Bonn, SUSY 2010

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Beyond the Standard SUSY Seesaw

Neutrino masses from Kähler operators and broken SUSY:

I – Effective theory

II – Explicit realizations

with Filipe Joaquim and Anna Rossi

arXiv:1007.1942 [hep-ph], to appear in JHEP

SEESAW : m_ν tiny because suppressed by large $M \gg v$

- Standard suppression : $\boxed{m_\nu \sim \frac{v^2}{M}}$ $\Rightarrow$ $M \lesssim 10^{15}$ GeV
- ΔL=2 effective operator with d=5 (lowest dim.): $\frac{1}{M}(H_2 L)^2 \subset W$ (SUSY)
- Realized, e.g., by tree-level echange of massive singlets (I) or triplets (II – III)

Could m_ν be suppressed by higher powers of 1/M ?

- Simplest possibility: $\boxed{m_\nu \sim \frac{m\, v^2}{M^2}}$ $(\, m \ll M \,)$

If $m \sim v$ $\Rightarrow$ $M \lesssim 10^9$ GeV

Effective operators? Explicit realizations?

$m_\nu \sim \frac{m\, v^2}{M^2}$ from $\Delta L=2$, $d=6$ SUSY effective operators

From W : $\int d^2\theta \, \frac{1}{M^2} S(H_2 L)^2$ with $\langle S \rangle \sim v$ $\Rightarrow$ $m \sim v$

Gogoladze,Okada,Shafi 08

From K : $\int d^4\theta \, \frac{1}{M^2} \left[(H_1^\dagger L)(H_2 L) \; + \; (H_1^\dagger L)^2 \right]$ $\Rightarrow$ $m \sim \mu$

Casas,Espinosa,Navarro 02

$\langle F_{H_1}^\dagger \rangle = -\mu \langle H_2 \rangle$

General analysis B,J,R 10

- Symmetry properties
- Operator mixing, involving also $LLLE^cH_2 \subset W$, $LLQD^cH_2 \subset W$, $LLU^{c\dagger}D^c \subset K$
- Inclusion of SUSY breaking
- Tree+loop contributions to m_ν ; RGEs
- Explicit realizations of Kähler operators (heavy states)
- Common source for neutrino and sparticle masses ; LFV

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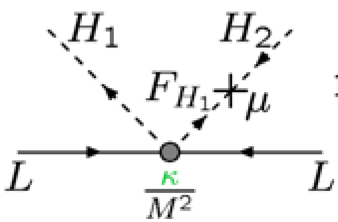
$$\mathcal{L}_{\rm eff} = \int d^4\theta \frac{1}{2M^2}\Big(\underbrace{\kappa}_{\rm SUSY} + \underbrace{\beta_\kappa \frac{X}{M_S} + \tilde\beta_\kappa \frac{X^\dagger}{M_S} + \gamma_\kappa \frac{XX^\dagger}{M_S^2}}_{\cancel{\rm SUSY}}\Big)_{ij} (H_1^\dagger L_i)(H_1^\dagger L_j) + \text{h.c.}$$

$$X = \theta^2 F_X$$

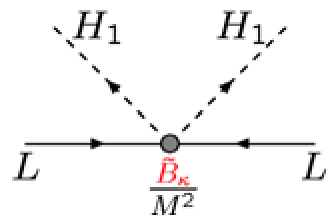
$$\begin{aligned} \mathbf{B}_\kappa &= \beta_\kappa F_X / M_S \\ \tilde{\mathbf{B}}_\kappa &= \tilde\beta_\kappa F_X^* / M_S \\ \mathbf{C}_\kappa &= \gamma_\kappa |F_X|^2 / M_S^2 \end{aligned}$$

$$= \int d^4\theta \frac{1}{2M^2}\left(\kappa + \theta^2 \mathbf{B}_\kappa + \bar\theta^2 \tilde{\mathbf{B}}_\kappa + \theta^2\bar\theta^2 \mathbf{C}_\kappa\right)_{ij} (H_1^\dagger L_i)(H_1^\dagger L_j) + \text{h.c.}$$

