BSM and Flavour in the Lepton Sector
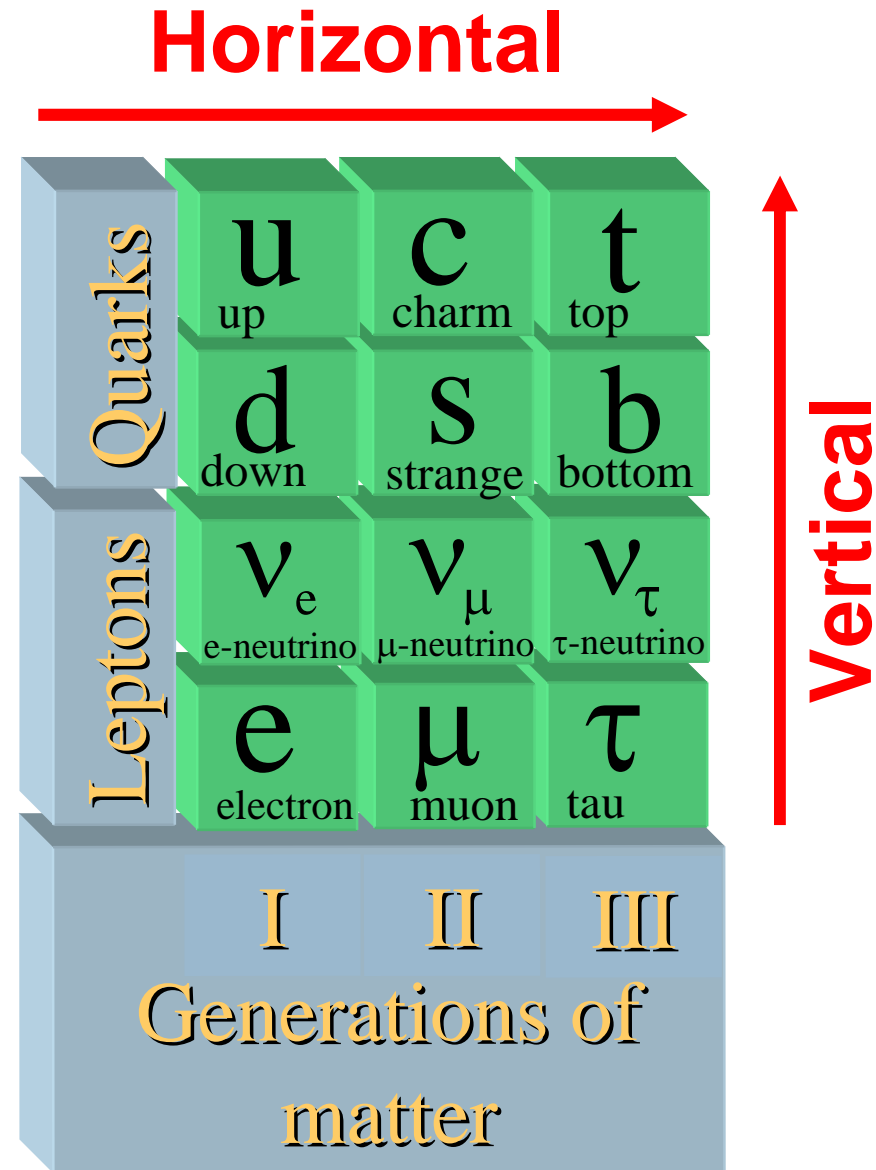
Plan of talk:

I. The Flavour Problem

II. The SUSY Flavour Problem

III. Flavour Dependent Leptogenesis
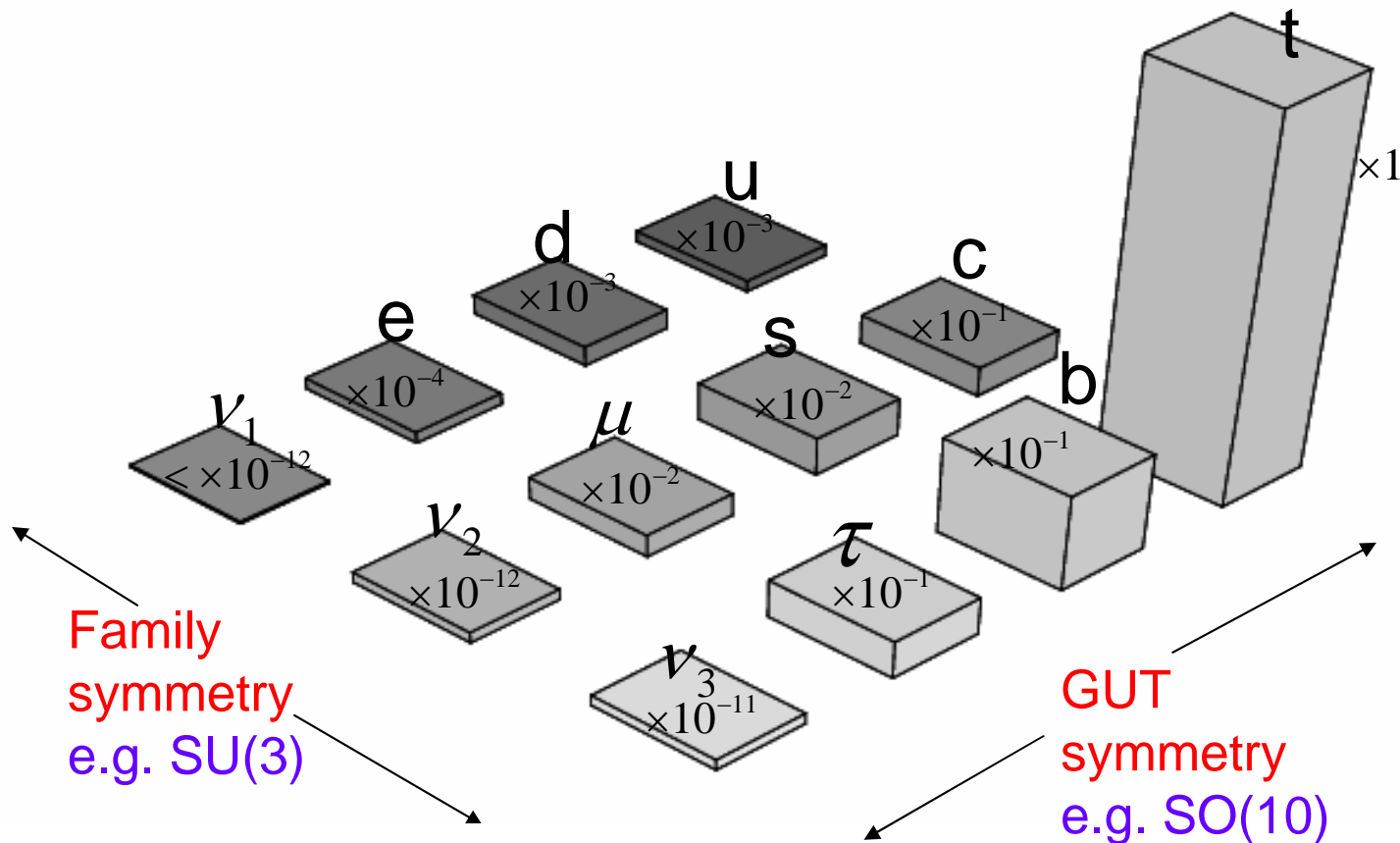
The Flavour Problem

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

Horizontal

Vertical

Quarks

| u up | c charm | t top |
| d down | S strange | b bottom |

Leptons

| ν_e e-neutrino | ν_μ μ-neutrino | ν_τ τ-neutrino |
| e electron | μ muon | τ tau |

