Flavour in the Era of LHC

WG3 theory report

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Tallinn

Outline

- Review of presentations
  - 10 experimental talks
  - 6 theory talks

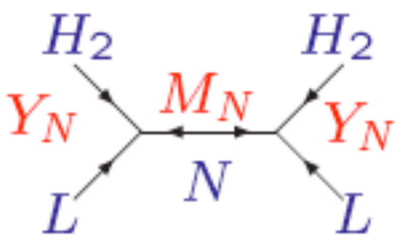
- Structure of the writeup

Gauge and Yukawa mediate SUSY breaking in triplet seesaw

Anna Rossi

Singlets $N \sim (1,0)$

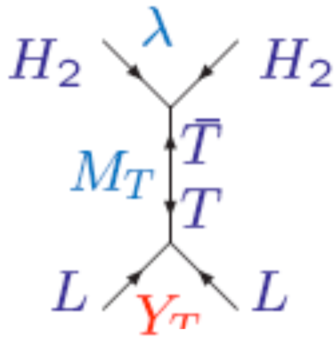
$$Y_N H_2 L N + \frac{1}{2} M_N N N$$



$$m_\nu = v_2^2 \; Y_N^T M_N^{-1} Y_N$$

Triplets $T, \bar{T} \sim (3, \pm 1)$

$$Y_T L T L + \lambda H_2 \bar{T} H_2 + M_T T \bar{T}$$



$$m_\nu = \frac{v_2^2 \lambda}{M_T} Y_T$$

Lepton Flavour Violation in $\tilde{L}^\dagger m^2_{\tilde{L}} \tilde{L}$

$$(m^2_{\tilde{L}})_{ij} \sim \frac{m_0^2}{16\pi^2}\left(\frac{M_T}{\lambda v_2^2}\right)(m_\nu^\dagger m_\nu)_{ij} \ln \frac{M_X}{M_T}$$

$$\frac{BR(\tau \to \mu\gamma)}{BR(\mu \to e\gamma)} \approx \left(\frac{(m^2_{\tilde{L}})_{\tau\mu}}{(m^2_{\tilde{L}})_{\mu e}}\right)^2 \frac{BR(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}{BR(\mu \to e\nu_\mu\bar{\nu}_e)} \sim 300$$

$$\frac{BR(\tau \to e\gamma)}{BR(\mu \to e\gamma)} \approx \left(\frac{(m^2_{\tilde{L}})_{\tau e}}{(m^2_{\tilde{L}})_{\mu e}}\right)^2 \frac{BR(\tau \to e\nu_\tau\bar{\nu}_e)}{BR(\mu \to e\nu_\mu\bar{\nu}_e)} \sim 10^{-1}$$

T-Seesaw Motivates Grand Unified Theory (GUT)

Minimal extension: SUSY SU(5)

Triplets T fit into 15: $15 = S + T + Z$

$SU(3)_C \times SU(2)_W \times U(1)_Y$ decomposition

$$S \sim (6, 1, -\frac{2}{3}), \quad T \sim (1, 3, 1), \quad Z \sim (3, 2, \frac{1}{6})$$

$$Y_{15}\ \bar{5}\ 15\ \bar{5} = Y_T LTL + \ldots$$

$[\bar{5} = d^c + \ell]$

SUSY breaking

Then impose B-L Conservation

$$W_{SU(5)} = \xi X 15\ \overline{15} + Y_{15}\ \bar{5}\ 15\ \bar{5} + \lambda 5_H\ \overline{15}\ 5_H$$
$$+ Y_5\ 10\ \bar{5}\ \bar{5}_H + Y_{10}\ 10\ 10\ 5_H + M_5 \bar{5}_H\ 5_H$$

$10 = (u^c, d^c, Q); 5_H = (t, H_2)$

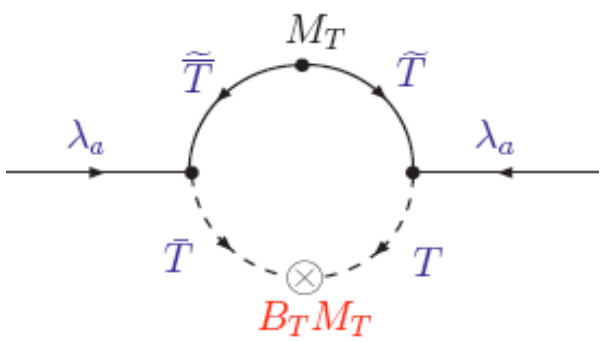
$\bar{5}_H = (\bar{t}, H_1)$

$$\langle X \rangle = \langle S_X \rangle + \theta^2 \langle F_X \rangle$$

$$\xi \langle S_X \rangle = M_{15} \qquad \xi \langle F_X \rangle = B_{15} M_{15}$$

- ~~B-L~~ via Yukawa interactions at tree level
- ~~SUSY~~ via Gauge and Yukawa interactions

$$\mathcal{L}_{SSB} = -B_T M_T(T\bar{T} + Z\bar{Z} + Z\bar{Z}) + \text{h.c.}$$



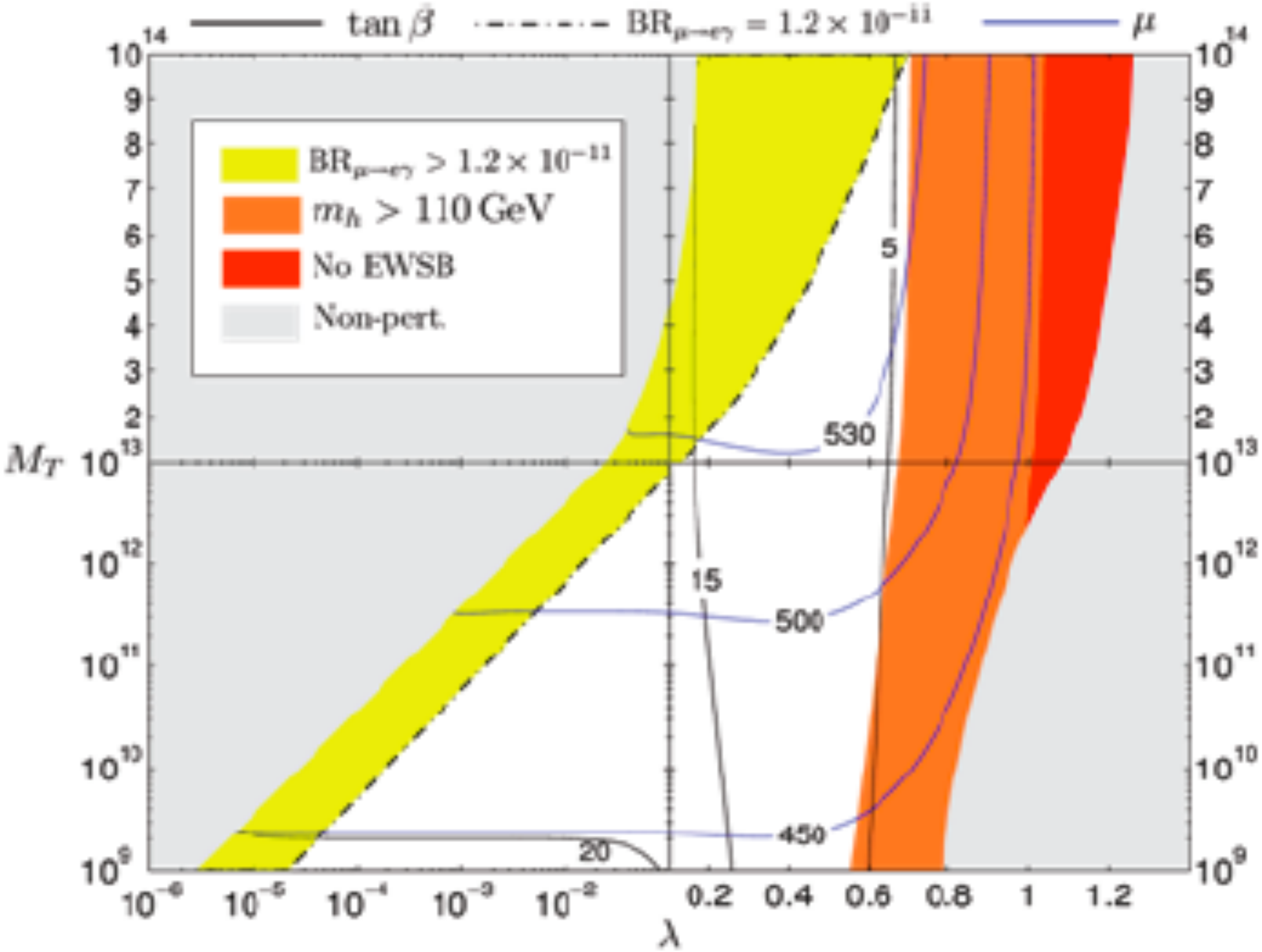
All SSB mass parameters $\tilde{M} \sim \frac{B_T}{16\pi^2}$