- From κ, $\tilde{\mathbf{B}}_\kappa$: tree contrib. to m_ν



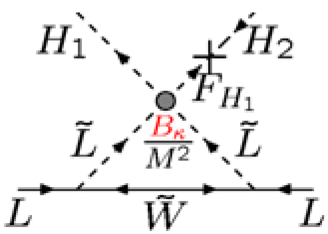
$$\mathbf{m}_\nu^{(\kappa)} = 2\,\kappa\,\mu \frac{v^2}{M^2} \sin\beta\cos\beta$$



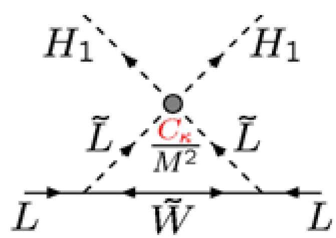
$$\mathbf{m}_\nu^{(\tilde{B}_\kappa)} = \tilde{\mathbf{B}}_\kappa \frac{v^2}{M^2} \cos^2\beta$$

Either of these can dominate...

- From $\mathbf{B}_\kappa$, $\mathbf{C}_\kappa$: tree contrib. to $\tilde\nu\tilde\nu$ mass terms ($\tilde\nu$ osc.?) + loop contrib. to m_ν



$$\delta_{B_\kappa} \mathbf{m}_\nu = \ldots$$



$$\delta_{C_\kappa} \mathbf{m}_\nu = \ldots$$

Suppressed, unless $\mathbf{B}_\kappa \gg \tilde{m}$, $\mathbf{C}_\kappa \gg \tilde{m}^2$ (cfr. d=5 case Grossman,Haber 97; Hirsch et al. 97)

R G E s

d=5 (W) : $8\pi^2\frac{d\kappa_5}{dt} = -\left[3g^2+g'^2-3\mathrm{Tr}(\mathbf{Y}_u^\dagger\mathbf{Y}_u)\right]\boldsymbol{\kappa}_5+\frac{1}{2}\left[\boldsymbol{\kappa}_5\mathbf{Y}_e^\dagger\mathbf{Y}_e+(\mathbf{Y}_e^\dagger\mathbf{Y}_e)^T\boldsymbol{\kappa}_5\right]$

Chankowski,Pluciennik 93; Babu,Leung,Pantaleone 93

d=6 (K) : $8\pi^2\frac{d\kappa}{dt} = \left[g^2+g'^2+\mathrm{Tr}(\mathbf{Y}_e^\dagger\mathbf{Y}_e+3\mathbf{Y}_d^\dagger\mathbf{Y}_d)\right]\boldsymbol{\kappa}-\frac{1}{2}\left[\boldsymbol{\kappa}\mathbf{Y}_e^\dagger\mathbf{Y}_e+(\mathbf{Y}_e^\dagger\mathbf{Y}_e)^T\boldsymbol{\kappa}\right]$

Casas,Espinosa,Navarro 02

Including SUSY :