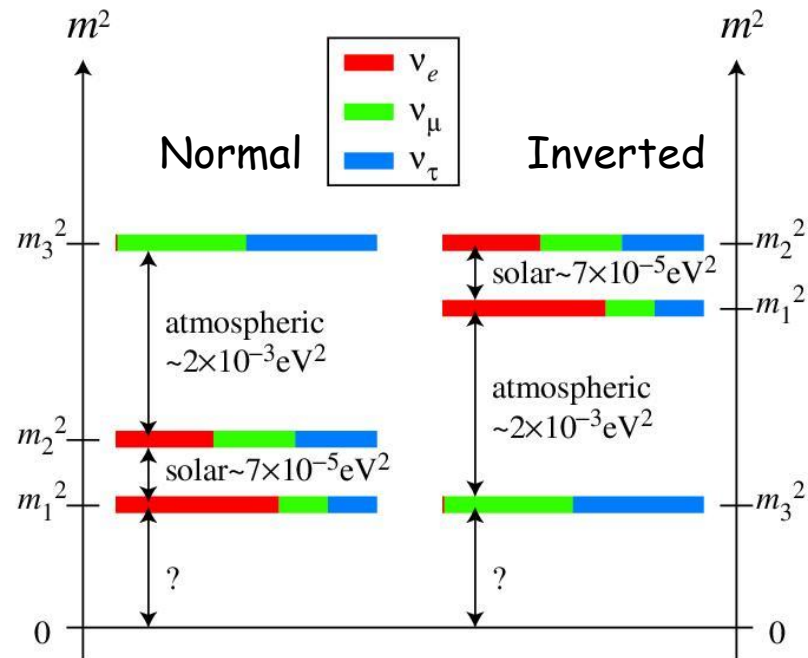I   II   III

Generations of matter

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

The Flavour Problem
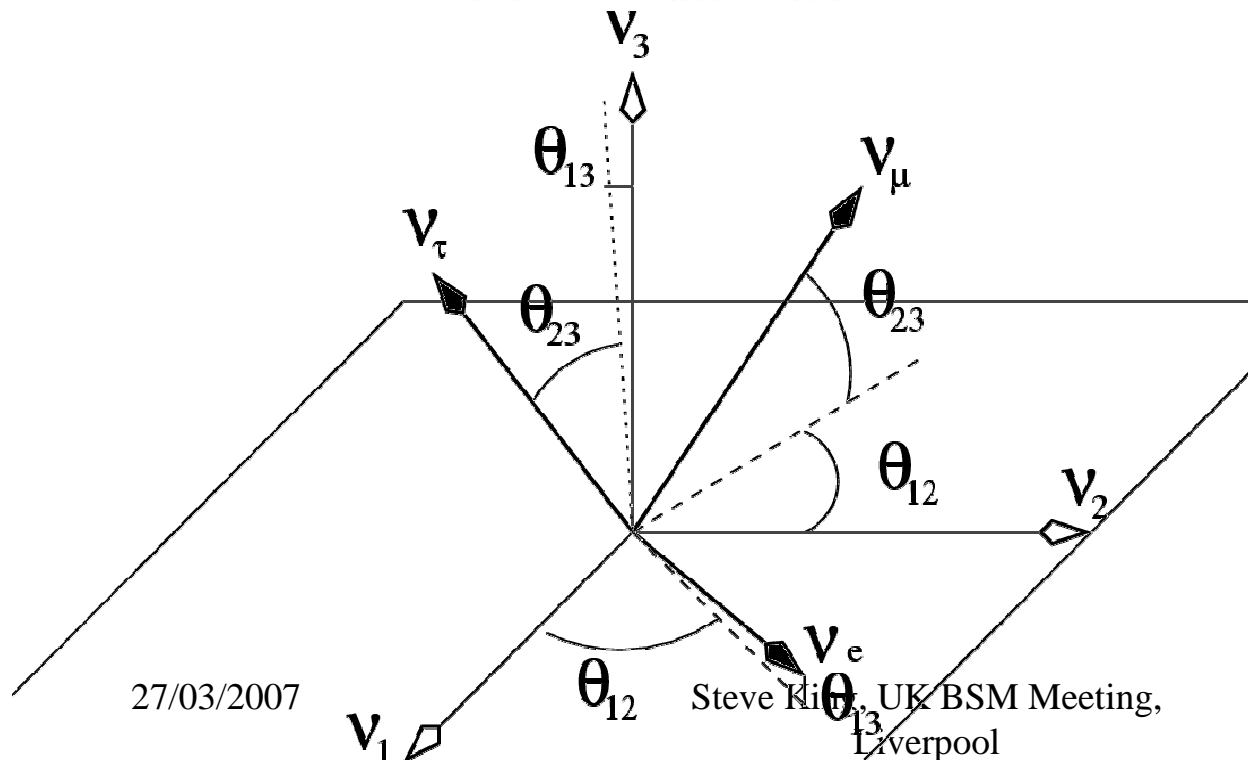# III. Why are neutrino masses so small?

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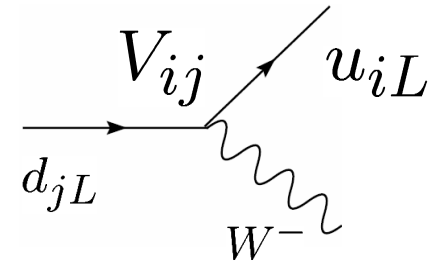# IV. Why is lepton mixing so large?

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

e.g.Tri-bimaximal

Harrison, Perkins, Scott

c.f. small quark mixing

V_{ij} u_{iL}

d_{jL}

W^-

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

ν_3

θ_{13}

ν_τ

ν_μ

θ_{23}

θ_{23}

θ_{12}

ν_2

ν_e

θ_{12} θ_{13}

ν_1

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

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

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 $\Longrightarrow$

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

Sequential dominance $\Longrightarrow$

Dominant m_3 Subdominant m_2 Decoupled m_1

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

$$V^{\nu_L \dagger} \approx \begin{pmatrix} -\sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Constrained SD

Tri-bimaximal

Non-Abelian family symmetry

Need

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

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)

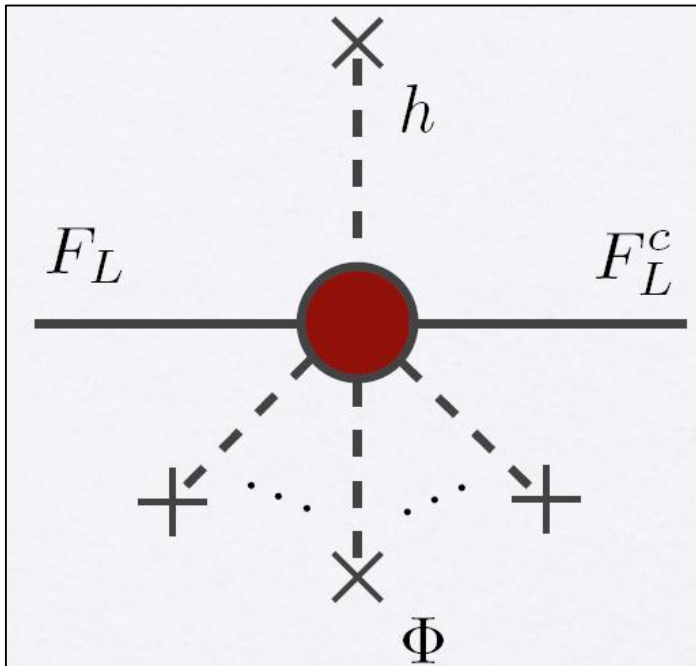### Examples of suitable non-Abelian family symmetries:

SFK, Ross; Velasco-Sevilla; Varzelias $SU(3) \quad \Delta_{27}$ } Discrete subgroups preferred by vacuum alignment

