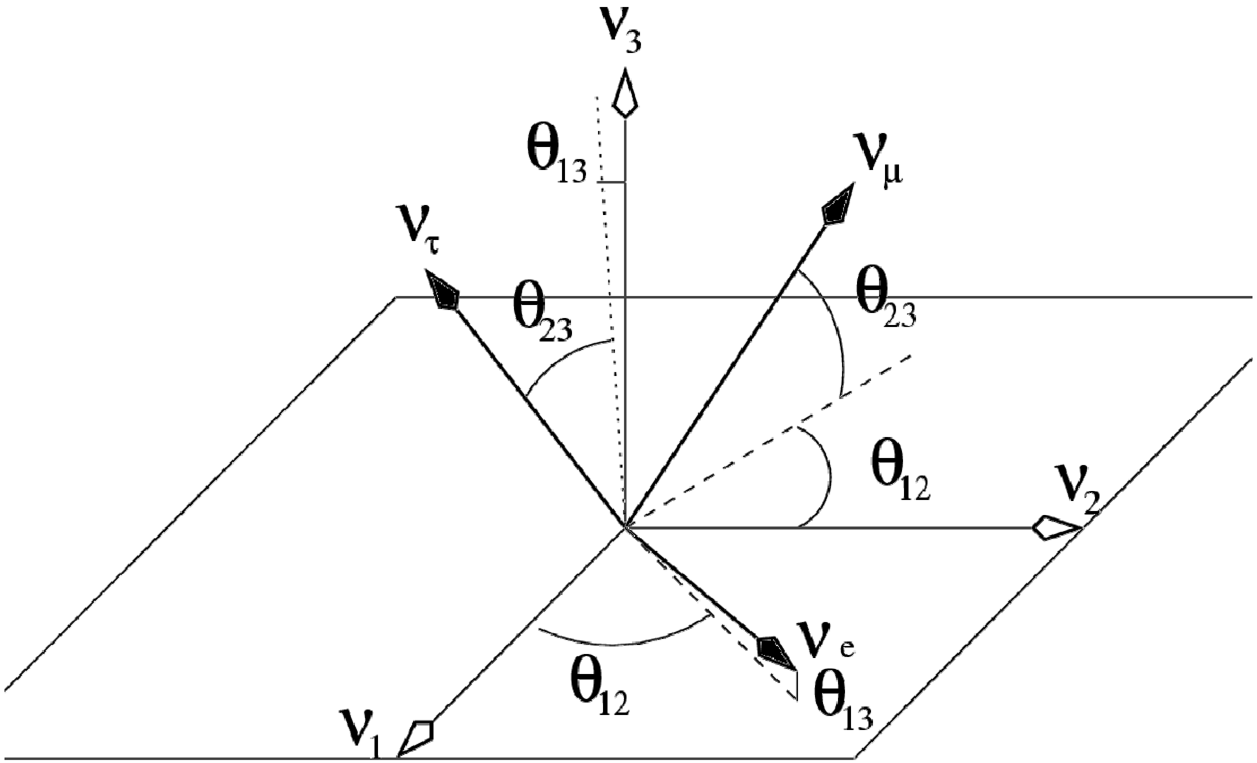


The Flavour Problem
IV. Why is lepton mixing so large?

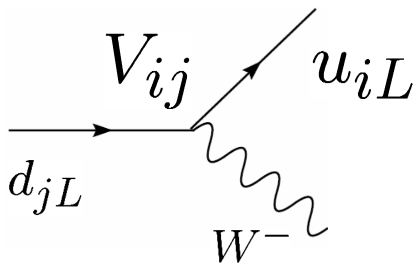
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

e.g.Tri-bimaximal

Harrison, Perkins, Scott



c.f. small quark mixing



$$V_{ij} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

See-saw mechanism can account for small neutrino mass

Possible type II contribution
(ignored here)

Dirac matrix

$$\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_{LR} \\ m_{LR}^T & M_{RR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Heavy Majorana matrix

$$m_{LL}^{\nu} = m_{LR} M_{RR}^{-1} m_{LR}^T \sim m_{LR}^2 / M_{RR}$$

Sequential dominance can account for large neutrino mixing

SFK

Diagonal RH nu basis

$$M_{\mathrm{RR}} = \begin{pmatrix} X & 0 & 0 \\ 0 & Y & 0 \\ 0 & 0 & Z \end{pmatrix}$$

columns

$$Y^{\nu}_{\mathrm{LR}} = \begin{pmatrix} A & B & C \end{pmatrix}$$

See-saw ⇒

$$m^{\nu}_{LL} = \frac{AA^T}{X} + \frac{BB^T}{Y} + \frac{CC^T}{Z}$$

Sequential dominance ⇒ Dominant, Subdominant, Decoupled

m$_3$ m$_2$ m$_1$

$$\left.\begin{aligned} |A_1| &= 0, \\ |A_2| &= |A_3|, \\ |B_1| &= |B_2| = |B_3|, \\ A^\dagger B &= 0 \end{aligned}\right\} \Rightarrow \quad V^{\nu_L\dagger} \approx \begin{pmatrix} -\sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Constrained SD

Tri-bimaximal

Non-Abelian family symmetry

Need

$$Y^{\nu}_{LR} = \begin{pmatrix} 0 & B_1 & - \\ A_2 & B_2 & - \\ A_3 & B_3 & - \end{pmatrix}$$

with CSD

$$\begin{aligned} |A_1| &= 0, \\ |A_2| &= |A_3|, \\ |B_1| &= |B_2| = |B_3|, \\ A^{\dagger}B &= 0 \end{aligned}$$

$2 \leftrightarrow 3$ symmetry (from maximal atmospheric mixing)

$1 \leftrightarrow 2 \leftrightarrow 3$ symmetry (from tri-maximal solar mixing)

Examples of suitable non-Abelian family symmetries:

SFK, Ross; Velasco-Sevilla; Varzelias $SU(3)$ Δ_{27}

SFK, Malinsky $SO(3)$ A_4

$\left.\begin{array}{l} \Delta_{27} \\ A_4 \end{array}\right\}$ Discrete subgroups preferred by vacuum alignment

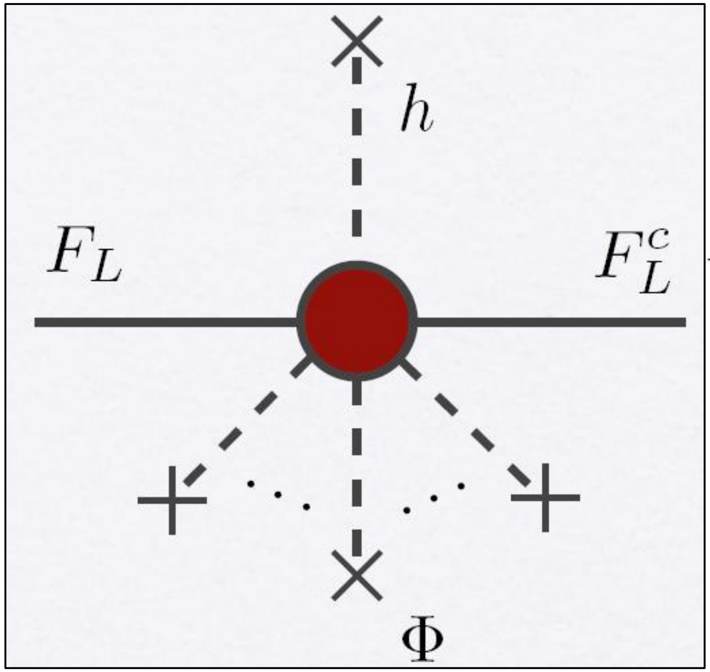
A_4 Pati-Salam Model

SFK,Malinsky

field	$SU(4)\otimes SU(2)_L\otimes SU(2)_R$	A_4	$U(1)$	Z_2
F	$(4,2,1)$	3	0	$+$
F^c_1	$(\overline{4},1,2)$	1	$+2$	$-$
F^c_2	$(\overline{4},1,2)$	1	$+1$	$+$
F^c_3	$(\overline{4},1,2)$	1	-3	$-$
h	$(1,2,2)$	1	0	$+$
$H,\overline{H}$	$(4,1,2),\ (\overline{4},1,2)$	1	± 3	$+$
$H',\overline{H'}$	$(4,1,2),\ (\overline{4},1,2)$	1	∓ 3	$+$
Σ	$(15,1,3)$	1	-1	$-$
ϕ_1	$(1,1,1)$	3	$+4$	$+$
ϕ_2	$(1,1,1)$	3	0	$+$
ϕ_3	$(1,1,1)$	3	$+3$	$-$
ϕ_{23}	$(1,1,1)$	3	-2	$-$
$\tilde{\phi}_{23}$	$(1,1,1)$	3	0	$-$
ϕ_{123}	$(1,1,1)$	3	-1	$+$