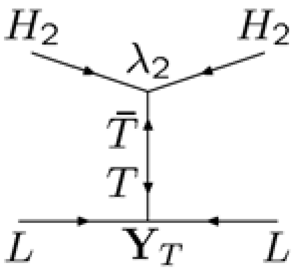
$$
\begin{aligned}
8\pi^2\frac{d\mathbf{B}_\kappa}{dt} &= \left[g^2+g'^2+\mathrm{Tr}(\mathbf{Y}_e^\dagger\mathbf{Y}_e+3\mathbf{Y}_d^\dagger\mathbf{Y}_d)\right]\mathbf{B}_\kappa-\frac{1}{2}\left[\mathbf{B}_\kappa\mathbf{Y}_e^\dagger\mathbf{Y}_e+(\mathbf{Y}_e^\dagger\mathbf{Y}_e)^T\mathbf{B}_\kappa\right] \\
&\quad+\left[g^2M_2+g'^2M_1\right]\boldsymbol{\kappa} \\
8\pi^2\frac{d\tilde{\mathbf{B}}_\kappa}{dt} &= \left[g^2+g'^2+\mathrm{Tr}(\mathbf{Y}_e^\dagger\mathbf{Y}_e+3\mathbf{Y}_d^\dagger\mathbf{Y}_d)\right]\tilde{\mathbf{B}}_\kappa-\frac{1}{2}\left[\tilde{\mathbf{B}}_\kappa\mathbf{Y}_e^\dagger\mathbf{Y}_e+(\mathbf{Y}_e^\dagger\mathbf{Y}_e)^T\tilde{\mathbf{B}}_\kappa\right] \\
&\quad+\left[g^2M_2^*+g'^2M_1^*-2\,\mathrm{Tr}(\mathbf{A}_e^\dagger\mathbf{Y}_e+3\mathbf{A}_d^\dagger\mathbf{Y}_d)\right]\boldsymbol{\kappa}+\boldsymbol{\kappa}\,\mathbf{A}_e^\dagger\mathbf{Y}_e+(\mathbf{A}_e^\dagger\mathbf{Y}_e)^T\boldsymbol{\kappa}\,, \\
8\pi^2\frac{d\mathbf{C}_\kappa}{dt} &= \left[g^2+g'^2+\mathrm{Tr}(\mathbf{Y}_e^\dagger\mathbf{Y}_e+3\mathbf{Y}_d^\dagger\mathbf{Y}_d)\right]\mathbf{C}_\kappa-\frac{1}{2}\left[\mathbf{C}_\kappa\mathbf{Y}_e^\dagger\mathbf{Y}_e+(\mathbf{Y}_e^\dagger\mathbf{Y}_e)^T\mathbf{C}_\kappa\right] \\
&\quad+\left[g^2M_2^*+g'^2M_1^*-2\,\mathrm{Tr}(\mathbf{A}_e^\dagger\mathbf{Y}_e+3\mathbf{A}_d^\dagger\mathbf{Y}_d)\right]\mathbf{B}_\kappa+\mathbf{B}_\kappa\mathbf{A}_e^\dagger\mathbf{Y}_e+(\mathbf{A}_e^\dagger\mathbf{Y}_e)^T\mathbf{B}_\kappa \\
&\quad+\left[g^2M_2+g'^2M_1\right]\tilde{\mathbf{B}}_\kappa+4\left[2\,g^2|M_2|^2+g'^2|M_1|^2\right]\boldsymbol{\kappa}-\boldsymbol{\kappa}\,\mathbf{P}-\mathbf{P}^T\boldsymbol{\kappa}
\end{aligned}
$$

($\mathbf{P}\equiv\mathbf{A}_e^\dagger\mathbf{A}_e+(\mathbf{m}_{\tilde{L}}^2)^T\mathbf{Y}_e^\dagger\mathbf{Y}_e+\mathbf{Y}_e^\dagger(\mathbf{m}_{\tilde{e}^c}^2)^T\mathbf{Y}_e+m_{H_1}^2\mathbf{Y}_e^\dagger\mathbf{Y}_e$)

B,J,R 10

Explicit SEESAW realizations

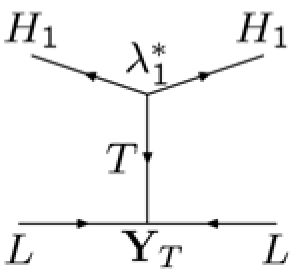
Type II mediators: heavy SU(2) triplets $T \sim (3,1),\ \bar{T} \sim (3,-1)$



d=5

$$\boxed{W_{\text{eff}} \supset \frac{\lambda_2}{2M_T}\mathbf{Y}_T^{ij}(H_2L_i)(H_2L_j)}$$

usually leading… unless $\lambda_2 \to 0$ (symmetries)



d=6

$$\boxed{K_{\text{eff}} \supset \frac{\lambda_1^*}{2|M_T|^2}\mathbf{Y}_T^{ij}(H_1^\dagger L_i)(H_1^\dagger L_j)}$$

$M^2 = |M_T|^2$

$\boldsymbol{\kappa} = \lambda_1^* \mathbf{Y}_T$

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$\mathbf{B}_\kappa\,,\tilde{\mathbf{B}}_\kappa\,,\mathbf{C}_\kappa$? dep. on ~~SUSY~~ mechanism and mediation scale M_S