SFK, Malinsky $SO(3) \quad A_4$

A_4 Pati-Salam Model

SFK,Malinsky

Family symmetry must be broken

- Flavons break family symmetry

- Yukawas as `little flavour magnets'

field	$SU(4) \otimes SU(2)_L \otimes SU(2)_R$	A_4	$U(1)$	Z_2
F	$(4,2,1)$	3	0	$+$
F_1^c	$(\overline{4},1,2)$	1	$+2$	$-$
F_2^c	$(\overline{4},1,2)$	1	$+1$	$+$
F_3^c	$(\overline{4},1,2)$	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	$+$

$$\frac{1}{M}y_{23}F.\phi_{23}F_1^c h + \frac{1}{M}y_{123}F.\phi_{123}F_2^c h + \frac{1}{M}y_3 F.\phi_3 F_3^c h + \frac{1}{M^2}y_{GJ}F.\tilde{\phi}_{23}F_2^c \Sigma h$$

$$+ \frac{1}{M^2}y_{13}F.(\phi_2 \times \phi_3)F_3^c h + \frac{1}{M^2}y'_{13}F.(\phi_2 * \phi_3)F_3^c h + \frac{1}{M^3}y_{23}^i I_i(F, \tilde{\phi}_{23}, \tilde{\phi}_{23}, \phi_3)F_3^c h$$

$$Y_{LR}^f = \begin{pmatrix} 0 & y_{123}\varepsilon_{123}^f & \overline{y}_{13}\varepsilon_2^f \varepsilon_3^f \\ y_{23}\varepsilon_{23}^f & y_{123}\varepsilon_{123}^f + C^f y_{GJ}\tilde{\varepsilon}_{23}^f \sigma & \overline{y}_{23}(\tilde{\varepsilon}_{23}^f)^2 \varepsilon_3^f \\ -y_{23}\varepsilon_{23}^f & y_{123}\varepsilon_{123}^f - C^f y_{GJ}\tilde{\varepsilon}_{23}^f \sigma & y_3\varepsilon_3^f \end{pmatrix}$$

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

Neutrino Sector

Majorana magnets

$$\frac{<\phi_{23}>}{M} = \begin{pmatrix} 0 \\ \varepsilon_{23} \\ -\varepsilon_{23} \end{pmatrix} \qquad \frac{<\phi_{123}>}{M} = \begin{pmatrix} \varepsilon_{123} \\ \varepsilon_{123} \\ \varepsilon_{123} \end{pmatrix} \qquad \frac{<\phi_3>}{M} = \begin{pmatrix} 0 \\ 0 \\ \varepsilon_3 \end{pmatrix}$$
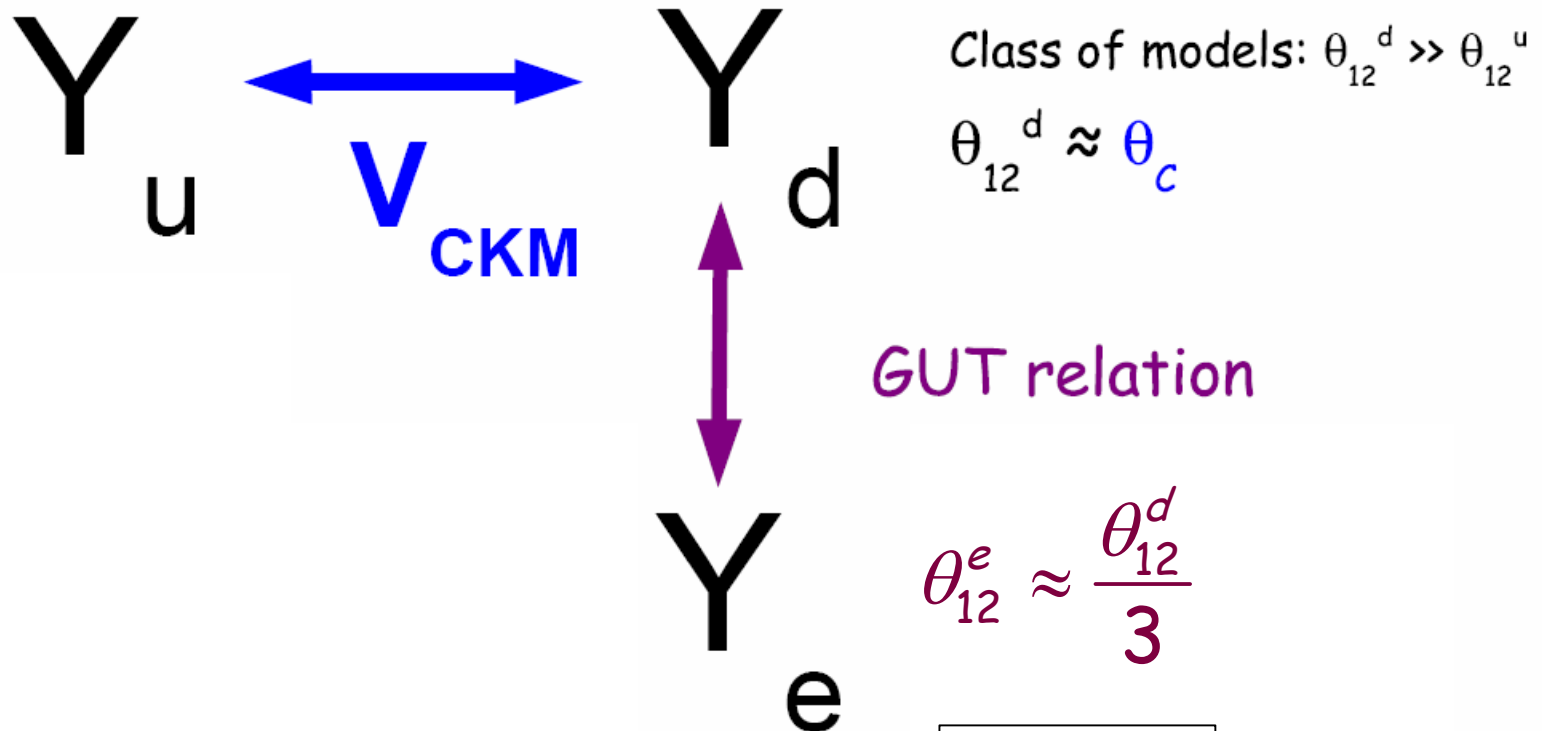
$$\frac{1}{M_\nu^3} w_1 F_1^{c2} H H' \phi_{23}^2 + \frac{1}{M_\nu^3} w_2 F_2^{c2} H H' \phi_{123}^2 + \frac{1}{M_\nu} w_3 F_3^{c2} H^2$$

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

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

$$\frac{1}{M} F . \phi_{23} \nu_R^1 h \qquad \frac{1}{M} F . \phi_{123} \nu_R^2 h \qquad \frac{1}{M} F . \phi_3 \nu_R^3 h$$