$\tilde{M} \sim \mathcal{O}(100 \text{ GeV}) \longrightarrow B_T \sim \mathcal{O}(10 \text{ TeV})$

one mass scale fixes all the SSB masses

$$(m^2_{\tilde{L}})_{ij} \propto Y_T^\dagger Y_T + Y_Z^\dagger Y_Z, \qquad (m^2_{\tilde{d}^c})_{ij} \propto Y_S Y_S^\dagger + Y_Z Y_Z^\dagger$$

$$\frac{(m^2_{\tilde{d}^c})_{bs}}{(m^2_{\tilde{d}^c})_{sd}} \sim \frac{(m^2_{\tilde{L}})_{\tau\mu}}{(m^2_{\tilde{L}})_{\mu e}} \approx \frac{[U(m_\nu^D)^2 U^\dagger]_{\tau\mu}}{[U(m_\nu^D)^2 U^\dagger]_{\mu e}} \sim 40$$

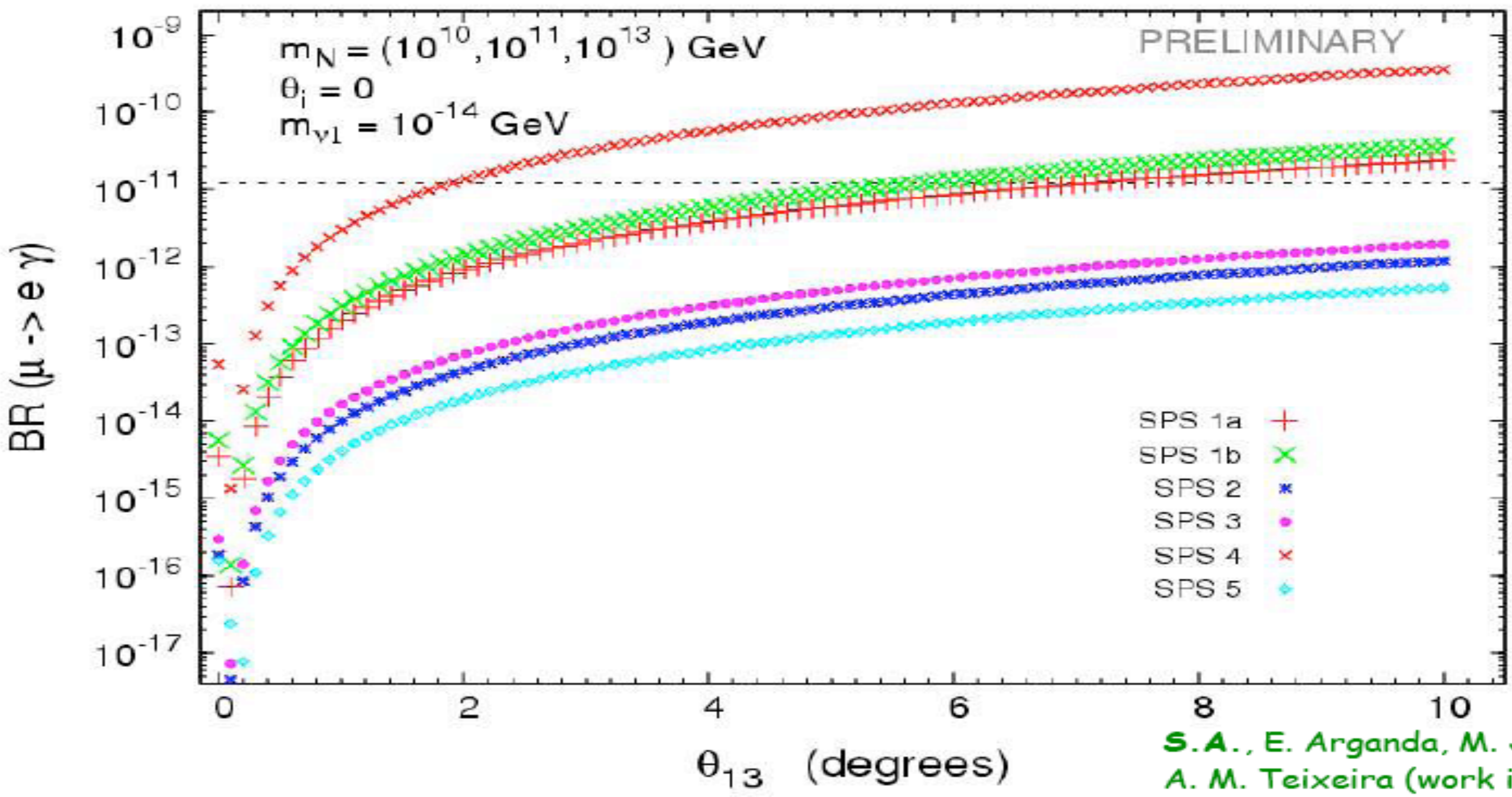


tan β
BR$_{\mu\to e\gamma}$ = 1.2 × 10^{-11}
μ
BR$_{\mu\to e\gamma}$ > 1.2 × 10^{-11}
m_h > 110 GeV
No EWSB
Non-pert.
M_T
λ
530
500
450
5
15
20