- $\boxed{M_S > M_T}$: $\mathbf{B}_\kappa\,,\tilde{\mathbf{B}}_\kappa\,,\mathbf{C}_\kappa$ function of ~~SUSY~~ parameters of the triplets

$$\mathbf{B}_\kappa = \lambda_1^*(\mathbf{Y}_T B_T - \mathbf{A}_T)\ ,\ \tilde{\mathbf{B}}_\kappa = (\lambda_1^* B_T^* - A_1^*)\mathbf{Y}_T\ ,\ \mathbf{C}_\kappa = (\lambda_1^* B_T^* - A_1^*)(\mathbf{Y}_T B_T - \mathbf{A}_T) - \lambda_1^* \mathbf{Y}_T m_{\bar{T}}^2$$

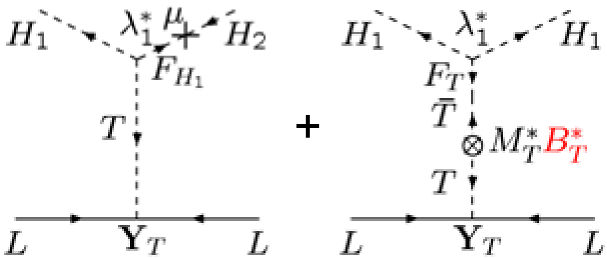
- $\boxed{M_S < M_T}$: $\mathbf{B}_\kappa\,,\tilde{\mathbf{B}}_\kappa\,,\mathbf{C}_\kappa$ can arise radiatively (messenger loops + RGEs)

- $\boxed{M_S = M_T}$: very interesting scenario…

$$M_T = M_S \; : \;$$ SEESAW mediators = SUSY mediators

Originally proposed in type II scheme with m_ν generated by W_{eff} (d=5) Joaquim,Rossi 06

Now extended to present case, with m_ν generated by K_{eff} B,J,R 10

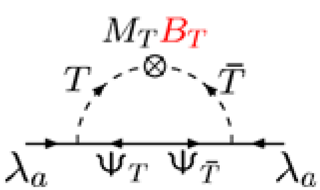


$$\mathbf{m}_\nu = \kappa \left(B_T^* + 2\,\mu \tan\beta \right) \cos^2\beta \, \frac{v^2}{|M_T|^2}$$

leading

$\kappa = \lambda_1^* \mathbf{Y}_T$ $\qquad$ $\tilde{\mathbf{B}}_\kappa = \lambda_1^* \mathbf{Y}_T B_T^* = \kappa B_T^*$ (Flavour alignment)

Yukawas



+ ....

$$M_a \sim \frac{\alpha}{\pi} B_T \, , \quad m_i^2 \sim \left[\left(\frac{\alpha}{\pi}\right)^2 + \ldots \right] |B_T|^2$$

SUSY parameter B_T : corresponds to effective SUSY scale Λ of GMSB models

Messenger sector also includes coloured fields (to generate gluino mass and to preserve gauge coupling unification). Total messenger index is N ≥ 4

Ex. 1: unified multiplets $\quad T + \bar{T} \subset 15 + \overline{15}$ $\quad$ N=7

Ex. 2: non-unified multiplets $\quad T + \bar{T} + (3,1,-1/3) + (\bar{3},1,+1/3) + (8,1,0)$ $\quad$ N=4

MSSM soft parameters at M_T

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$$M_a = -\frac{NB_T}{16\pi^2} g_a^2 \quad , \qquad B_H = \frac{3B_T}{16\pi^2} |\lambda_1|^2$$

$$\mathbf{A}_e = \frac{3B_T}{16\pi^2}\mathbf{Y}_e(\mathbf{Y}_T^\dagger \mathbf{Y}_T + |\lambda_1|^2) \;,\; \mathbf{A}_d = \frac{3B_T}{16\pi^2}\mathbf{Y}_d|\lambda_1|^2 \;, \quad \mathbf{A}_u = 0$$