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

Charged Fermion Yukawa Sector

$$Y_u \longleftrightarrow Y_d$$

$$V_{CKM}$$

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

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

GUT relation

$$Y_e$$

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

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

Charged Lepton Corrections

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

Assume I: charged lepton mixing angles are small

$$s_{23} e^{-i\delta_{23}} \approx s_{23}^\nu e^{-i\delta_{23}^\nu} - \theta_{23}^E c_{23}^\nu e^{-i\delta_{23}^E}$$

$$\theta_{13} e^{-i\delta_{13}} \approx \cancel{\theta_{13}^\nu e^{-i\delta_{13}^\nu}} - \cancel{\theta_{13}^E c_{23}^\nu} e^{-i\delta_{13}^E} - \theta_{12}^E s_{23}^\nu e^{-i(\delta_{12}^E + \delta_{23}^\nu)}$$

$$s_{12} e^{-i\delta_{12}} \approx s_{12}^\nu e^{-i\delta_{12}^\nu} + \cancel{\theta_{13}^E c_{12}^\nu} s_{23}^\nu e^{i(\delta_{23}^\nu - \delta_{13}^E)} - \theta_{12}^E c_{23}^\nu c_{12}^\nu e^{-i\delta_{12}^E}$$
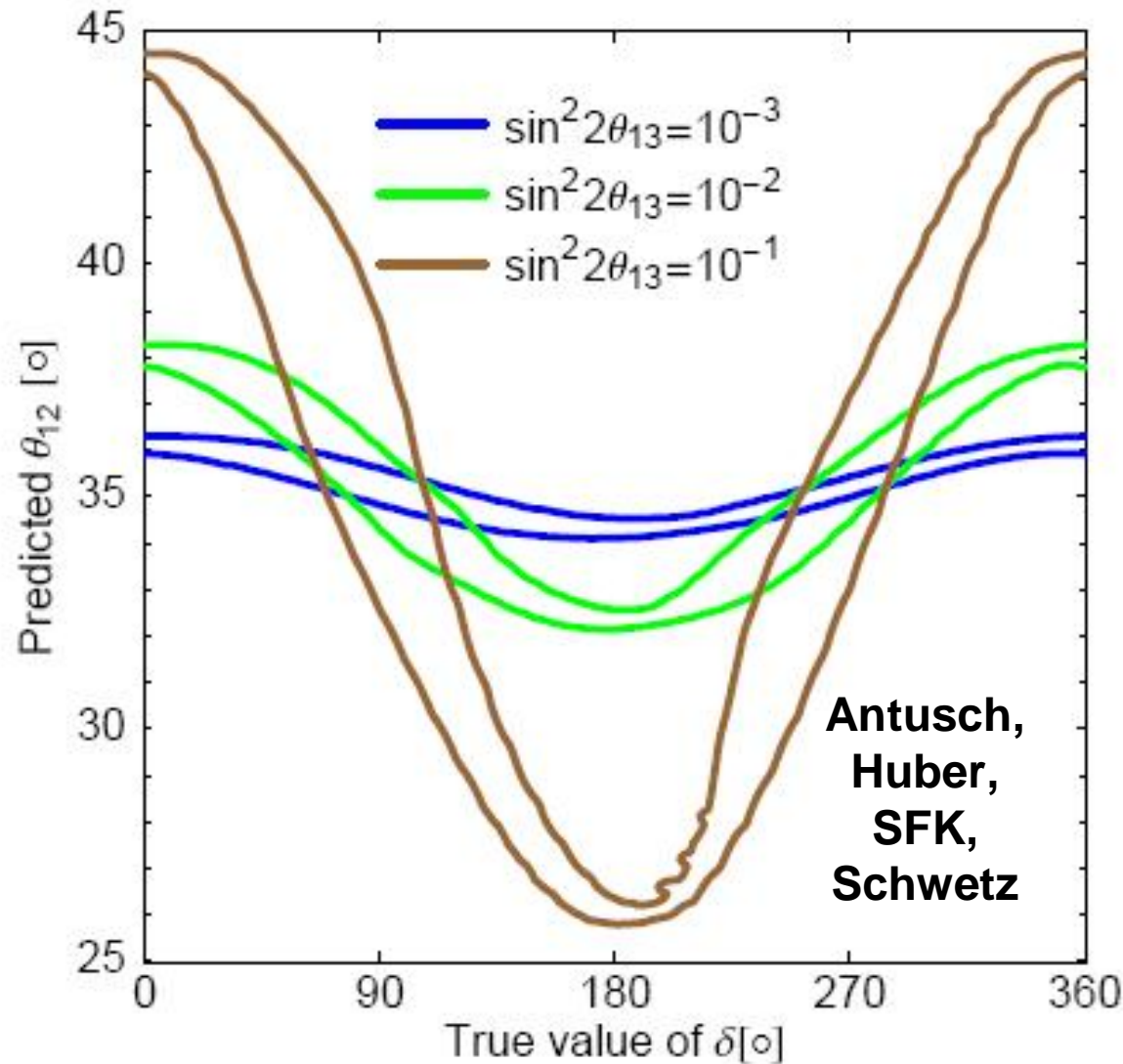
Assume II: all 13 angles are very small

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

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

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

Note the sum rule
$$\theta_{12} \approx \theta_{12}^\nu + \theta_{13} \cos\delta$$

Steve King, UK BSM Meeting, Liverpool

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

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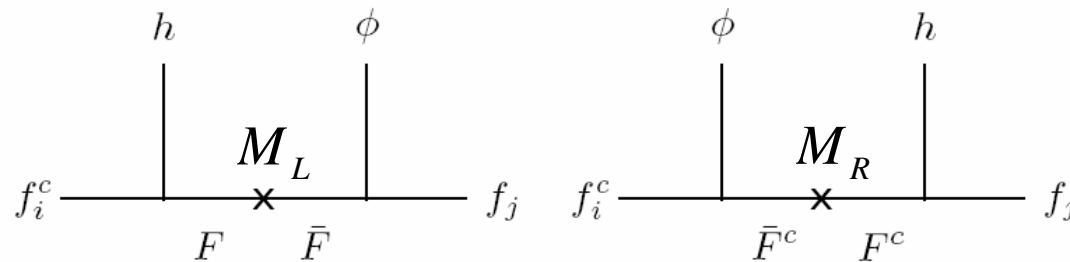$$\rightarrow \sin^2 2\theta_{13} \approx 10^{-2}$$

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

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

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

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

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

$m_u = m_d = 0 \to$ Accidental sym

$\dfrac{m_c}{m_t} \ll \dfrac{m_s}{m_b} \ll 1 \quad$ Not bad! But…

$\tan\beta \sim 50 \qquad \tan\theta_C \sim 1$

$\dfrac{m_s}{m_b} \approx |V_{cb}| \qquad$ Need broken Pati-Salam…

The SUSY Flavour Problem

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

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

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

- ## But also the soft masses

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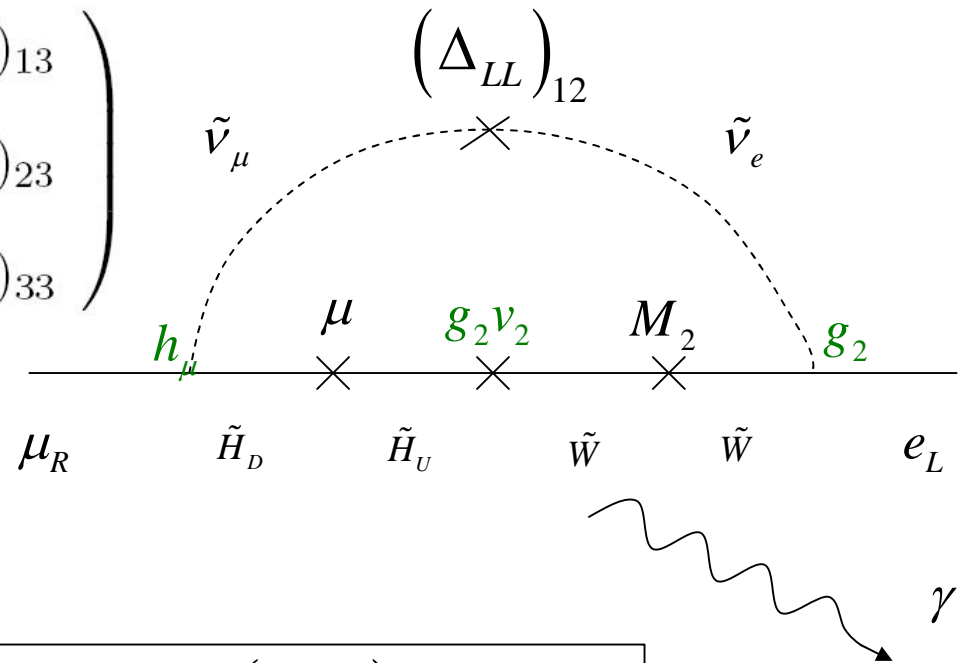& + m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + \widetilde{Q}_i^\alpha m_{Q_{ij}}^2 \widetilde{Q}_j^{\alpha *} \\
& + \widetilde{L}_i^\alpha m_{L_{ij}}^2 \widetilde{L}_j^{\alpha *} + \widetilde{U}_i^{c*} m_{U_{ij}}^2 \widetilde{U}_j^c + \widetilde{D}_i^{c*} m_{D_{ij}}^2 \widetilde{D}_j^c + \widetilde{E}_i^{c*}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