LFV and Θ_{13} in SUSY N seesaw

Stefan Antusch

Motivation: Br ($\mu \to e \gamma$) and θ_{13} in an Example (R = 1)



S.A., E. Arganda, M. J. I
A. M. Teixeira (work in p

Analytically

$$M_{LL}^{ij2} = -\frac{1}{8\pi^2}(3M_0^2 + A_0^2)(Y_\nu^* L Y_\nu^T)_{ij}$$

$$\mathrm{Br}(l_i \to l_j\, \gamma) \propto |Y_\nu^* L\ Y_\nu^T|_{ij}^2 \tan^2\beta$$

$$v_u^2\,(Y_\nu^*\,L\,Y_\nu^T)_{21} \overset{\theta_1=\theta_2=\theta_3=0}{=}$$

$$L_3\, M_3\, e^{i\delta}\, m_3\, c_{13}\, s_{13}\, s_{23}$$

$$+L_2\, M_2\, m_2\, c_{13}\, s_{12}\, \left(c_{12}\, c_{23} - e^{i\delta}\, s_{12}\, s_{13}\, s_{23}\right)$$

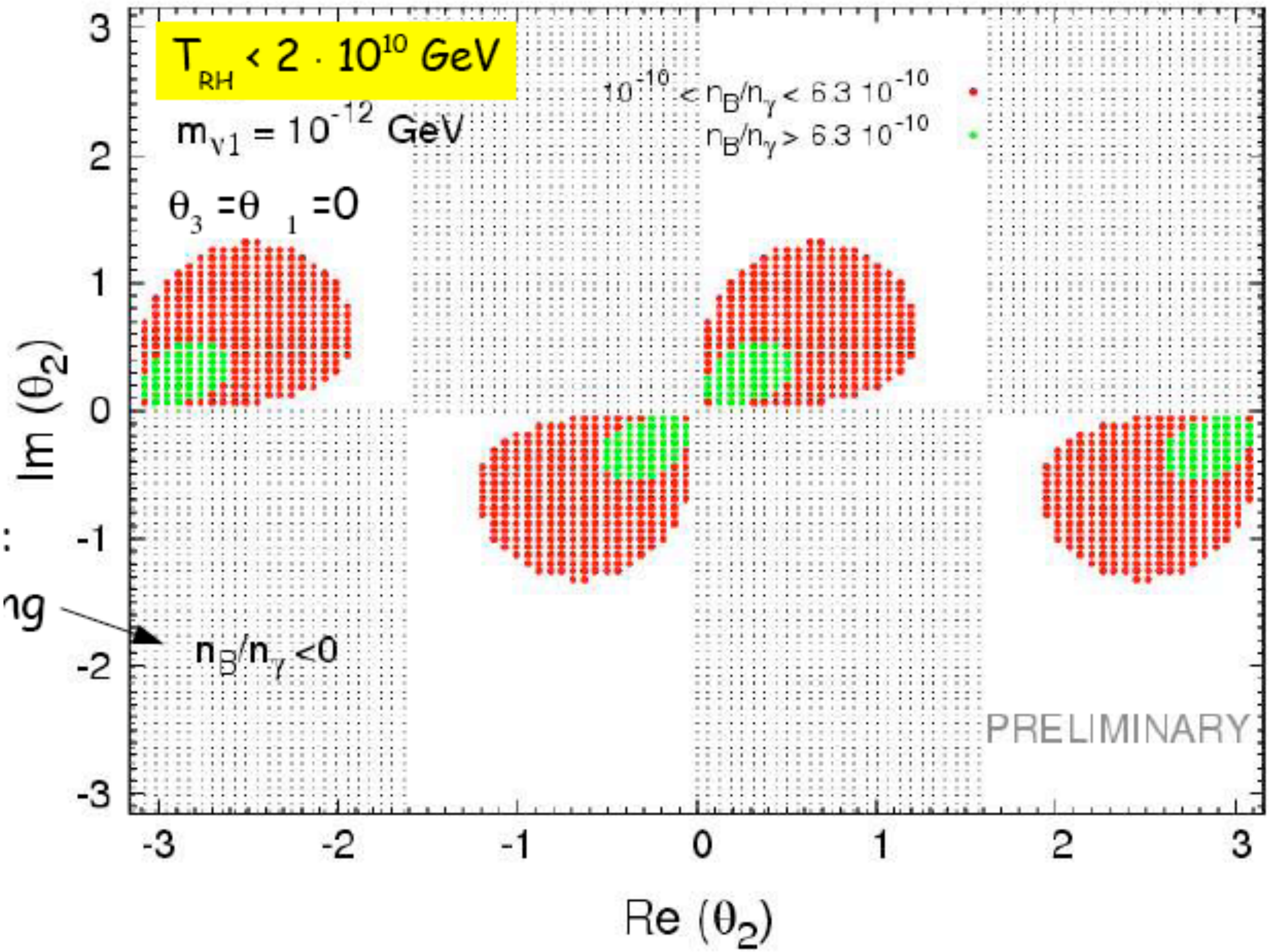
$$+L_1\, M_1\, m_1\, c_{12}\, c_{13}\, \left(-c_{23}\, s_{12} - e^{i\delta}\, c_{12}\, s_{13}\, s_{23}\right)$$

$$Y_\nu\, v_u = m_D \approx \begin{pmatrix} i\, e^{\frac{i}{2}\phi_1}\sqrt{m_1}\sqrt{M_1}\, c_{12} & i\, e^{\frac{i}{2}\phi_2}\sqrt{m_2}\sqrt{M_2}\, s_{12} & \propto s_{13} \\ -i\, e^{\frac{i}{2}\phi_1}\sqrt{m_1}\sqrt{M_1}\, c_{23}\, s_{12} & i\, e^{\frac{i}{2}\phi_2}\sqrt{m_2}\sqrt{M_2}\, c_{12}\, c_{23} & i\sqrt{m_3}\sqrt{M_3}\, s_{23} \\ i\, e^{\frac{i}{2}\phi_1}\sqrt{m_1}\sqrt{M_1}\, s_{12}\, s_{23} & -i\, e^{\frac{i}{2}\phi_2}\sqrt{m_2}\sqrt{M_2}\, c_{12}\, s_{23} & i\sqrt{m_3}\sqrt{M_3}\, c_{23} \end{pmatrix}$$