$$\begin{aligned}
\mathbf{m}^2_{\tilde{L}} &= \left(\frac{|B_T|}{16\pi^2}\right)^2 \Big[N\left(\frac{3}{10}g_1^4 + \frac{3}{2}g_2^4\right) - \left(\frac{27}{5}g_1^2 + 21 g_2^2\right)\mathbf{Y}_T^\dagger \mathbf{Y}_T + 3|\lambda_1|^2(\mathbf{Y}_T^\dagger \mathbf{Y}_T - \mathbf{Y}_e^\dagger \mathbf{Y}_e) \\
&\qquad +3\,\mathbf{Y}_T^\dagger(\mathbf{Y}_e^\dagger \mathbf{Y}_e)^T \mathbf{Y}_T + 18\,(\mathbf{Y}_T^\dagger \mathbf{Y}_T)^2 + 3\,\mathbf{Y}_T^\dagger \mathbf{Y}_T \mathrm{Tr}(\mathbf{Y}_T^\dagger \mathbf{Y}_T)\Big] \;, \\
\mathbf{m}^2_{\tilde{e}^c} &= \left(\frac{|B_T|}{16\pi^2}\right)^2 \Big[N\left(\frac{6}{5}g_1^4\right) - 6\,\mathbf{Y}_e(\mathbf{Y}_T^\dagger \mathbf{Y}_T + |\lambda_1|^2)\mathbf{Y}_e^\dagger\Big] \;, \\
\mathbf{m}^2_{\tilde{Q}} &= \left(\frac{|B_T|}{16\pi^2}\right)^2 \Big[N\left(\frac{1}{30}g_1^4 + \frac{3}{2}g_2^4 + \frac{8}{3}g_3^4\right) - 3|\lambda_1|^2\,\mathbf{Y}_d^\dagger \mathbf{Y}_d\Big] \;, \\
\mathbf{m}^2_{\tilde{u}^c} &= \left(\frac{|B_T|}{16\pi^2}\right)^2 \Big[N\left(\frac{8}{15}g_1^4 + \frac{8}{3}g_3^4\right)\Big] \;, \\
\mathbf{m}^2_{\tilde{d}^c} &= \left(\frac{|B_T|}{16\pi^2}\right)^2 \Big[N\left(\frac{2}{15}g_1^4 + \frac{8}{3}g_3^4\right) - 6|\lambda_1|^2\,\mathbf{Y}_d \mathbf{Y}_d^\dagger\Big] \;, \\
m^2_{H_2} &= \left(\frac{|B_T|}{16\pi^2}\right)^2 \Big[N\left(\frac{3}{10}g_1^4 + \frac{3}{2}g_2^4\right)\Big] \;, \\
m^2_{H_1} &= \left(\frac{|B_T|}{16\pi^2}\right)^2 \Big[N\left(\frac{3}{10}g_1^4 + \frac{3}{2}g_2^4\right) - \left(\frac{27}{5}g_1^2 + 21 g_2^2\right)|\lambda_1|^2 + 21|\lambda_1|^4 \\
&\qquad +3|\lambda_1|^2\,\mathrm{Tr}(\mathbf{Y}_T^\dagger \mathbf{Y}_T + \mathbf{Y}_e^\dagger \mathbf{Y}_e + 3\mathbf{Y}_d^\dagger \mathbf{Y}_d) - 3\,\mathrm{Tr}(\mathbf{Y}_T^\dagger \mathbf{Y}_T \mathbf{Y}_e^\dagger \mathbf{Y}_e)\Big]
\end{aligned}$$

A flavoured variant of GMSB. Departure from flavour blindness ?