- 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

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

Lepton Flavour Violation
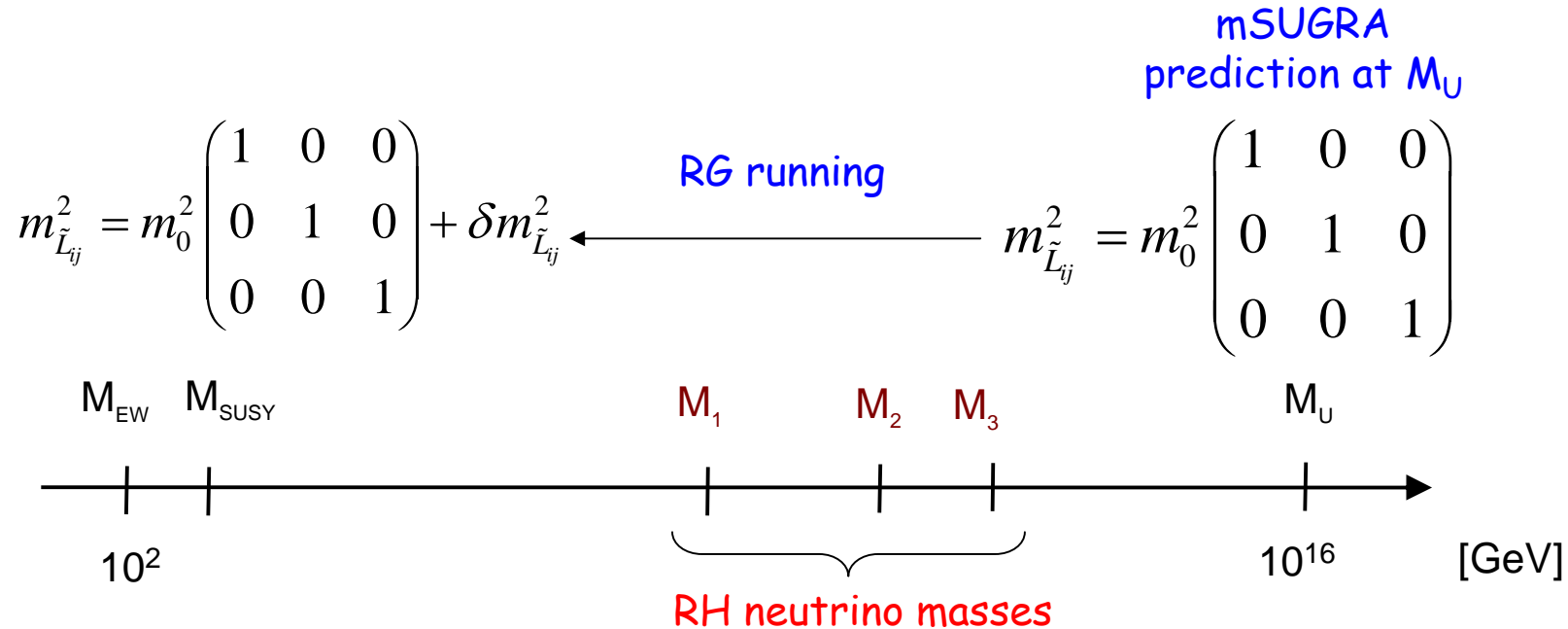
Ciuchini,Masiero, Paradisi,Silvestrini, Vempati,Vives

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}	$\mathcal{O}(10^{-13} - 10^{-14})$
$\mathrm{BR}(\mu \to e$ 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_{12}^l	$\mu \to e\gamma$	$\mu \to eee$	$\mu \to e$ conversion in Ti	Type of δ_{23}^l	$\tau \to \mu\gamma$	Type of δ_{13}^l	$\tau \to e\gamma$
LL	6×10^{-4}	2×10^{-3}	2×10^{-3}	LL	0.12	LL	0.15
RR	-	0.09	-	RR	-	RR	-
LR/RL	1×10^{-5}	3.5×10^{-5}	3.5×10^{-5}	LR/RL	0.03	LR/RL	0.04

Predicting LFV in mSUGRA

mSUGRA
prediction at M_U

$$m^2_{\tilde{L}_{ij}} = m^2_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \delta m^2_{\tilde{L}_{ij}} \longleftarrow \quad m^2_{\tilde{L}_{ij}} = m^2_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

RG running

M_{EW} M_{SUSY} M_1 M_2 M_3 M_U

10^2 10^{16} [GeV]