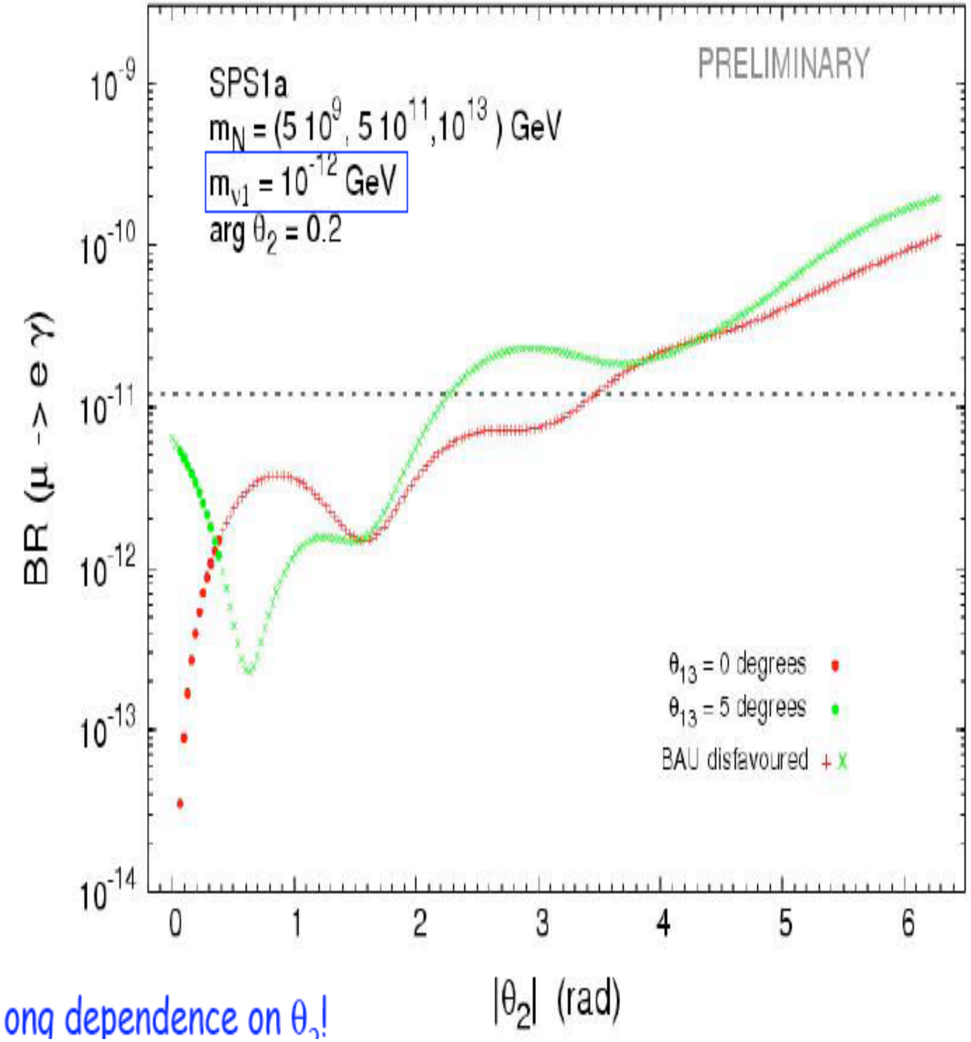
+ our Software: Routines for LFV decays*, Leptogenesis**, EDMs, Neutrino RGEs

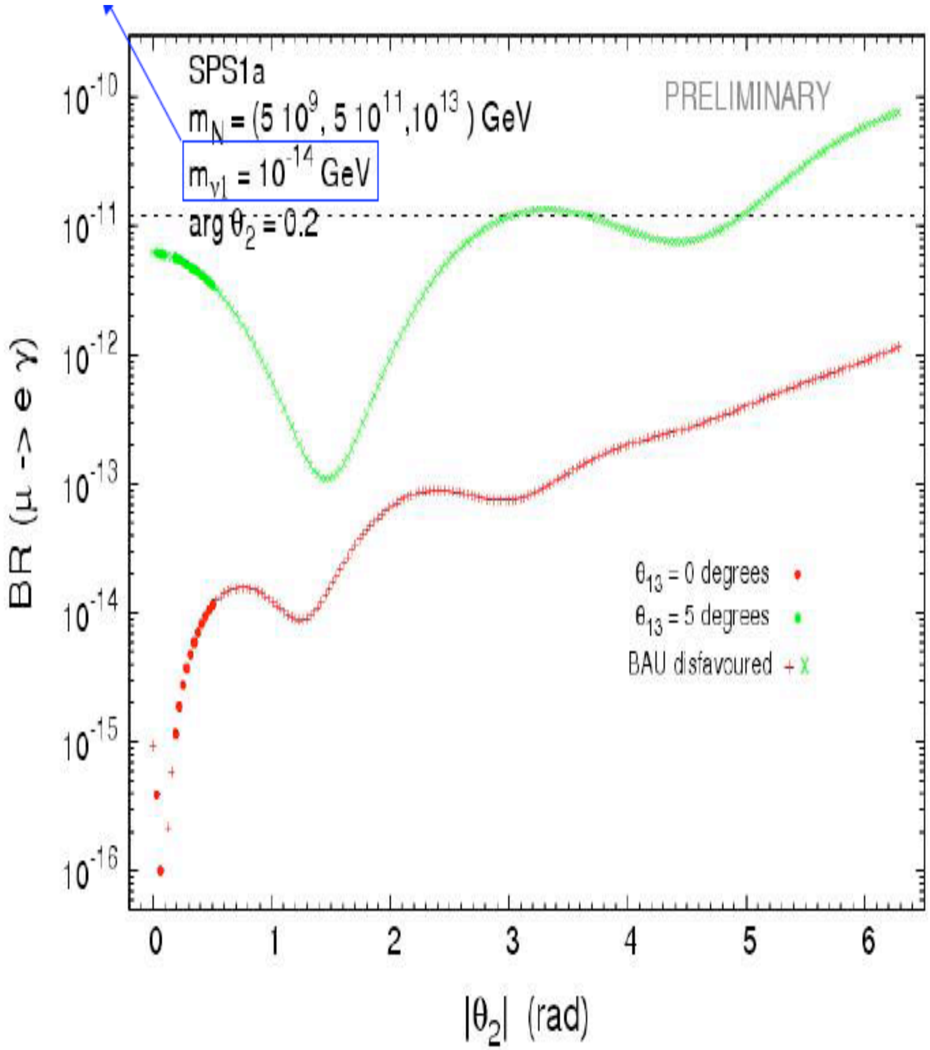
- We require: BAU $\in [10^{-9}, 10^{-10}]$ (via thermal leptogenesis)
  $\mathrm{EDM}_{e\mu\tau} \lesssim (6.9 \times 10^{-28}, 3.7 \times 10^{-19}, 0.45 \times 10^{-16})$ e.cm
  $T_{RH} < 2\ 10^{10}$ GeV (Gravitino→ nonthermal LSP prod., $m_{LSP} \sim 100$ GeV)

$$R = \begin{pmatrix} c_2 c_3 & -c_1 s_3 - s_1 s_2 c_3 & s_1 s_3 - c_1 s_2 c_3 \\ c_2 s_3 & c_1 c_3 - s_1 s_2 s_3 & -s_1 c_3 - c_1 s_2 s_3 \\ s_2 & s_1 c_2 & c_1 c_2 \end{pmatrix}$$