Determined by quark and lepton Yukawa matrices (MFV)…

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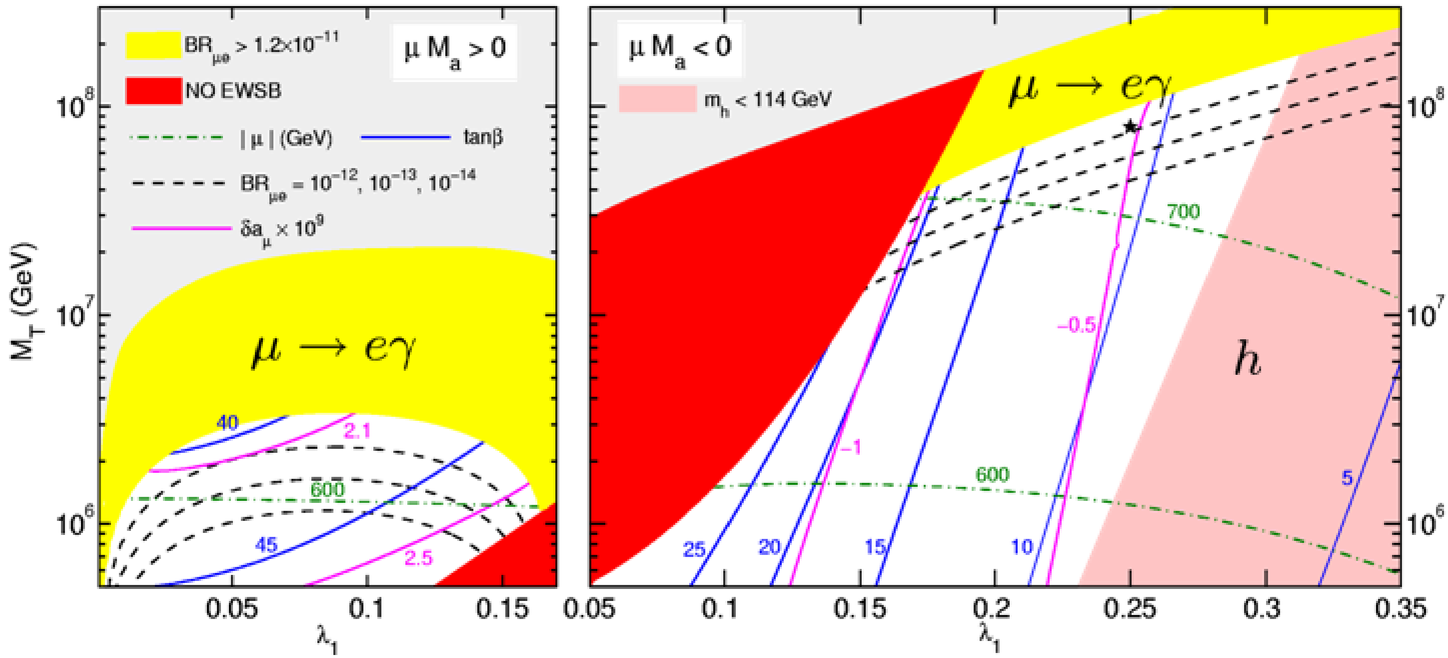


$B_T = 60$ TeV

$N = 4$

$\star\,(M_T = 8\times10^7$ GeV, $\lambda_1 = 0.25)$

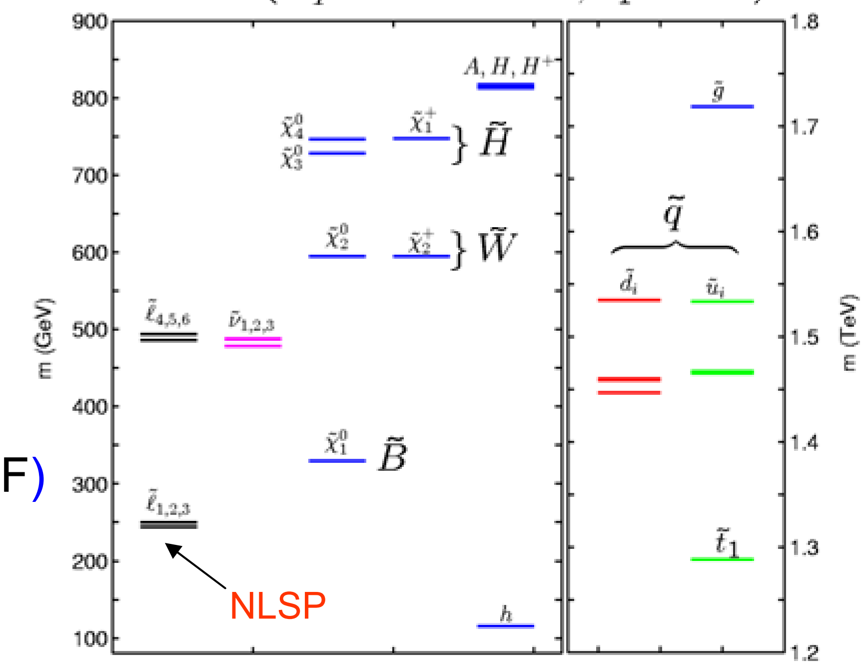
Scenario testable at colliders + LFV searches

LHC : production of $\tilde{q}$, $\tilde{g}$ + cascade decays

NLSP : $\tilde{\ell}_1 \sim \tilde{\tau}_R$, as in GMSB with N>1

$\tilde{\ell}_1 \to \tau\tilde{G}$: prompt, displaced, outside (dep. on F)