Family symmetry must be broken

- Flavons break family symmetry
- Yukawas as `little flavour magnets'



$$\frac{1}{M}y_{23}F.\phi_{23}F^c_1h+\frac{1}{M}y_{123}F.\phi_{123}F^c_2h+\frac{1}{M}y_3F.\phi_3F^c_3h+\frac{1}{M^2}y_{GJ}F.\tilde{\phi}_{23}F^c_2\Sigma h$$

$$+\frac{1}{M^2}y_{13}F.(\phi_2\times\phi_3)F^c_3h+\frac{1}{M^2}y'_{13}F.(\phi_2*\phi_3)F^c_3h+\frac{1}{M^3}y^i_{23}I_i(F,\tilde{\phi}_{23},\tilde{\phi}_{23},\phi_3)F^c_3h$$

$$Y^f_{LR}=\begin{pmatrix} 0 & y_{123}\varepsilon^f_{123} & \overline{y}_{13}\varepsilon^f_2\varepsilon^f_3 \\ y_{23}\varepsilon^f_{23} & y_{123}\varepsilon^f_{123}+C^f y_{GJ}\tilde{\varepsilon}^f_{23}\sigma & \overline{y}_{23}(\tilde{\varepsilon}^f_{23})^2\varepsilon^f_3 \\ -y_{23}\varepsilon^f_{23} & y_{123}\varepsilon^f_{123}-C^f y_{GJ}\tilde{\varepsilon}^f_{23}\sigma & y_3\varepsilon^f_3 \end{pmatrix}$$

$$C^f=-2,0,1,3\ (\text{for } f=u,\nu,d,e) \qquad \varepsilon^f_x\equiv\frac{|\langle\phi_x\rangle|}{M_f}$$

Neutrino Sector

Vacuum alignment

Majorana magnets

$$\frac{1}{M_\nu^3} w_1 F_1^{c2} H H' \phi_{23}^2 + \frac{1}{M_\nu^3} w_2 F_2^{c2} H H' \phi_{123}^2 + \frac{1}{M_\nu} w_3 F_3^{c2} H^2$$

$$M_{RR} = \begin{pmatrix} \varepsilon_{23}^2 \delta & & \\ & \varepsilon_{123}^2 \delta & \\ & & 1 \end{pmatrix} \frac{\langle H \rangle^2}{M}$$

$$\frac{<\phi_{23}>}{M} = \begin{pmatrix} 0 \\ \varepsilon_{23} \\ -\varepsilon_{23} \end{pmatrix} \qquad \frac{<\phi_{123}>}{M} = \begin{pmatrix} \varepsilon_{123} \\ \varepsilon_{123} \\ \varepsilon_{123} \end{pmatrix} \qquad \frac{<\phi_{3}>}{M} = \begin{pmatrix} 0 \\ 0 \\ \varepsilon_{3} \end{pmatrix}$$

$$Y_{LR}^{\nu} \sim \begin{pmatrix} 0 & \varepsilon_{123} e^{i\delta_2} & 0 \\ \varepsilon_{23} e^{i\delta_1} & \varepsilon_{123} e^{i\delta_2} & 0 \\ -\varepsilon_{23} e^{i\delta_1} & \varepsilon_{123} e^{i\delta_2} & e^{i\delta_3} \end{pmatrix}$$

$$\frac{1}{M} F \ .\phi_{23} \nu_R^1 h \qquad \frac{1}{M} F \ .\phi_{123} \nu_R^2 h \qquad \frac{1}{M} F \ .\phi_{3} \nu_R^3 h$$

Satisfies constrained sequential dominance giving tri-bimaximal neutrino mixing, with charged lepton corrections

Charged Fermion Yukawa Sector

$$Y_u \xleftrightarrow{V_{CKM}} Y_d$$

Class of models: $\theta_{12}^{d} \gg \theta_{12}^{u}$

$\theta_{12}^{d} \approx \theta_{c}$

$$Y_d \updownarrow Y_e$$

GUT relation

$$\theta_{12}^{e} \approx \frac{\theta_{12}^{d}}{3}$$

From above we see that $\boxed{\theta_{12}^{e} \approx \frac{\theta_{c}}{3}}$

Charged Lepton Corrections

SFK,Antusch; Masina,….

$$V_{MNS} = V^{E_L} V^{\nu_L \dagger}$$

Assume I: charged lepton mixing angles are small

$$s_{23} e^{-i\delta_{23}} \approx s^{\nu}_{23} e^{-i\delta^{\nu}_{23}} - \theta^{E}_{23} c^{\nu}_{23} e^{-i\delta^{E}_{23}}$$

$$\theta_{13} e^{-i\delta_{13}} \approx \cancel{\theta^{\nu}_{13} e^{-i\delta^{\nu}_{13}}} - \cancel{\theta^{E}_{13}} c^{\nu}_{23} e^{-i\delta^{E}_{13}} - \theta^{E}_{12} s^{\nu}_{23} e^{-i(\delta^{E}_{12}+\delta^{\nu}_{23})}$$

$$s_{12} e^{-i\delta_{12}} \approx s^{\nu}_{12} e^{-i\delta^{\nu}_{12}} + \cancel{\theta^{E}_{13}} c^{\nu}_{12} s^{\nu}_{23} e^{i(\delta^{\nu}_{23}-\delta^{E}_{13})} - \theta^{E}_{12} c^{\nu}_{23} c^{\nu}_{12} e^{-i\delta^{E}_{12}}$$