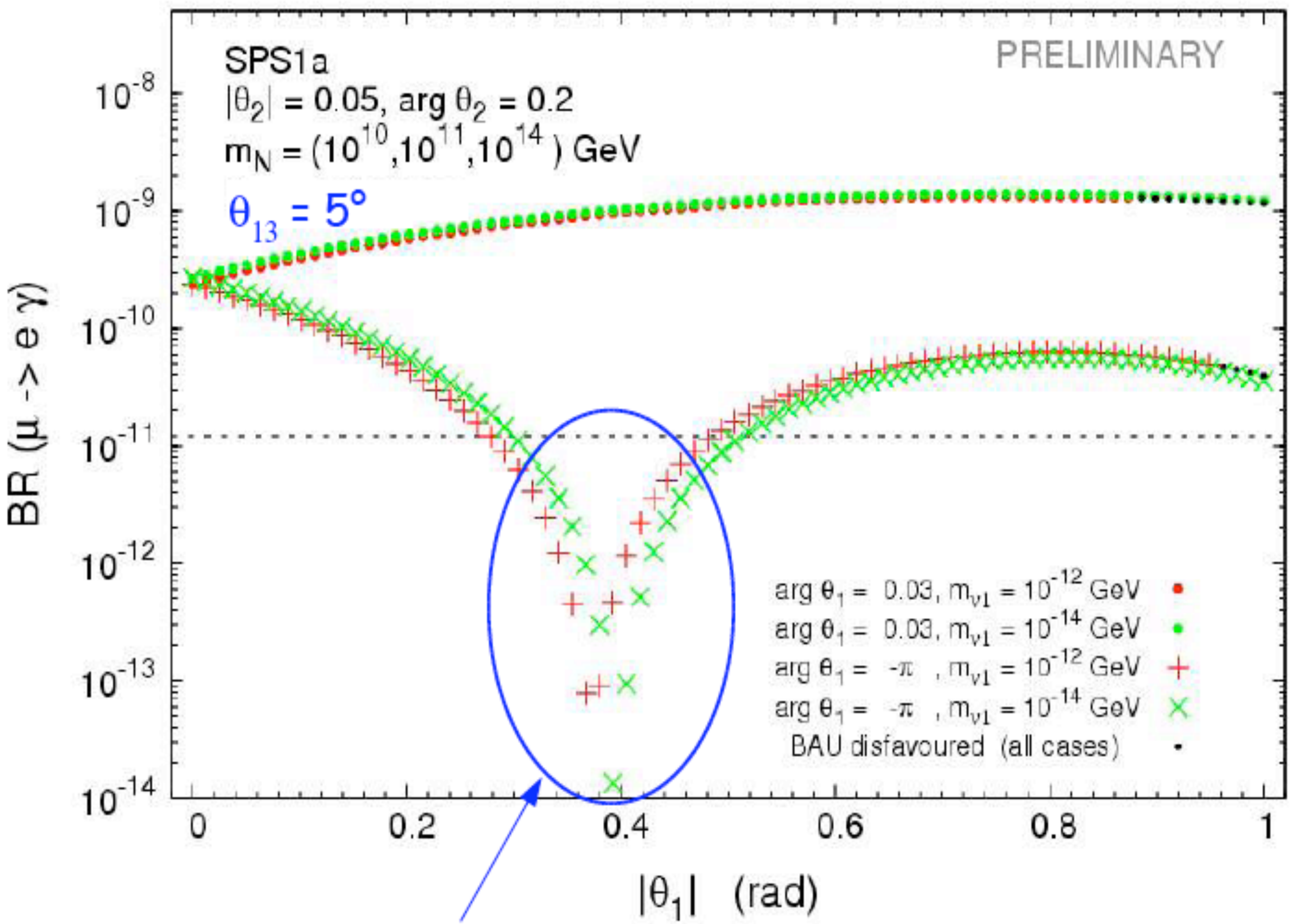


$T_{RH} < 2 \cdot 10^{10}$ GeV
$m_{\nu 1} = 10^{-12}$ GeV
$\theta_3 = \theta_1 = 0$
$10^{-10} < n_B/n_\gamma < 6.3\ 10^{-10}$
$n_B/n_\gamma > 6.3\ 10^{-10}$
$n_B/n_\gamma < 0$
PRELIMINARY
Im (θ_2)
Re (θ_2)





ong dependence on θ_2!

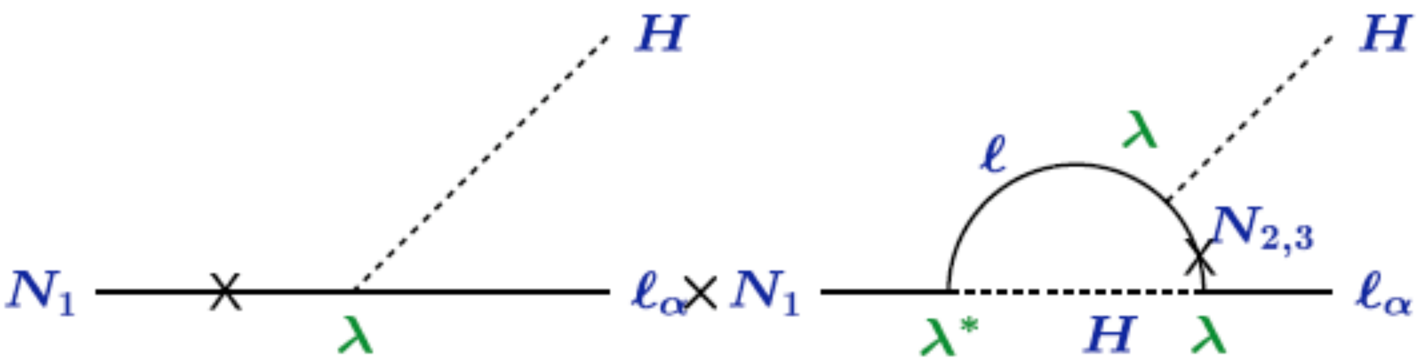


SPS1a
|θ2| = 0.05, arg θ2 = 0.2
mN = (10^10,10^11,10^14) GeV
θ13 = 5°
PRELIMINARY
BR (μ -> e γ)
|θ1| (rad)
arg θ1 = 0.03, mν1 = 10^-12 GeV
arg θ1 = 0.03, mν1 = 10^-14 GeV
arg θ1 = -π , mν1 = 10^-12 GeV
arg θ1 = -π , mν1 = 10^-14 GeV
BAU disfavoured (all cases)

Flavour matters in leptogenesis

Sacha Davidson

$$-\epsilon^{\alpha\alpha} = \frac{\Gamma(\bar{N}_1 \to \bar{H}\bar{\ell}_\alpha) - \Gamma(N_1 \to H\ell_\alpha)}{\Gamma(N \to H\ell) + \Gamma(\bar{N}_1 \to \bar{H}\bar{\ell})}$$



lepton asymmetry $\to$ baryon asymmetry

$$\frac{dY_N}{dz} = -\frac{z}{sH}(\frac{Y_N}{Y_N^{eq}} - 1)\gamma$$

$$\sum_\alpha \frac{d}{dz} Y_L^{\alpha\alpha} = \frac{z}{sH}\left[\gamma\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\underbrace{(\epsilon^{ee} + \epsilon^{\mu\mu} + \epsilon^{\tau\tau})}_{\epsilon} - \frac{1}{Y_\ell^{eq}}\underbrace{(\gamma^{ee}Y_L^{ee} + \gamma^{\mu\mu}Y_L^{\mu\mu} + \gamma^{\tau\tau}Y_L^{\tau\tau})}_{\neq\gamma Y_L}\right]$$