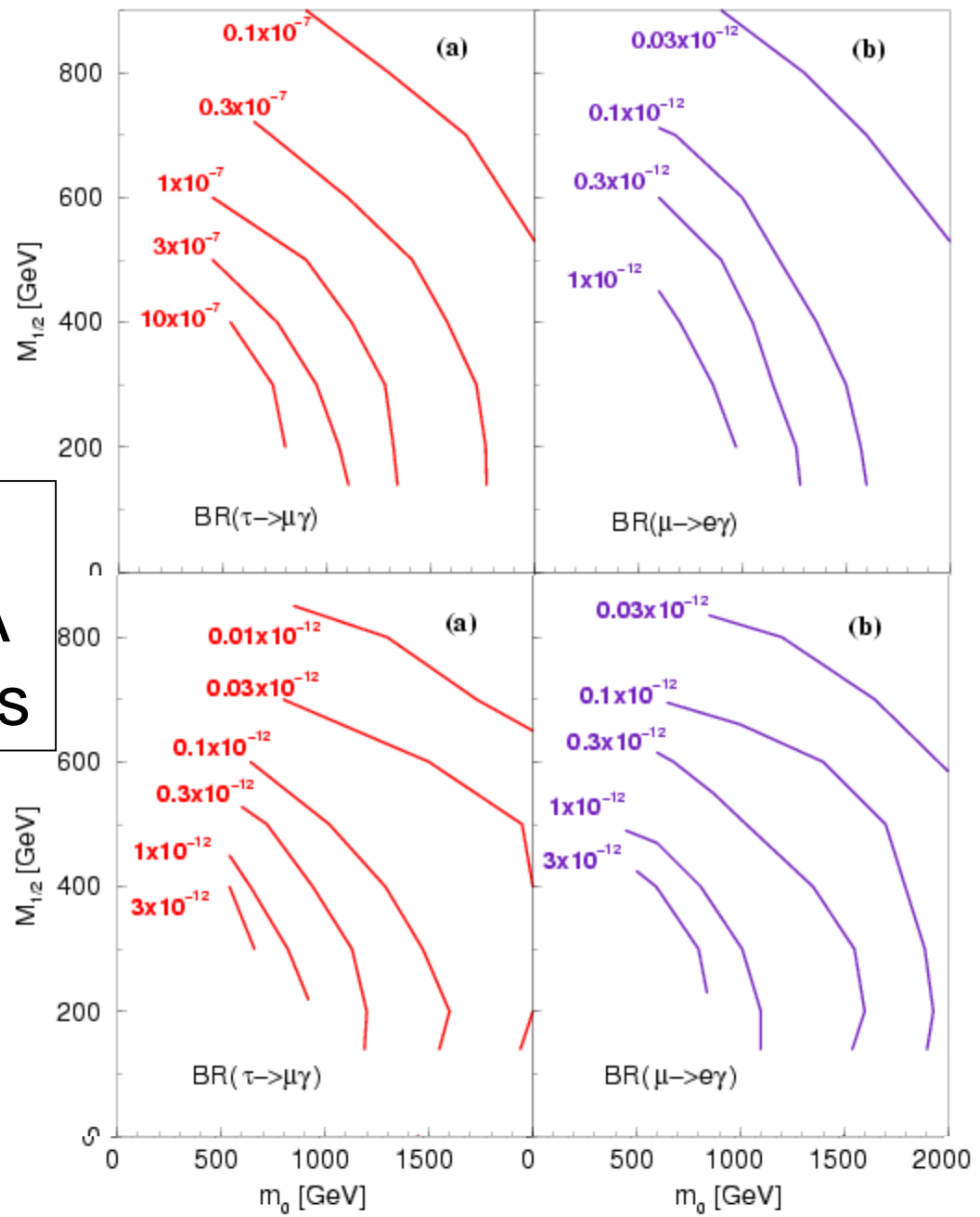RH neutrino masses

$$\frac{dm^2_{\tilde{L}}}{dt} \approx \left(\frac{dm^2_{\tilde{L}}}{dt} \right)_{Y^{\nu}=0} - \frac{(3m^2_0 + A^2_0)}{16\pi^2} \left[Y^{\nu} Y^{\nu\dagger} \right]$$

Depends strongly
on the see-saw
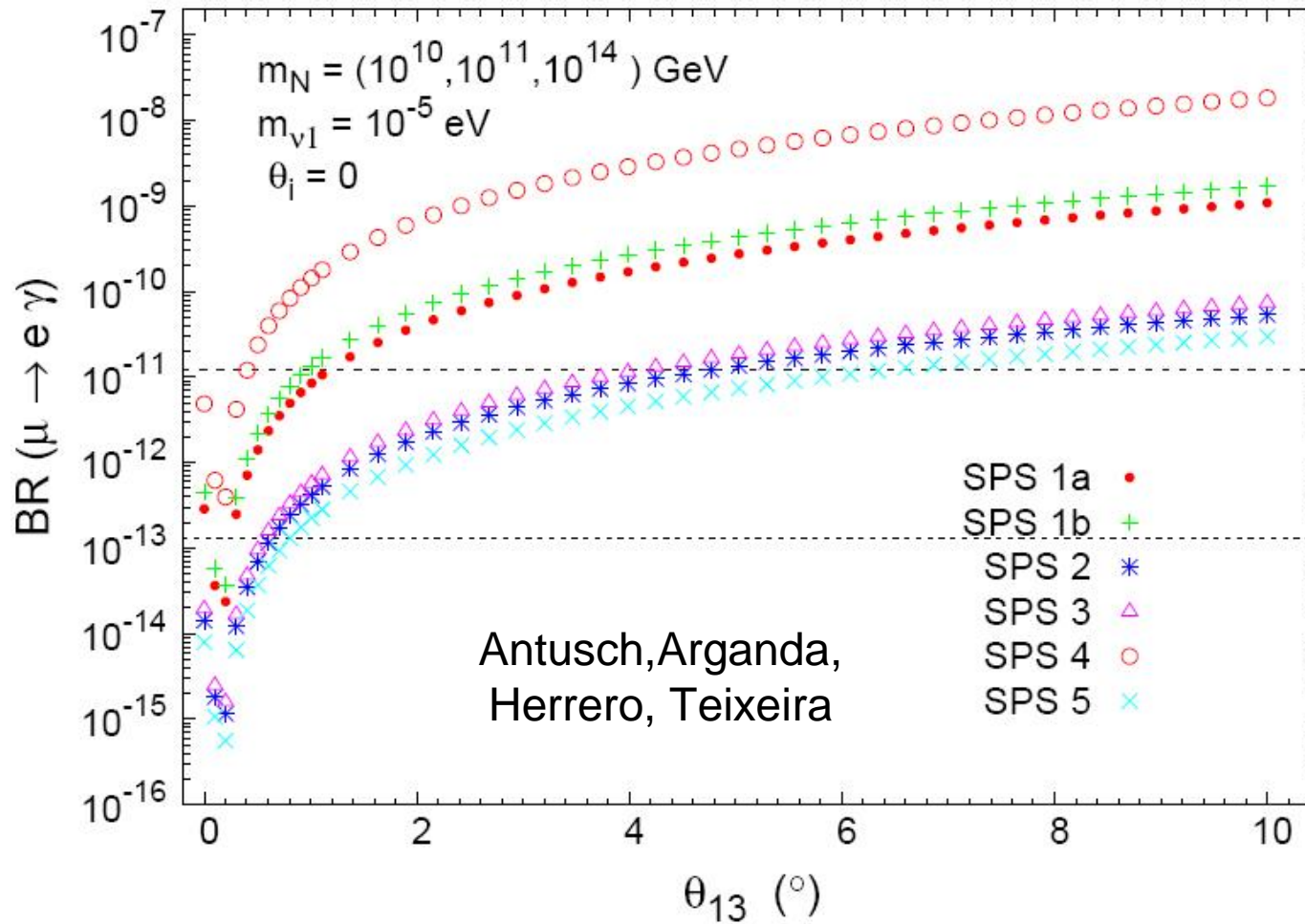parameters

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

$m_N = (10^{10}, 10^{11}, 10^{14})$ GeV

$m_{\nu 1} = 10^{-5}$ eV

$\theta_i = 0$

Antusch, Arganda, Herrero, Teixeira

SPS 1a •
SPS 1b +
SPS 2 ✳
SPS 3 △
SPS 4 ○
SPS 5 ✕

BR $(\mu \rightarrow e\,\gamma)$

θ_{13} (°)

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

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

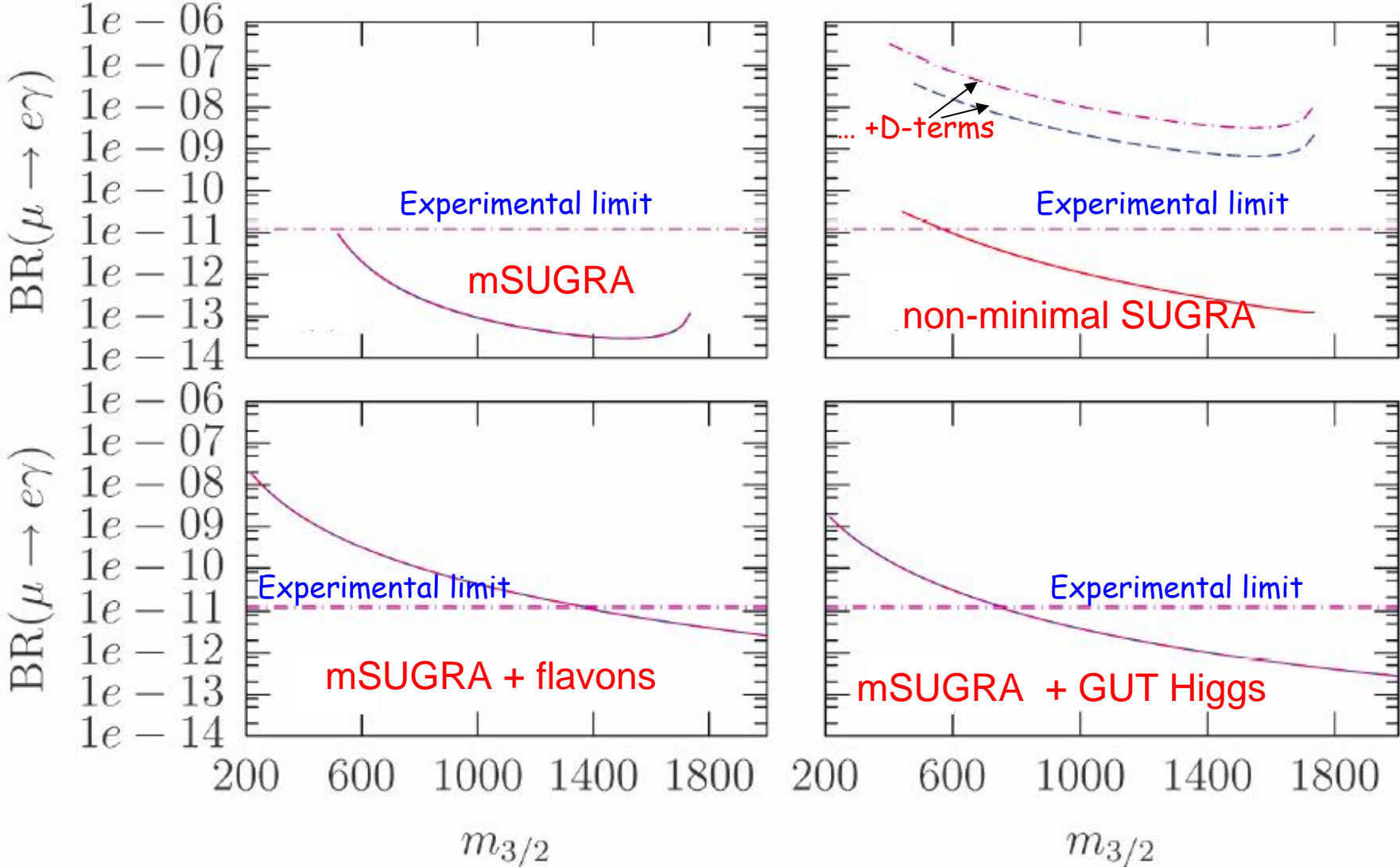$$F_\Phi \propto m_{3/2}\Phi \quad \rightarrow \Delta A \propto nm_{3/2}$$