Assume II: all 13 angles are very small

$$\rightarrow \theta_{13} \approx \frac{\theta^{E}_{12}}{\sqrt{2}}$$

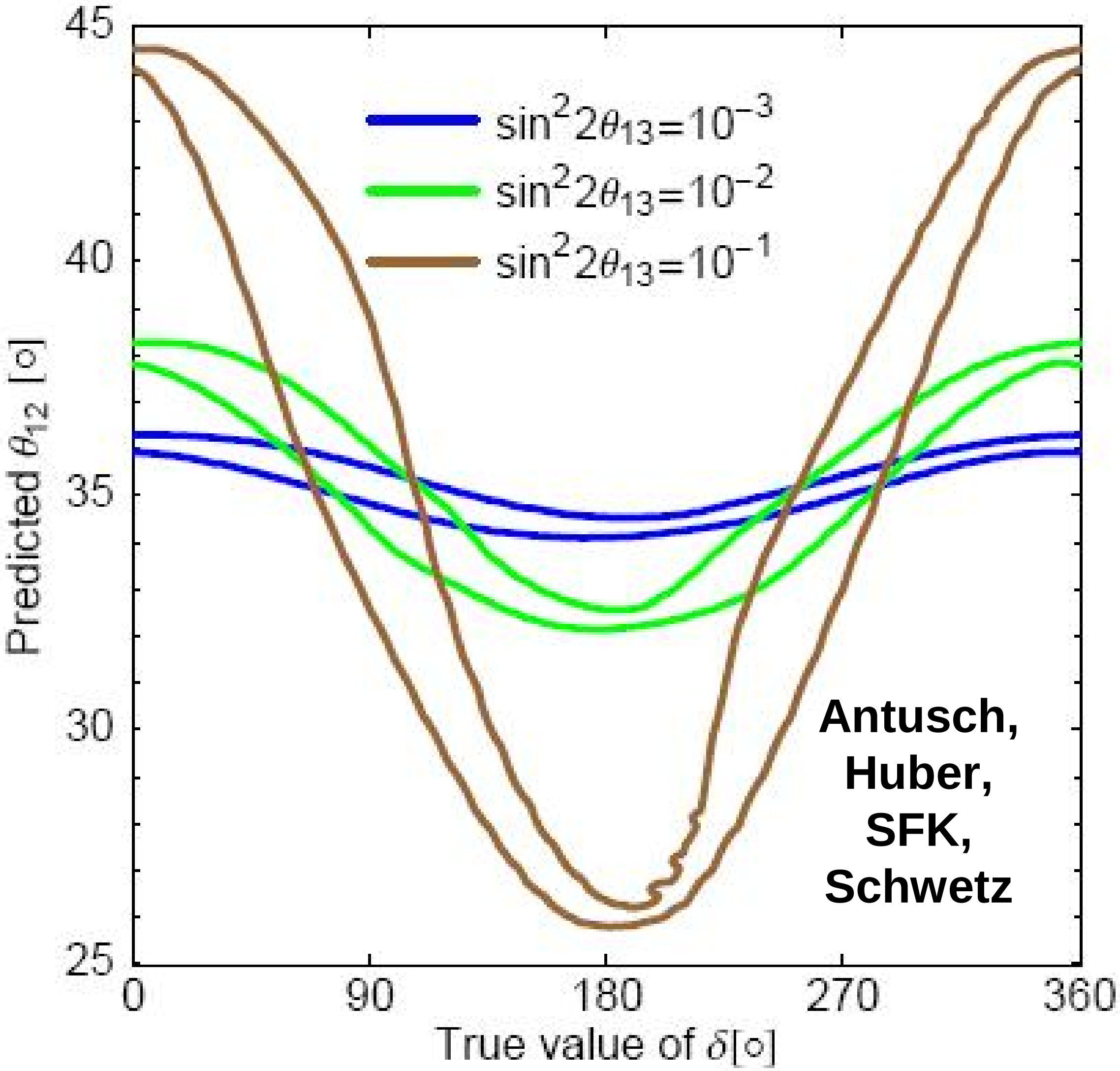
$$\rightarrow \theta_{12} \approx \theta^{\nu}_{12} + \frac{\theta^{E}_{12}}{\sqrt{2}} \cos\delta$$

In a given model we can predict θ^{E}_{12} and θ^{ν}_{12}.

Note the sum rule

$$\theta_{12} \approx \theta^{\nu}_{12} + \theta_{13} \cos\delta$$

Tri-bimaximal sum rule $\theta_{12} \approx 35.26^o + \theta_{13} \cos\delta$



Bands show 3 σ error for a neutrino factory determination of $\theta_{13}\cos\delta$

Current 3σ

$$\theta_{12} = 33^\circ \pm 5^\circ$$
$$\theta_{23} = 45^\circ \pm 10^\circ$$
$$\theta_{13} < 13^\circ$$

Model Prediction

$$\theta_{13} \approx \frac{\theta_{12}^E}{\sqrt{2}} \approx \frac{\theta_C}{3\sqrt{2}} \approx 3^\circ,$$
$$\rightarrow \sin^2 2\theta_{13} \approx 10^{-2}$$

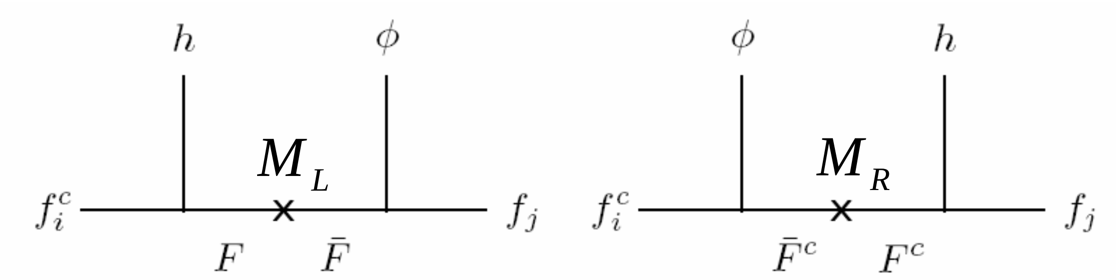
Do we need a family symmetry?

Ferretti, SFK, Romanino; Barr

$$W = M\bar{\Psi}\Psi + \alpha_i \bar{\Psi}\psi_i\phi + \lambda_i \Psi\psi_i h$$

One family of "messengers" dominates

Three families of quarks and leptons



$$M\bar{\Psi}\Psi \equiv M_Q\bar{Q}Q + M_U\bar{U}^cU^c + M_D\bar{D}^cD^c + M_L\bar{L}L + M_N\bar{N}^cN^c + M_E\bar{E}^cE^c$$

Suppose $M_Q \ll M_D \ll M_U$ then in a particular basis

$$Y_{LR}^U = \begin{pmatrix} 0 & 0 & 0 \\ 0 & ab\varepsilon_U & ad\varepsilon_U \\ 0 & cb\varepsilon_U & 1 \end{pmatrix} \frac{<\phi>}{M_Q} \qquad Y_{LR}^D = \begin{pmatrix} 0 & ef\varepsilon_D & ek\varepsilon_D \\ 0 & gf\varepsilon_D & gk\varepsilon_D \\ 0 & hf\varepsilon_D & 1 \end{pmatrix} \frac{<\phi>}{M_Q}$$

$$\varepsilon_U = \frac{M_Q}{M_U}, \quad \varepsilon_D = \frac{M_Q}{M_D}, \quad a,b,c,d,e,f,g,h,k \sim 1$$

$$\left\{ \begin{array}{l} m_u = m_d = 0 \\ \dfrac{m_c}{m_t} \ll \dfrac{m_s}{m_b} \ll 1 \\ \tan\beta \sim 50 \\ \dfrac{m_s}{m_b} \approx |V_{cb}| \end{array} \right.$$

$\longrightarrow$ Accidental sym

Not bad! But…

$\tan\theta_C \sim 1$

Need broken Pati-Salam…

The SUSY Flavour Problem

- In SUSY we want to understand not only the origin of Yukawa couplings

$$W = \epsilon_{\alpha\beta}[-\hat{H}_u^\alpha \hat{Q}_i^\beta Y_{u_{ij}} \hat{U}_j^c + \hat{H}_d^\alpha \hat{Q}_i^\beta Y_{d_{ij}} \hat{D}_j^c + \hat{H}_d^\alpha \hat{L}_i^\beta Y_{e_{ij}} \hat{E}_j^c - \mu \hat{H}_d^\alpha \hat{H}_u^\beta]$$

$$\Delta W = -\epsilon_{ab} \hat{H}_u^a \hat{L}_i^b Y_{\nu_{ij}} \hat{N}_j^c + \frac{1}{2} \hat{N}_i^c M_{R_i} \hat{N}_i^c$$ ←See-saw parts