NOT the same.

$$\frac{dY_L}{dz} = \frac{z}{sH(M)}\left[\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\epsilon\gamma - (\gamma^{ee} + \gamma^{\mu\mu} + \gamma^{\tau\tau})\frac{Y_L^{ee} + Y_L^{\mu\mu} + Y_L^{\tau\tau}}{Y_\ell^{eq}}\right]$$

pheno consequences 1 - $C\not{P}$ and the bound on m_ν

$$\sum_\alpha \epsilon^{\alpha\alpha} \leq \frac{3M_1 \Delta m^2_{atm}}{8\pi v^2 m_{max}} \qquad \qquad \epsilon^{\alpha\alpha} \leq \frac{3M_1 m_{max}}{8\pi v^2}$$

$\Rightarrow$ no leptogenesis bound $m_{max} \lesssim .1$ eV
(leptogenesis can work between green lines)

pheno consequences 2 - mild decrease in min M_1

$$\text{single flavour}: \; Y_B \quad \propto \quad \frac{\epsilon}{\Gamma_D} \simeq 10^{-3} \epsilon \frac{m_*}{\tilde{m}}$$

$$\text{summed flavours}: \; Y_B \quad \propto \quad \left(\frac{\epsilon^{ee}}{\Gamma_D^{ee}} + \frac{\epsilon^{\mu\mu}}{\Gamma_D^{\mu\mu}} + \frac{\epsilon^{\tau\tau}}{\Gamma_D^{\tau\tau}} \right) \simeq 3 \times 10^{-3} \epsilon \frac{m_*}{\tilde{m}}$$

The lower bound on M_1 decreases

consequences for models...to estimate Y_B

model predictions with flavour : $\epsilon^{ee}, \epsilon^{\mu\mu}, \epsilon^{\tau\tau}, \widetilde{m}^{ee}, \widetilde{m}^{\mu\mu}, \widetilde{m}^{\tau\tau}$

1. strong washout all flavours: $\widetilde{m}^{\alpha\alpha} > m_*$

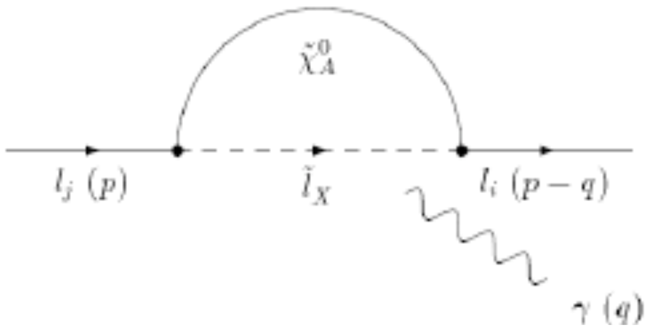
2. weak washout all flavours: $\widetilde{m}^{\alpha\alpha} < m_*$

3. weak washout in flavours: α , strong in β

LFV from SUSY GUTs

Lorenzo Calibbi

SUSY induced LFV:



GUT effect, e.g. SU(5), if $\boldsymbol{M_X > M_{GUT}}$

$$(\Delta_{RR})_{i\neq j} = -3 \cdot \frac{3m_0^2 + a_0^2}{16\pi^2} Y_t^2 V_{i3} V_{j3} \ln\left(\frac{M_X^2}{M_{GUT}^2}\right)$$

See-saw:

$$m_\nu = -Y_\nu \hat{M}_R^{-1} Y_\nu^T \langle H_u \rangle^2$$

$$(\Delta_{LL})_{i\neq j} = -\frac{3m_0^2 + A_0^2}{16\pi^2} Y_{\nu\, i3} Y_{\nu\, j3} \ln\left(\frac{M_X^2}{M_{R_3}^2}\right)$$

$$W_{SO(10)} = Y_{ij}^{10} 16_i 16_j 10 + Y_{ij}^{126} 16_i 16_j 126 + Y_{ij}^{120} 16_i 16_j 120$$

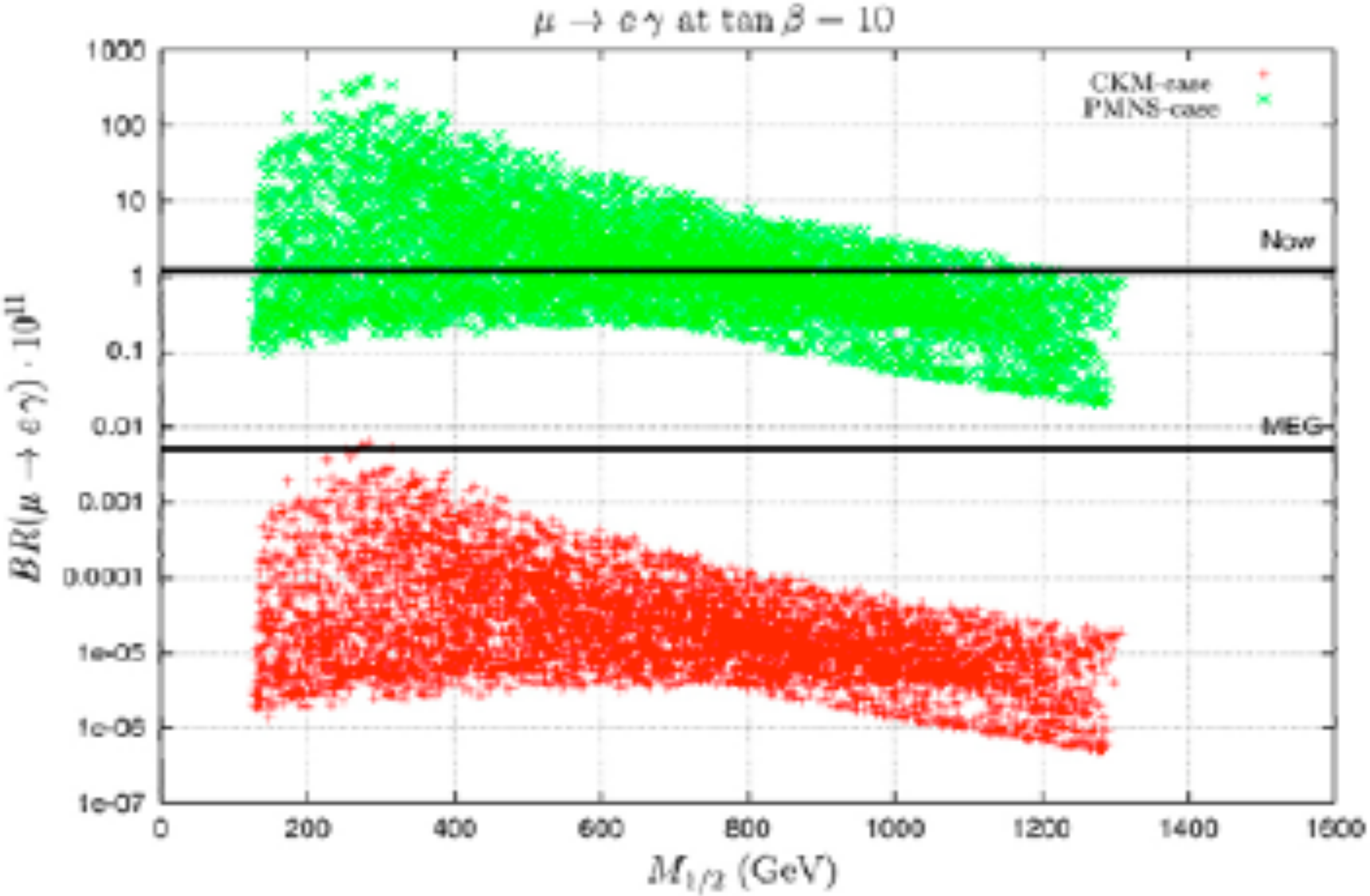
$$\Rightarrow \begin{cases} m_D^\nu = M_{10} - 3M_{126} + M_{120} \\ m_u = M_{10} + M_{126} + M_{120} \end{cases}$$