Difference with pure GMSB ? LFV signals…

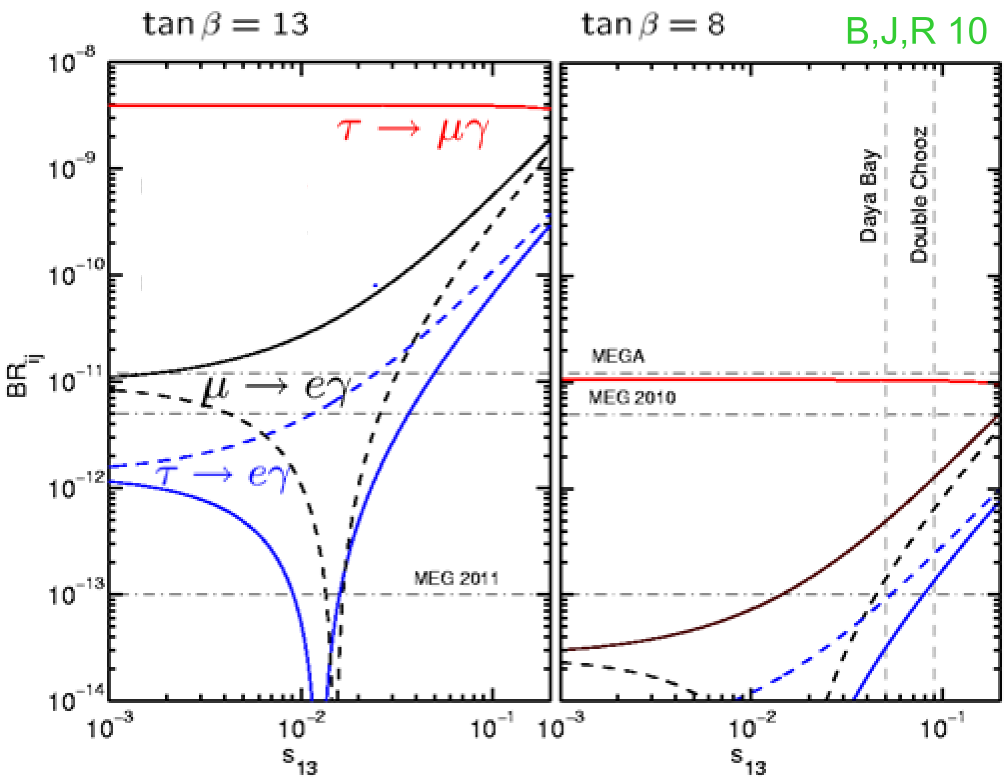


LFV signals : $\begin{cases} \text{Colliders} \quad \tilde{\chi}_2^0 \to \ell_i^+ \ell_j^- \tilde{\chi}_1^0 \quad , \ \ldots \\ \text{MEG + Flavour factories} \quad \ell_i \to \ell_j \gamma \quad , \ \ldots \end{cases}$

LFV structure : predicted, thanks to $\mathbf{Y}_T \leftrightarrow \mathbf{m}_\nu$ correspondence (virtue of type II Rossi 02)

Ex. ($\tan\beta \lesssim 20$) : $\mathrm{BR}(\ell_i \to \ell_j \gamma) \propto \left[\frac{(\mathbf{m}_L^2)_{ij}}{\tilde{m}^4} \tan\beta\right]^2 \propto \underbrace{\left(\frac{M_T}{B_T}\right)^8 (\tan\beta)^{12}}_{\text{model parameters (unflavoured)}} \underbrace{\left[\mathbf{V}(\mathbf{m}_\nu^D)^2\mathbf{V}^\dagger\right]_{ij}}_{\text{neutrino parameters (flavour)}}$

$M_T = 8 \times 10^7\,\mathrm{GeV}\ ,\ B_T = 60\,\mathrm{TeV}$



Searches for LFV decays

Measurement of θ_{13}

Summary

- Neutrino masses from K_{eff} instead of standard W_{eff}
- Important rôle of SUSY breaking
- Explicit type-II realizations
- Seesaw mediators = SUSY breaking mediators