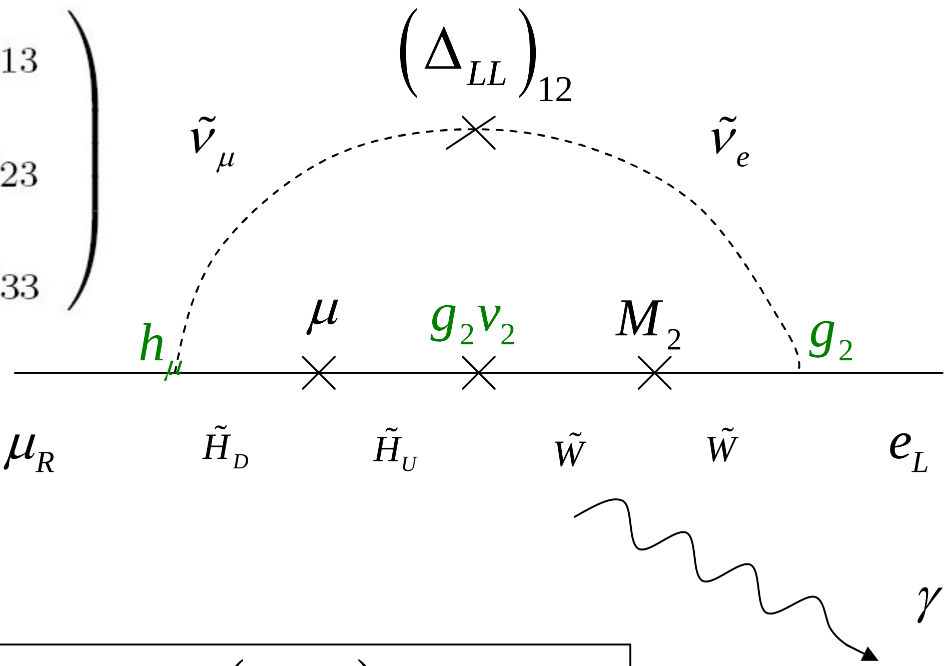
- But also the soft masses

$$\begin{aligned}
-\mathcal{L}_{soft} &= \frac{1}{2}\left[M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B}\right] \\
&+ \epsilon_{\alpha\beta}[-bH_d^\alpha H_u^\beta - H_u^\alpha \widetilde{Q}_i^\beta \widetilde{A}_{u_{ij}} \widetilde{U}_j^c + H_d^\alpha \widetilde{Q}_i^\beta \widetilde{A}_{d_{ij}} \widetilde{D}_j^c + H_d^\alpha \widetilde{L}_i^\beta \widetilde{A}_{e_{ij}} \widetilde{E}_j^c + \text{h.c.}] \\
&+ m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + \widetilde{Q}_i^\alpha m_{Q_{ij}}^2 \widetilde{Q}_j^{\alpha *} \\
&+ \widetilde{L}_i^\alpha m_{L_{ij}}^2 \widetilde{L}_j^{\alpha *} + \widetilde{U}_i^{c*} m_{U_{ij}}^2 \widetilde{U}_j^c + \widetilde{D}_i^{c*} m_{D_{ij}}^2 \widetilde{D}_j^c + \widetilde{E}_i^{c*} m_{E_{ij}}^2 \widetilde{E}_j^c
\end{aligned}$$

•SUSY FCNC's result from off-diagonal soft masses in the basis where the charged Yukawas are diagonal (also EDMs result from soft phases)

e.g. slepton doublet mass matrix

$$m_{LL}^2 = \begin{pmatrix} (m_{LL}^2)_{11} & (\Delta_{LL})_{12} & (\Delta_{LL})_{13} \\ (\Delta_{LL})_{21} & (m_{LL}^2)_{22} & (\Delta_{LL})_{23} \\ (\Delta_{LL})_{31} & (\Delta_{LL})_{32} & (m_{LL}^2)_{33} \end{pmatrix}$$



Off-diagonal slepton masses lead to LFV

$$\boxed{BR(\mu \to e\gamma) < 10^{-11} \to \delta_{LL12} = \frac{(\Delta_{LL})_{12}}{m_{LL}^2} < 10^{-3}}$$

Lepton Flavour Violation

Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives

Process	Present Bounds	Expected Future Bounds
$\mathrm{BR}(\mu \to e\,\gamma)$	1.2×10^{-11}	$\mathcal{O}(10^{-13} - 10^{-14})$
$\mathrm{BR}(\mu \to e\,e\,e)$	1.1×10^{-12}	$\mathcal{O}(10^{-13} - 10^{-14})$
$\mathrm{BR}(\mu \to e \text{ in Nuclei (Ti)})$	1.1×10^{-12}	$\mathcal{O}(10^{-18})$
$\mathrm{BR}(\tau \to e\,\gamma)$	1.1×10^{-7}	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,e\,e)$	2.7×10^{-7}	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,\mu\,\mu)$	$2. \times 10^{-7}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\gamma)$	6.8×10^{-8}	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	2×10^{-7}	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,e\,e)$	2.4×10^{-7}	$\mathcal{O}(10^{-8})$

Type of δ^l_{12}	$\mu \to e\,\gamma$	$\mu \to e\,e\,e$	$\mu \to e$ conversion in Ti
LL	6×10^{-4}	2×10^{-3}	2×10^{-3}
RR	-	0.09	-
LR/RL	1×10^{-5}	3.5×10^{-5}	3.5×10^{-5}

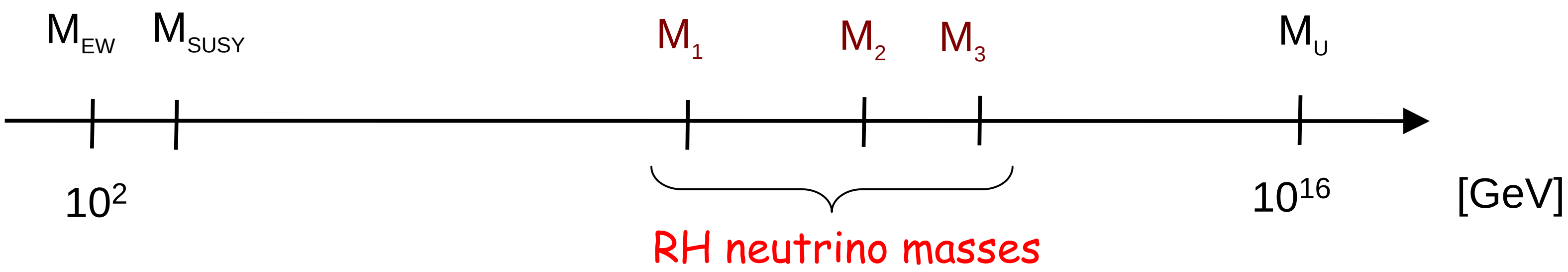
Type of δ^l_{23}	$\tau \to \mu\,\gamma$
LL	0.12
RR	-
LR/RL	0.03

Type of δ^l_{13}	$\tau \to e\,\gamma$
LL	0.15
RR	-
LR/RL	0.04

Predicting LFV in mSUGRA

mSUGRA prediction at M_U

$$m^2_{\tilde{L}_{ij}} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \delta m^2_{\tilde{L}_{ij}} \xleftarrow{\text{RG running}} m^2_{\tilde{L}_{ij}} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