"Minimal" mixing (CKM):

$$Y^\nu = Y^u \;\Rightarrow\; Y^\nu = V_{\rm CKM}^T Y_{diag}^u V_{\rm CKM}$$

"Maximal" mixing (PMNS):

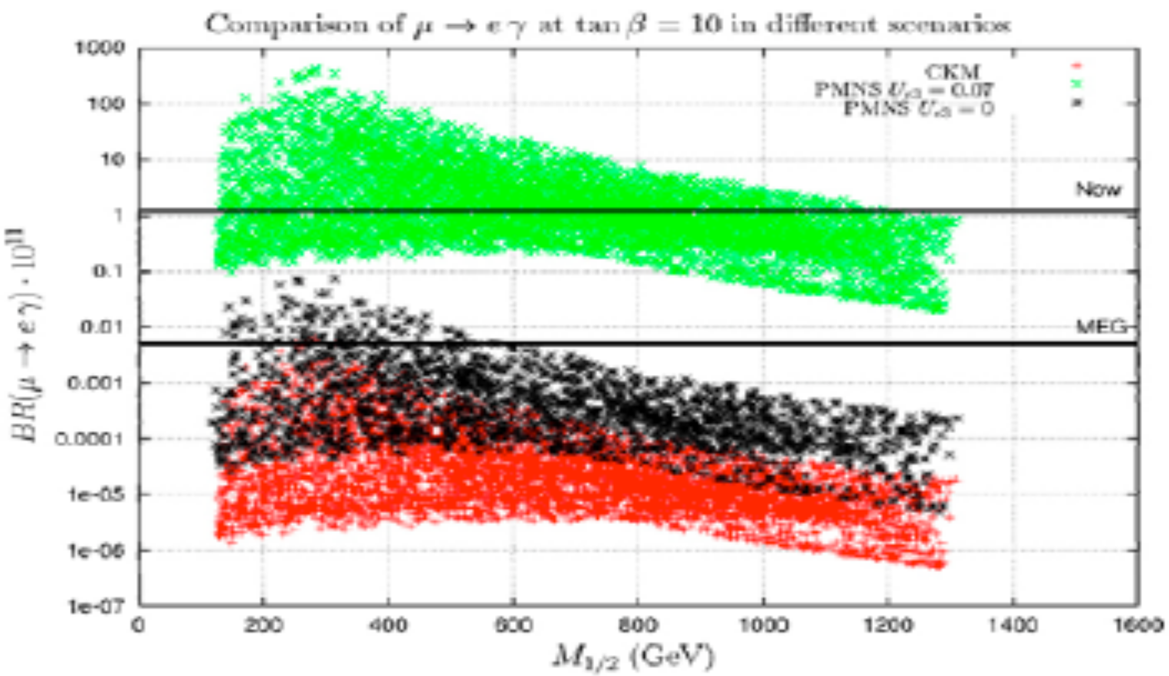
$$Y^\nu = U_{\rm PMNS} Y_{diag}^u$$

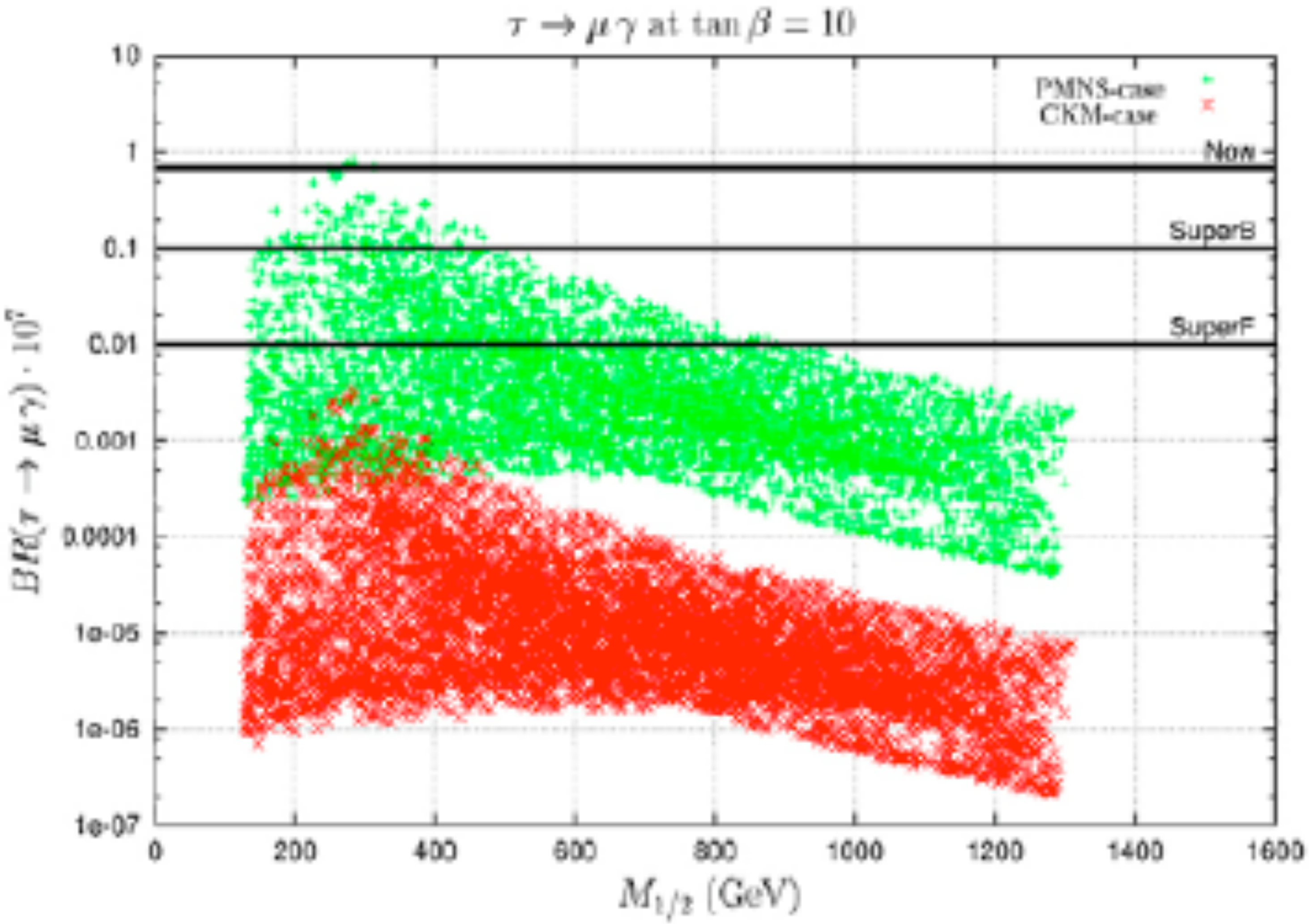

$\mu \to e\gamma$ at $\tan\beta = 10$
CKM-case
PMNS-case
Now
MEG
$BR(\mu \to e\gamma) \cdot 10^{11}$
$M_{1/2}$ (GeV)
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0
200
400
600
800
1000
1200
1400
1600

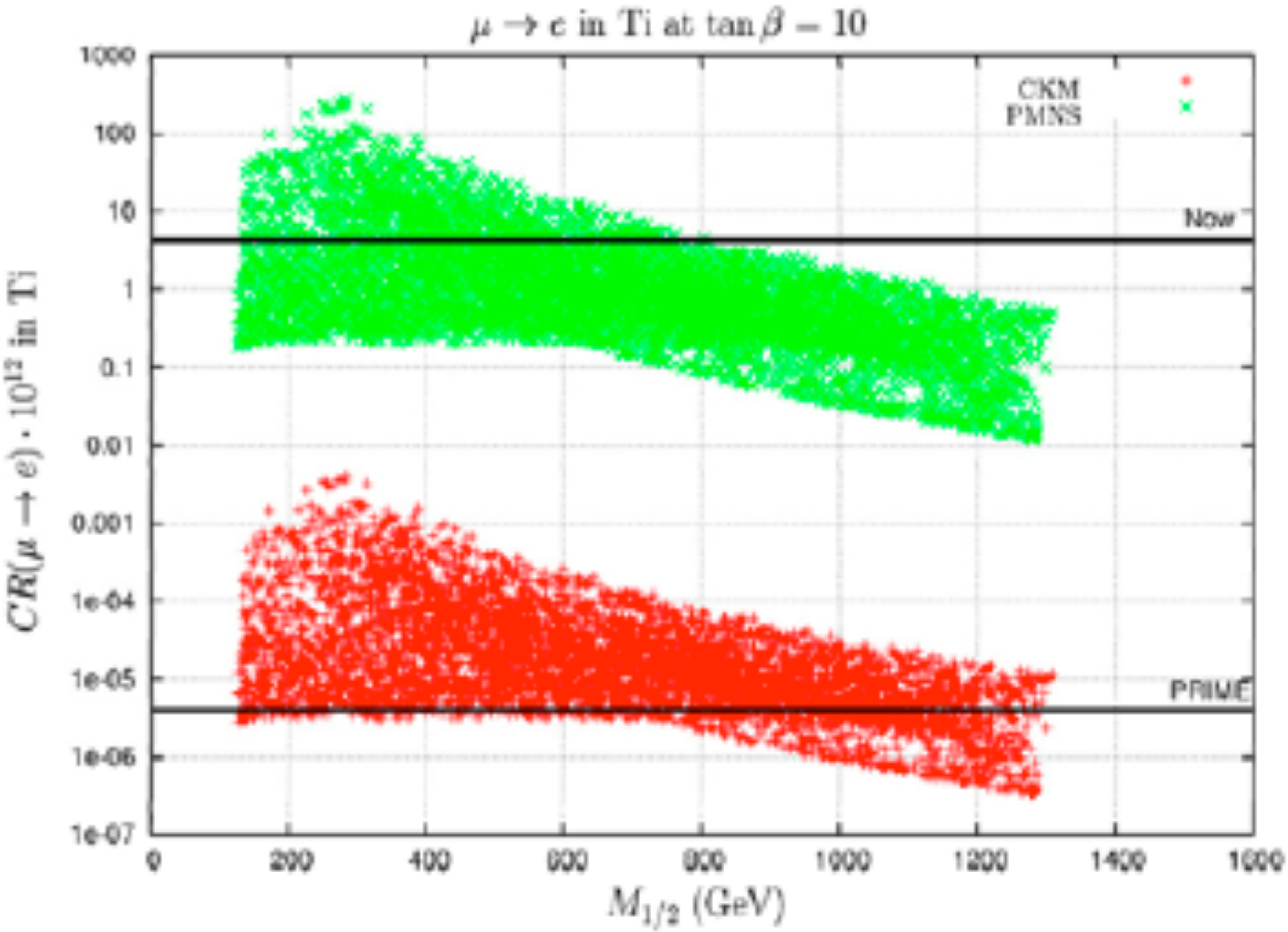
$$(\delta_{LL})_{\mu e} = -\frac{3}{8\pi^2} Y_t^2 U_{e3} U_{\mu 3} \ln \frac{M_X}{M_{R_3}}$$

And if $U_{e3} = 0$:

$$(\delta_{LL})_{\mu e} = -\frac{3}{8\pi^2} Y_c^2 U_{e2} U_{\mu 2} \ln \frac{M_X}{M_{R_2}}$$




$\tau \to \mu\gamma$ at $\tan\beta = 10$
PMNS-case
CKM-case
Now
SuperB
SuperF
$BR(\tau \to \mu\gamma) \cdot 10^7$
$M_{1/2}$ (GeV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0
200
400
600
800
1000
1200
1400
1600


$\mu \to e$ in Ti at $\tan\beta = 10$
CKM
PMNS
Now
PRIME
$CR(\mu \to e) \cdot 10^{12}$ in Ti
$M_{1/2}$ (GeV)
1000
100
10
1
0.1
0.01
0.001
1e-04
1e-05
1e-06
1e-07
0
200
400
600
800
1000
1200
1400
1600

Structure of the writeup

- WG3 contribution should be selfconsistent

- Contains related:
  - Theory part
  - Experiment part

Structure of theory part

1. Introduction: SM and flavour puzzle
2. Model independent description of observables
    1. Effective operators
    2. Low scale observables
    3. High scale observables
3. “Theory” of flavour
4. Phenomenology of models
    1. Non-SUSY extensions of SM
    2. SUSY extensions of SM
    3. GUTS
5. Experiments