Abel,Servant;

Abel, Khalil,Lebedev;

Ross,Vives;

Peddie,SFK.

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

Hayes, Peddie, SFK

SU(5) GUTs and Soft Masses

Ciuchini, Masiero,
Paradisi, Silvestrini,
Vempati, Vives

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

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

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

Relations at the weak scale	Relations at M_{GUT}
$(\delta^u_{ij})_{\mathrm{RR}} \approx (m^2_{e^c}/m^2_{u^c})\,(\delta^l_{ij})_{\mathrm{RR}}$	$m^2_{u^c_0} = m^2_{e^c_0}$
$(\delta^q_{ij})_{\mathrm{LL}} \approx (m^2_{e^c}/m^2_Q)\,(\delta^l_{ij})_{\mathrm{RR}}$	$m^2_{Q_0} = m^2_{e^c_0}$
$(\delta^d_{ij})_{\mathrm{RR}} \approx (m^2_L/m^2_{d^c})\,(\delta^l_{ij})_{\mathrm{LL}}$	$m^2_{d^c_0} = m^2_{L_0}$
$(\delta^d_{ij})_{\mathrm{LR}} \approx (m^2_{L_{avg}}/m^2_{Q_{avg}})\,(m_b/m_\tau)\,(\delta^l_{ij})^\star_{\mathrm{LR}}$	$A^e_{ij_0} = A^d_{ji_0}$

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	$(2.232 \pm 0.007) \times 10^{-3}$
$|(\varepsilon'/\varepsilon)_{SUSY}|$	$< 2 \times 10^{-2}$
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	
$\mathrm{BR}(b \to (s+d)\gamma)(E_\gamma > 2.0$ GeV$)$	$(3.06 \pm 0.49) \times 10^{-4}$
$\mathrm{BR}(b \to (s+d)\gamma)(E_\gamma > 1.8$ 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
$\mathrm{BR}(b \to sl^+l^-)(0.04$ GeV $< q^2 < 1$ GeV$)$	$(11.34 \pm 5.96) \times 10^{-7}$
$\mathrm{BR}(b \to sl^+l^-)(1$ GeV $< q^2 < 6$ GeV$)$	$(15.9 \pm 4.9) \times 10^{-7}$
$\mathrm{BR}(b \to sl^+l^-)(14.4$ GeV $< q^2 < 25$ GeV$)$	$(4.34 \pm 1.15) \times 10^{-7}$
$A_{CP}(b \to sl^+l^-)$	-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}

$\delta^d_{RR\,23}$ Hadronic constraints

$\delta^d_{RR\,23}$ Leptonic constraints

$\delta^d_{RL\,12}$ Hadronic constraints

$\delta^d_{RL\,12}$ Leptonic constraints

Ciuchini,Masiero, Paradisi,Silvestrini, Vempati,Vives
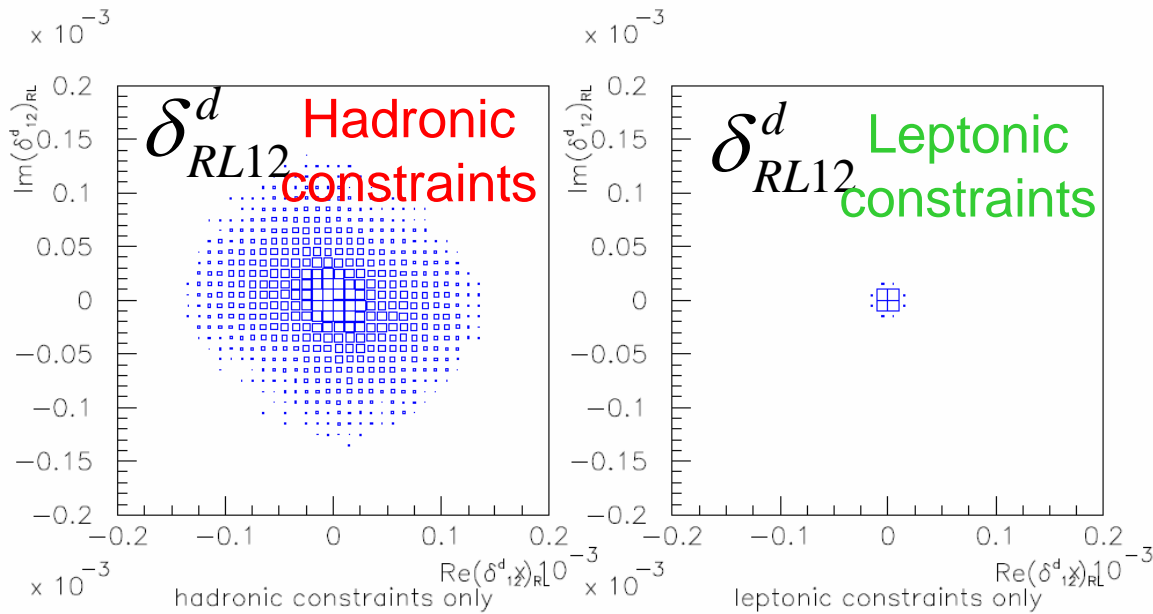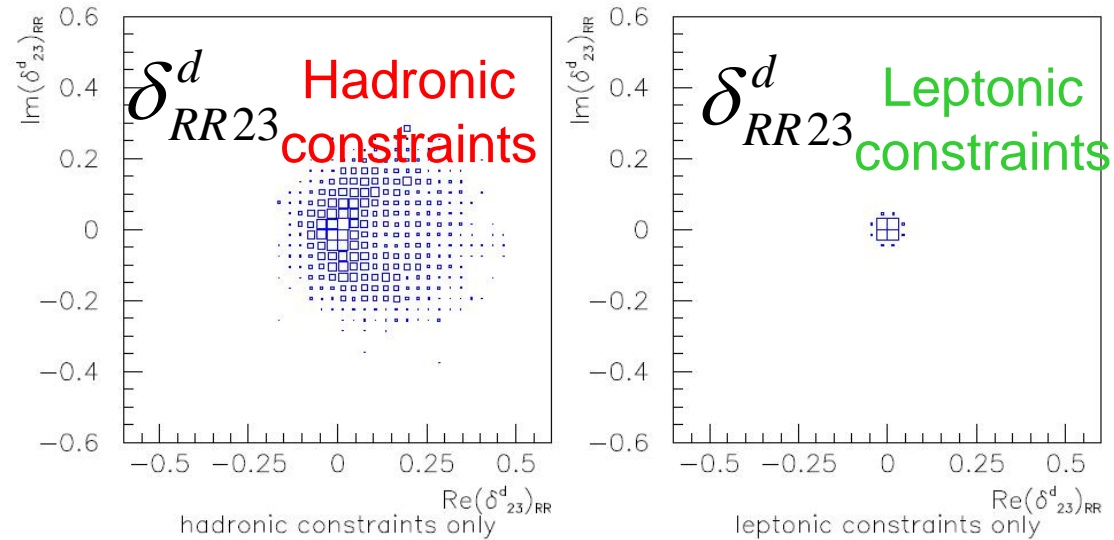
Quark-lepton connection: LFV processes can constrain Quark Flavour Violation via GUTs