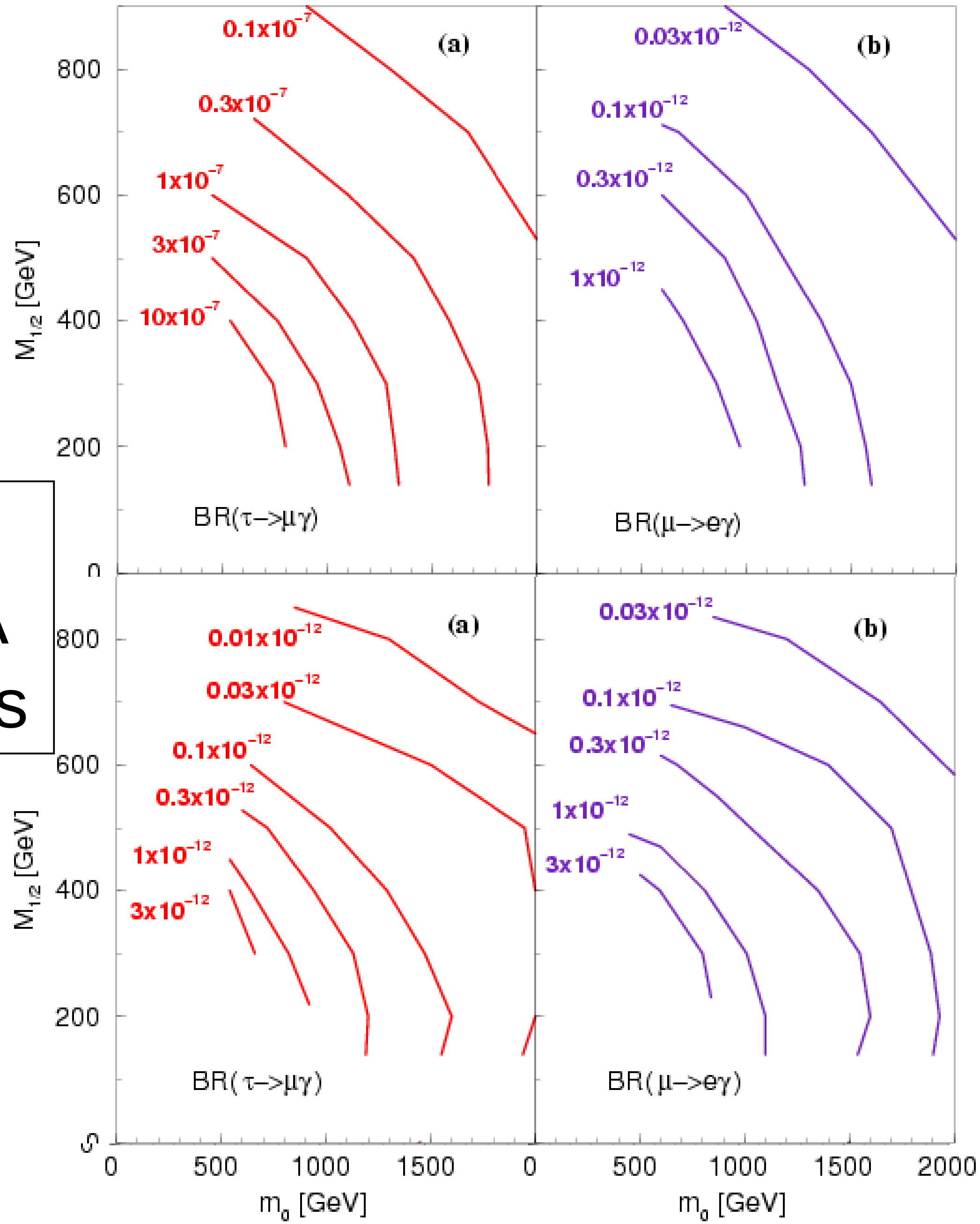


$$\frac{dm^2_{\tilde{L}}}{dt} \approx \left(\frac{dm^2_{\tilde{L}}}{dt}\right)_{Y^\nu=0} - \frac{(3m_0^2 + A_0^2)}{16\pi^2}\left[Y^\nu Y^{\nu\dagger}\right]$$

Depends strongly on the see-saw parameters

→WG3 contributors

Typical mSUGRA Predictions



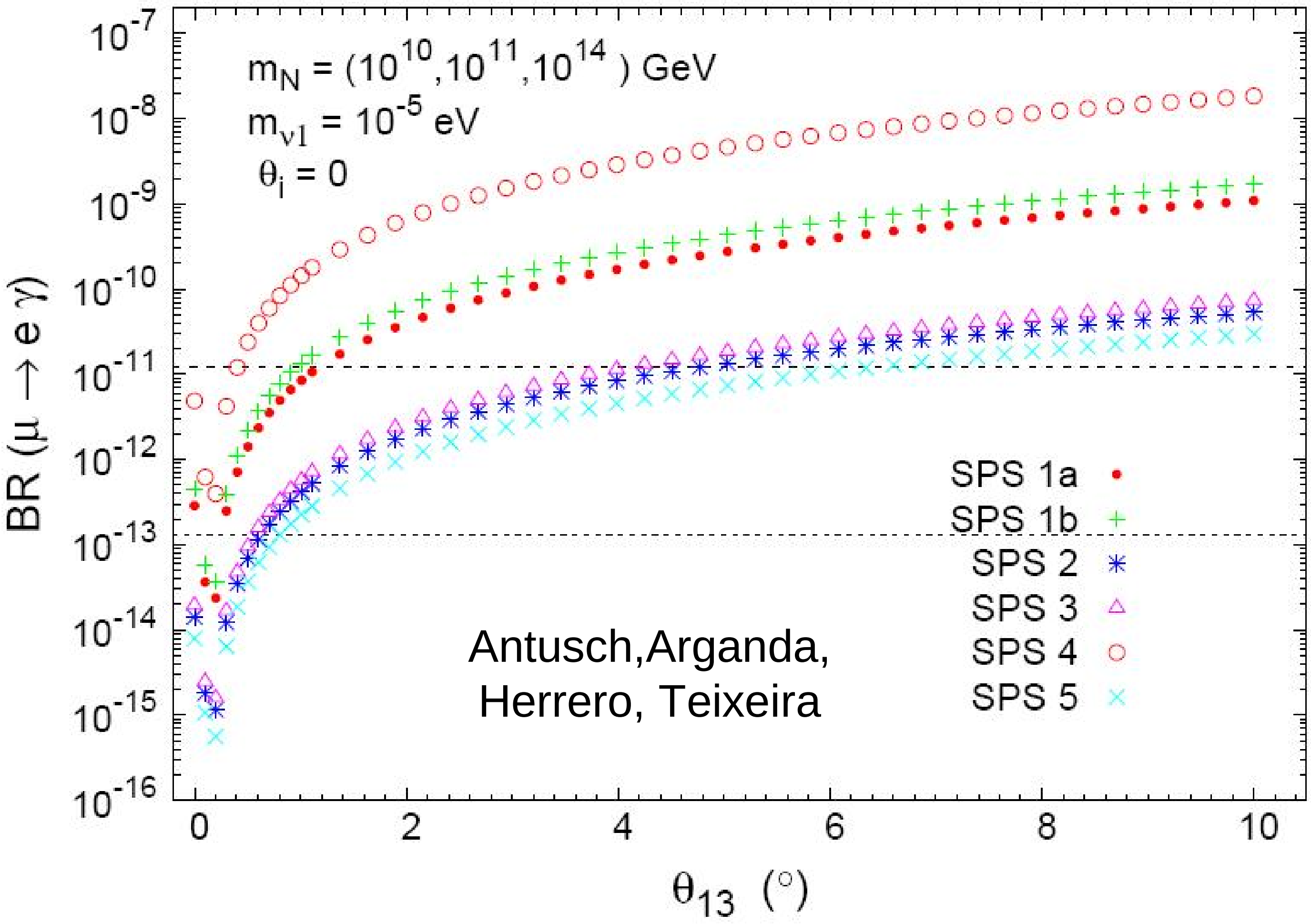
Heaviest RH neutrino is dominant ; predicts large $\tau \rightarrow \mu\,\gamma$

Blazek,SFK

$\tan\beta = 50$

Lightest RH neutrino is dominant

Correlation between $\mu \rightarrow e\,\gamma$ and θ_{13} for HSD



Three sources of non-universality

1. Non-minimal SUGRA

--due to different families coupling to the hidden sector differently

$$m_L^2 = m_{3/2}^2 \begin{bmatrix} a & & \\ & a & \\ & & b_L \end{bmatrix}$$

2. D-terms

--due to broken U(1) gauge groups with family dependent charges

$$m_{L_L}^2 = m_L^2 - \mathbf{1}(3g_4^2)D_H^2 + \begin{pmatrix} q_{L1} & & \\ & q_{L2} & \\ & & q_{L3} \end{pmatrix} g_F^2 D_\theta^2$$

3. Flavon SUSY breaking

--due to flavon dependent Yukawa couplings

$$\Delta A = F_\Phi \partial_\Phi \ln Y = F_\Phi \partial_\Phi \ln \Phi^n = F_\Phi \frac{n}{\Phi}$$

$$F_\Phi \propto m_{3/2}\Phi \quad \rightarrow \Delta A \propto n m_{3/2}$$

Abel,Servant;

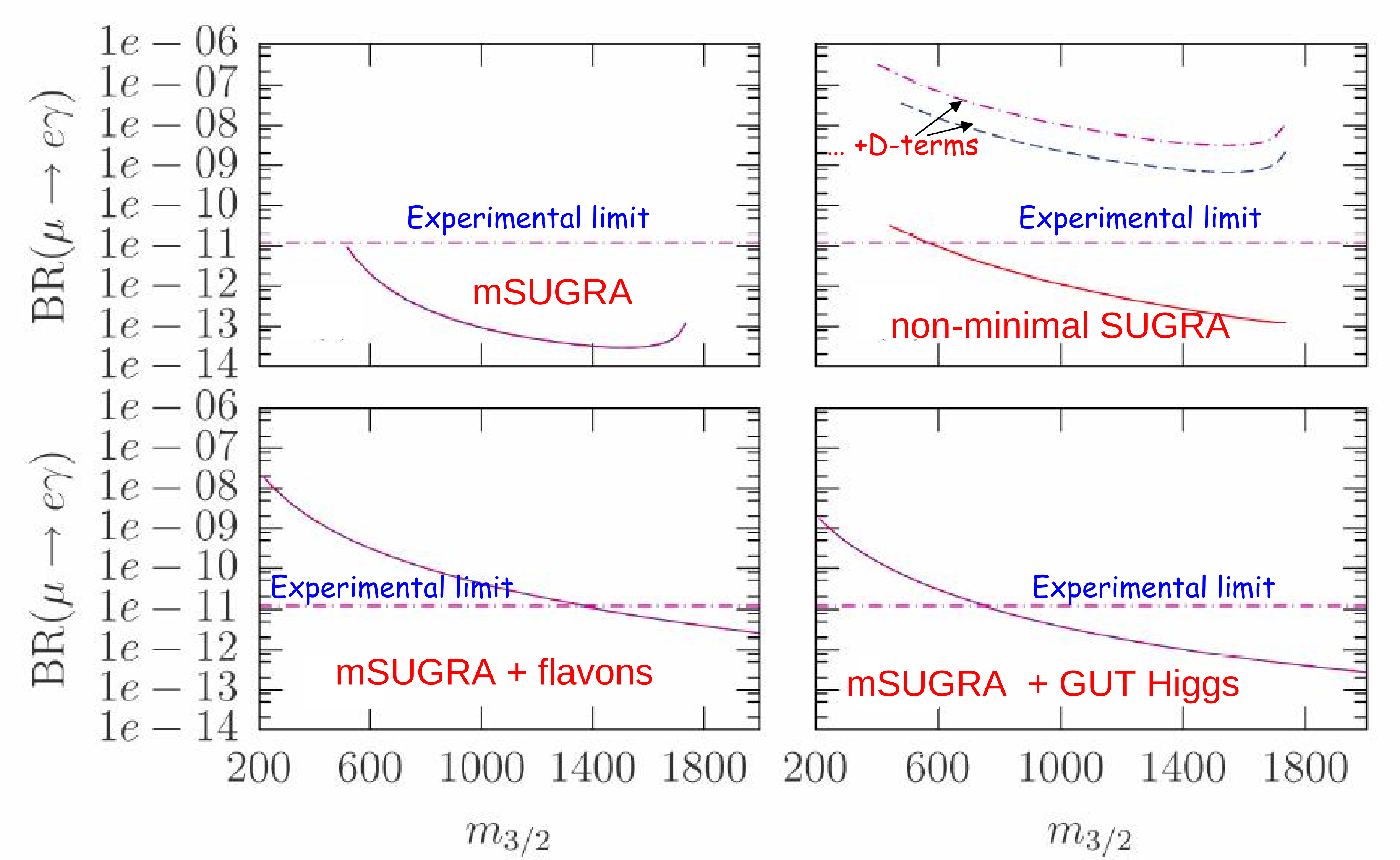
Abel, Khalil,Lebedev;

Ross,Vives;

Peddie,SFK.

$\mu \to e\gamma$ in non-Universal models

Hayes, Peddie, SFK



SU(5) GUTs and Soft Masses

Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives

$$\{Q = \begin{pmatrix} u \\ d \end{pmatrix} \quad e^c \quad u^c\} \subset \mathbf{10},$$

$$\{d^c \quad L = \begin{pmatrix} \nu \\ e \end{pmatrix}\} \subset \bar{\mathbf{5}}.$$

LHC connection: need to measure squark and slepton masses to relate quark and lepton flavour violation

Relations at the weak scale	Relations at $M_{\rm GUT}$
$(\delta^u_{ij})_{\rm RR} \approx (m^2_{e^c}/m^2_{u^c})\ (\delta^l_{ij})_{\rm RR}$	$m^2_{u^c{}_0} = m^2_{e^c{}_0}$
$(\delta^q_{ij})_{\rm LL} \approx (m^2_{e^c}/m^2_{Q})\ (\delta^l_{ij})_{\rm RR}$	$m^2_{Q_0} = m^2_{e^c{}_0}$
$(\delta^d_{ij})_{\rm RR} \approx (m^2_{L}/m^2_{d^c})\ (\delta^l_{ij})_{\rm LL}$	$m^2_{d^c{}_0} = m^2_{L_0}$
$(\delta^d_{ij})_{\rm LR} \approx (m^2_{L_{avg}}/m^2_{Q_{avg}})\ (m_b/m_\tau)\ (\delta^l_{ij})^\star_{\rm LR}$	$A^e_{ij_0} = A^d_{ji_0}$