SU(3) Family Symmetry and Soft Masses

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

SFK,Ross; Ross,Velasco-Sevilla,Vives

Yukawas

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

Soft masses

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

- Leading order universal due to SU(3)$_{fam}$

- Sub-leading mainly (2,3) flavour violation controlled by flavons

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

The SUSY CP Problem

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

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

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

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

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

Flavour Dependent Thermal Leptogenesis

- 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

$$\varepsilon_{1,\alpha} \approx \frac{\Gamma(\nu_{R1} \to L_\alpha \bar{H}_U) - \Gamma(\bar{\nu}_{R1} \to \bar{L}_\alpha H_U)}{\sum_\alpha \left(\Gamma(\nu_{R1} \to L_\alpha \bar{H}_U) + \Gamma(\bar{\nu}_{R1} \to \bar{L}_\alpha H_U) \right)}$$
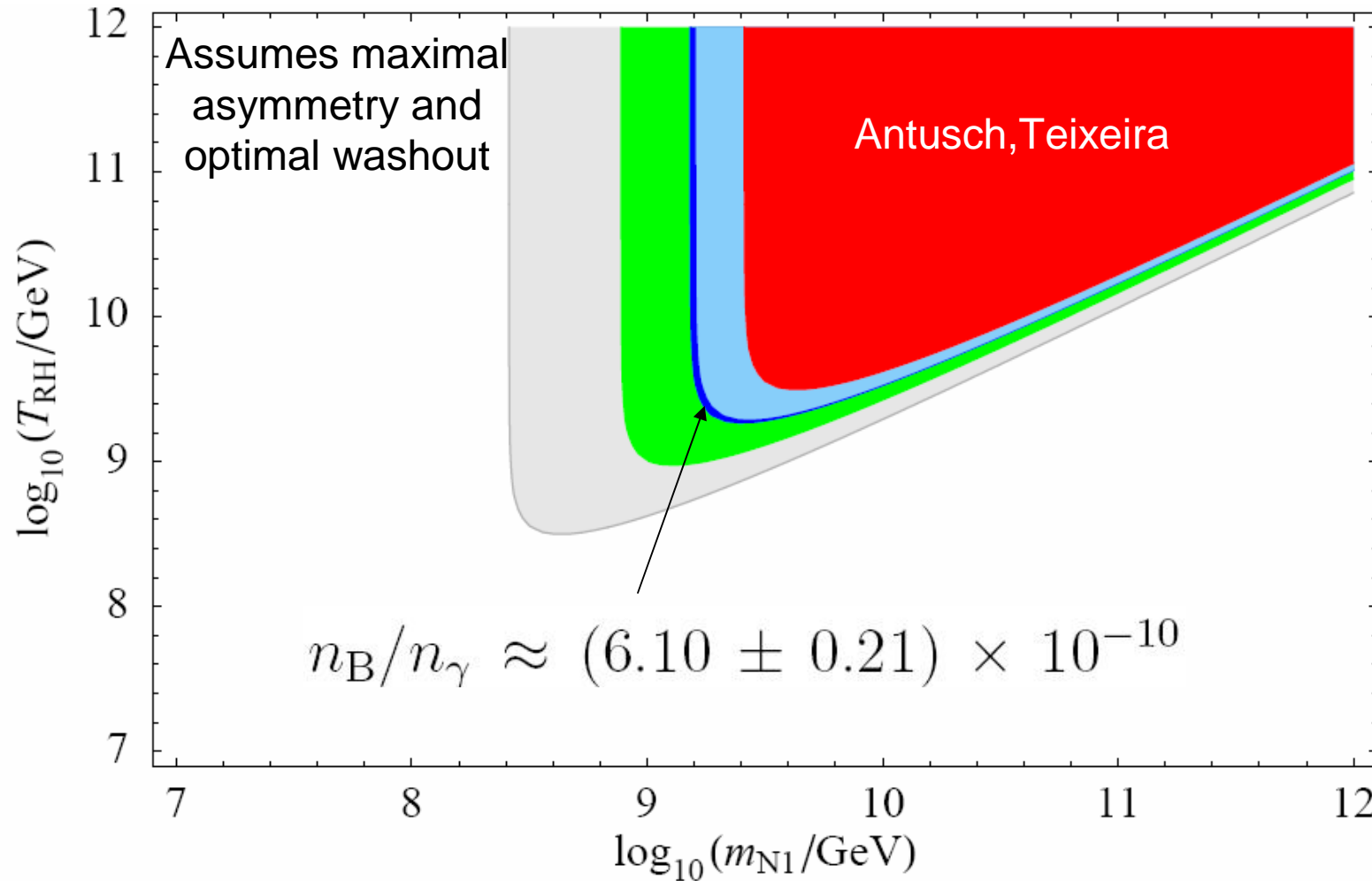
FD lepton asymmetry
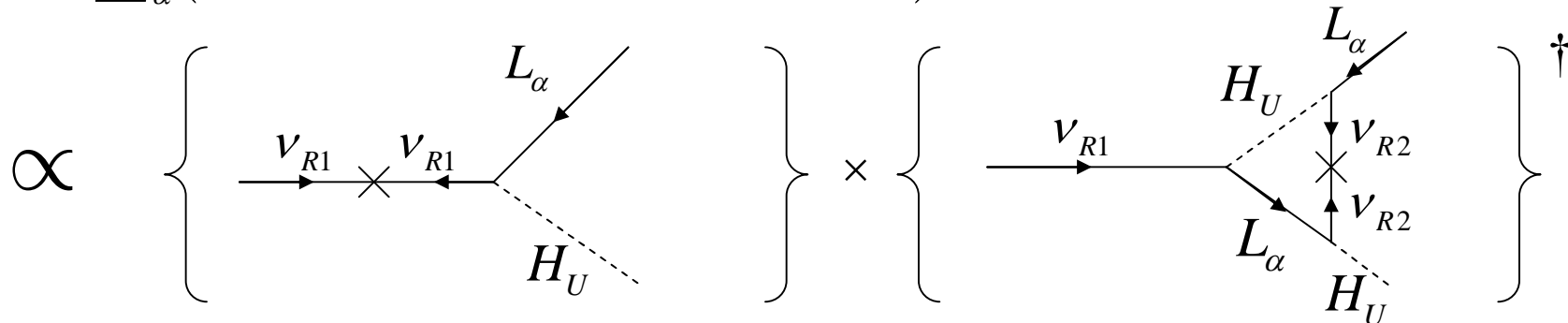
Flavour Dependent Leptogenesis with SD

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}

Assumes maximal asymmetry and optimal washout

Antusch,Teixeira

$$n_B/n_\gamma \approx (6.10 \pm 0.21) \times 10^{-10}$$

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