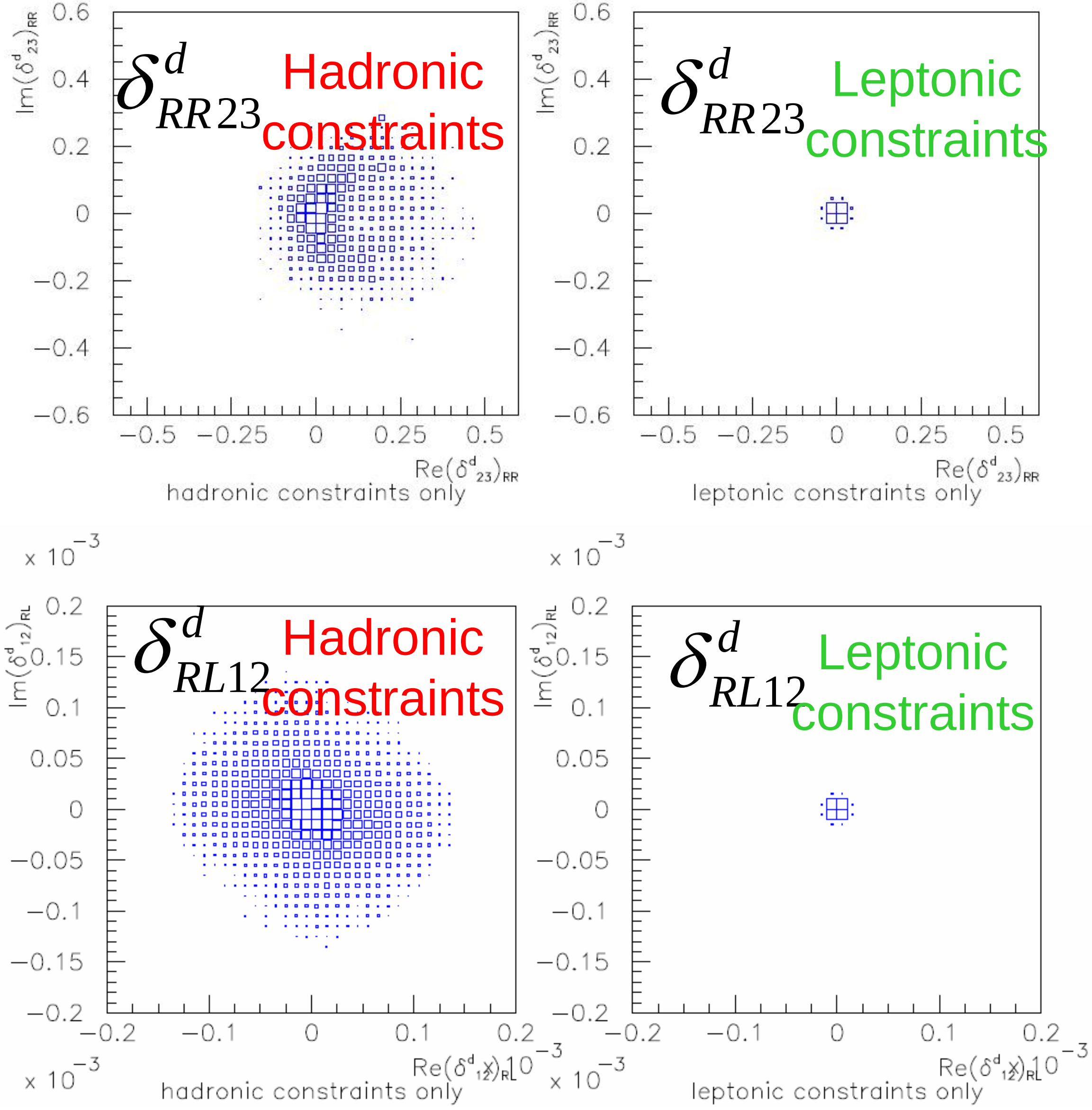
Flavour changing observables in the down sector

Ciuchini,Masiero, Paradisi,Silvestrini, Vempati,Vives

Observable	Measurement/Bound
Sector 1–2	
ΔM_K	$(0.0 - 5.3) \times 10^{-3}$ GeV
ε	$(2.232 \pm 0.007) \times 10^{-3}$
$\lvert(\varepsilon'/\varepsilon)_{SUSY}\rvert$	$< 2 \times 10^{-2}$
Sector 1–3	
ΔM_{B_d}	(0.507 ± 0.005) ps^{-1}
$\sin 2\beta$	0.675 ± 0.026
$\cos 2\beta$	> -0.4
Sector 2–3	
$\mathrm{BR}(b \to (s+d)\gamma)(E_\gamma > 2.0 \text{ GeV})$	$(3.06 \pm 0.49) \times 10^{-4}$
$\mathrm{BR}(b \to (s+d)\gamma)(E_\gamma > 1.8 \text{ GeV})$	$(3.51 \pm 0.43) \times 10^{-4}$
$\mathrm{BR}(b \to s\gamma)(E_\gamma > 1.9\ GeV)$	$(3.34 \pm 0.18 \pm 0.48) \times 10^{-4}$
$A_{CP}(b \to s\gamma)$	0.004 ± 0.036
$\mathrm{BR}(b \to s l^+ l^-)(0.04 \text{ GeV} < q^2 < 1 \text{ GeV})$	$(11.34 \pm 5.96) \times 10^{-7}$
$\mathrm{BR}(b \to s l^+ l^-)(1 \text{ GeV} < q^2 < 6 \text{ GeV})$	$(15.9 \pm 4.9) \times 10^{-7}$
$\mathrm{BR}(b \to s l^+ l^-)(14.4 \text{ GeV} < q^2 < 25 \text{ GeV})$	$(4.34 \pm 1.15) \times 10^{-7}$
$A_{CP}(b \to s l^+ l^-)$	-0.22 ± 0.26
ΔM_{B_s}	(17.77 ± 0.12) ps^{-1}

δ^d parameters

$ij \backslash AB$	LL	LR	RL	RR
12	1.4×10^{-2}	9.0×10^{-5}	9.0×10^{-5}	9.0×10^{-3}
13	9.0×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	7.0×10^{-2}
23	1.6×10^{-1}	4.5×10^{-3}	6.0×10^{-3}	2.2×10^{-1}



Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives

Quark-lepton connection:
LFV processes can constrain Quark Flavour Violation via GUTs

SU(3) Family Symmetry and Soft Masses

$\psi_i \in (Q_i, L_i) \sim \mathbf{3}$ Flavons $\phi \sim \overline{3}$

SFK,Ross; Ross,Velasco-Sevilla,Vives

Yukawas

$$\frac{1}{M^2}\phi_3^i \psi_i \phi_3^j \psi_j H + \frac{1}{M^2}\phi_{23}^i \psi_i \phi_{23}^j \psi_j H + \ldots$$

Soft masses

$$m^2 = m_0^2 \left(\delta_{ij} \quad + \quad a_3 \frac{\phi_3^* \phi_3}{M'^2} \quad + \quad a_{23} \frac{\phi_{23}^* \phi_{23}}{M'^2} + \ldots \right)$$

- Leading order universal due to $SU(3)_{fam}$
- Sub-leading mainly (2,3) flavour violation controlled by flavons

$$m^2 \sim \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} m_0^2 + \begin{pmatrix} 0 & & \\ & 0 & \\ & & \varepsilon_3^2 \end{pmatrix} m_3^3 + \begin{pmatrix} 0 & & \\ & \varepsilon_{23}^2 & \varepsilon_{23}^2 \\ & \varepsilon_{23}^2 & \varepsilon_{23}^2 \end{pmatrix} m_{23}^3 + \ldots$$

The SUSY CP Problem

Abel, Khalil, Lebedev;

Ross, Vives;

- SUSY neutron EDM $d_n \sim \left(\frac{300\ \mathrm{GeV}}{M}\right)^2 \sin\phi \times 10^{-24} e\ \mathrm{cm}$

$$\phi_\mu \sim \phi_A \equiv \phi \ll 1,\ \tan\beta \sim 3 \quad \rightarrow \phi < 10^{-2}$$

Why are SUSY phases so small?

- Postulate CP conservation (e.g. $\mu H_u H_d$ real) with CP is spontaneously broken by flavon vevs
- Trilinear soft

$$\tilde{A}_{ij} = A_0\left(a_3 \frac{\phi_3^i \phi_3^j}{M^2} + a_{23}\frac{\phi_{23}^i \phi_{23}^j}{M^2} + \ldots\right)$$

A_0 , a_3 , a_{23} , real gives real soft masses times complex Yukawa elements → no soft phases at leading order

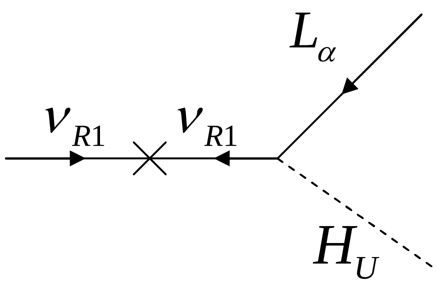
Flavour Dependent Thermal Leptogenesis

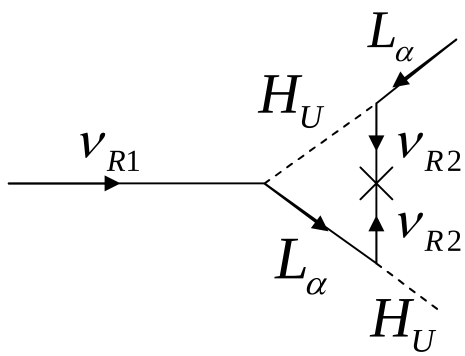
Barbieri,Creminelli,Strumia, Tetradis; Endoh,Morozumi,Xiong; Pilaftsis,Underwood; Vives; Abada,Davidson,Josse-Michaux,Losada,Riotto,Ibarra; Nardi,Nir,Roulet,Racker

- In leptogenesis neutrino CP violation is the origin of baryon asymmetry
- For typical leptogenesis temperatures $<10^{12}$ GeV FD effects are relevant
- Right-handed Majorana (L violating) neutrinos are produced in early universe and decay out of equilibrium giving net lepton numbers L_e , L_μ , L_τ
- Out of equilibrium Boltzmann eqs lead to L_e , L_μ , L_τ partial washouts
- Surviving L_e, L_μ , L_τ are processed into B via B-L conserving sphalerons

$$\varepsilon_{1,\alpha} \approx \frac{\Gamma(\nu_{R1} \to L_\alpha \bar{H}_U) - \Gamma(\bar{\nu}_{R1} \to \bar{L}_\alpha H_U)}{\sum_\alpha \left(\Gamma(\nu_{R1} \to L_\alpha \bar{H}_U) + \Gamma(\bar{\nu}_{R1} \to \bar{L}_\alpha H_U)\right)}$$

FD lepton asymmetry

$\propto \Bigg\{$ 

$\Bigg\} \times \Bigg\{$ 

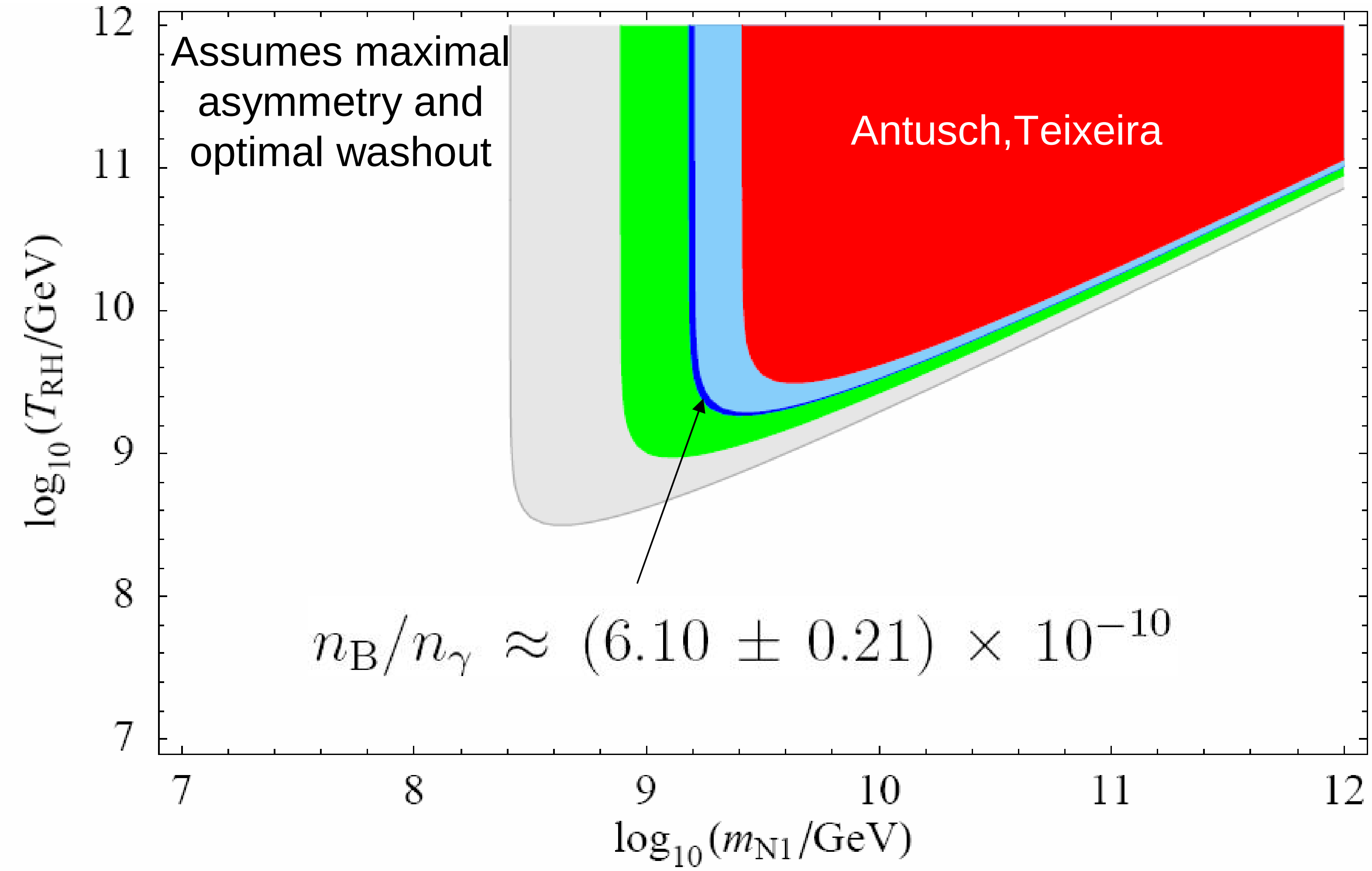
$\Bigg\}^\dagger$

Flavour Dependent Leptogenesis with SD

Antusch, SFK, Riotto

- What can we learn from FD Leptogenesis?
- If the dominant RH neutrino is lightest all asymmetries are suppressed by m_2/m_3 with $\varepsilon_{1,e}$ killed by a (1,1) texture zero and L_μ and L_τ strongly washed out
- most popular flavour models inconsistent with FD TLG!
- If the dominant RH neutrino is the heaviest $\varepsilon_{1,e}$ is suppressed by m_2/m_3 but $\varepsilon_{1,\mu}$,and $\varepsilon_{1,\tau}$ may be maximal and L_μ and L_τ may have optimal washout
- this case is OK and predicts large rate for $\tau \rightarrow \mu\, \gamma$

Allowed regions of T_{RH} and M_{R1}



Summary

- Neutrino data is consistent with tri-bimaximal lepton mixing
- Suggests see-saw with CSD and non-Abelian fam sym
- Yukawas as `little flavour magnets' with flavon vac alignment
- Class of models suggest $\theta_{13}=3^o$
- Charged lepton corrections give TBM sum rule $\theta_{12}=35^o+\theta_{13}\cos\delta$
- LFV in mSUGRA distinguishes see-saw models, gives correlations
- But expect non-universal corrections in general
- SUSY GUTs imply LFV can constrain Quark FC
- SUSY Fam Sym enforces approx universality but expect flavon corrections
- Flavon spontaneous CP violation solves SUSY CP Problem
- Flavour Dependent Leptogenesis discriminates flavour models