SUSY seesaw: interplay of low energy and LHC observables

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based on work with A. Abada, J. C. Romão and A. M. Teixeira

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Motivation (1/11)

Experimental discovery of 3 very light ν_L species

- Super-Kamiokande: evidence for ν oscillations in 1998
- Oscillations $\Rightarrow$ Misalignment between Mass and Flavour basis $(W^- l_i^\dagger \nu_i) \Rightarrow$ massive ν_L
- Neutrino Oscillations $\Rightarrow$ Neutral Lepton Flavour Violation
- Potentially inducing cLFV?

Since then

- 5 out of 7 (or 9) neutrino oscillation parameters determined to good precision

$$\Delta m^2_{21}, |\Delta m^2_{31}|, \theta_{12}, \theta_{23}, \theta_{13}$$

- Missing:

$$\delta, \phi_1, \phi_2, m_\nu \quad \text{(plus hierarchy)}$$

- Very recently (Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$):

$$\theta_{13} \neq 0 \text{ at } 5.2\sigma \text{ \& b.f.p. } \theta_{13} \approx 9^o$$

Massive ν SM extensions (2/11)

Naive ν_R-extended SM

- Unnaturally small Yukawa couplings $\Leftarrow$ Smallness should be related to a symmetry enhancement in the vanishing couplings limit! ('t-Hooft)
- Very suppressed cLFV observables: $\propto m_\nu/M_W \sim 0$, e.g.

$$BR(l_i \to l_j \gamma) < 10^{-53}$$

The seesaw mechanism:

- Assumes ν is a Majorana particle
- Naturalness: smallness of m_ν/v with $Y^\nu \sim \mathcal{O}(1)$ justified by breaking Lepton Number Conservation (or $B-L$) at a very high energy scale! (close to GUT?)

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  E.g. **F**ermionic seesaws (Type-I and -III): $Y^\nu_{ij} H_u L_i F_j \to$

$$\to \left(Y^\nu \frac{1}{\Lambda} Y^{\nu T} \right)_{ij} (H_u L_i)(H_u L_j) \overset{\text{EWSB}}{\Rightarrow} \boxed{m_\nu \simeq -Y^\nu \frac{v^2}{\Lambda} Y^{\nu T}}$$

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- Appealing scenario to explain the present BAU as generated by Leptogenesis from a B-symmetric big-bang

SM seesaw or SUSY seesaw? (3/11)

SM+Seesaw?

- If motivated by $Y_\nu \sim \mathcal{O}(1)$ ($\Leftrightarrow \Lambda > 10^{10}$ GeV), it can aggravate the Higgs "fine tuning" problem!
- Hard to reconstruct the parameters of the underlying mechanism and to falsify a particular seesaw mechanism
- Does not solve the Hierarchy problem nor does it provide a dark matter candidate
- Still, very suppressed cLFV since at low energy all LFV is as in the SM

SUSY+Seesaw?

- Solves the Hierarchy problem and ameliorates the Higgs "fine tuning" problem
- Provides dark matter candidates, the most popular being the lightest neutralino (χ_1^0)
- Potentially observable cLFV since the seesaw also leaves imprint upon the charged slepton sector!

SUSY seesaw assumptions (4/11)

Choose SUSY+Seesaw type-I

- Avoid CP and Flavour problems ⇒ **cMSSM**
  ⇒ Universal soft-breaking masses
  & tri-linear soft-breaking (proportional to Yukawas)

  Sleptons: $m^2_{\tilde{L}} = m^2_{\tilde{E}} = m^2_0 \mathbf{1}, \quad A^l = A_0 Y^l \qquad$ (@ GUT)

- Mimicking the light-neutrinos: three species of $\hat{N} \sim \nu^c_L \oplus \tilde{\nu}^\dagger_R$

$$W_{\text{seesaw-I}} = \frac{1}{2}\hat{N} M_N \hat{N} - \hat{H}_u \hat{L} Y^\nu \hat{N}$$

enlarging the soft-breaking sector

$$-\mathcal{L}^{\text{soft}}_{\text{seesaw-I}} = \tilde{\nu}^\dagger_R m^2_{\tilde{\nu}_R} \tilde{\nu}_R + \left(\frac{1}{2} \tilde{\nu}^\dagger_R B_\nu \tilde{\nu}^\dagger_R - H_u \tilde{L} A^\nu \tilde{\nu}^\dagger_R + h.c. \right)$$

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  $Y^\nu \sim \mathcal{O}(1)$ & $m_{\text{soft}} \lesssim \mathcal{O}(\text{TeV})$

$$\Rightarrow M_N \gg B_\nu \Rightarrow \tilde{\nu}_R^\dagger (B_\nu + M_N) \tilde{\nu}_R^\dagger \simeq \tilde{\nu}_R^\dagger M_N \tilde{\nu}_R^\dagger$$

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Extending minimal supergravity inspired SUSY-breaking

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$$m^2_{\tilde{\nu}_R} = m_0^2 \mathbf{1}, \quad A^\nu = A_0 Y^\nu \qquad \text{(@ GUT)}$$

Y^ν is the unique source of LFV!

SUSY seesaw consequences (5/11)

At low energies:

- m_ν, after EWSB, from the unique dimension five operator
- Higher dimension operators quite suppressed by naturalness requirements on Y^ν
- Deviation from mSUGRA-inspired flavour-blindness @ GUT due to RGE induced effects

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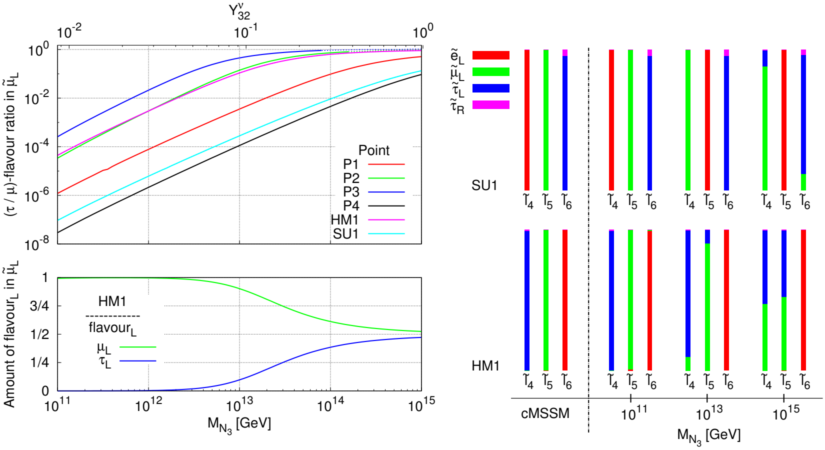
Slepton flavour mixing proportional to Y^ν

$$Y^{\nu T} v_u \simeq i\sqrt{M_N} R \sqrt{m_\nu} U^\dagger_{MNS}$$

Example of Slepton Flavour Mixing (6/11)



- Increasing the seesaw scale → natural Y^{ν} ⇒ slepton flavour mixing increases
- Usually: two-(flavour,left-handed) slepton mass eigenstates

cLFV observables (7/11)

At the **LHC** we expect to

- Discover SUSY!
- Study the Slepton sector via $\chi_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \ell^\pm \ell^\mp \chi_1^0$

Slepton Mass Splittings (SMS): $\dfrac{\Delta m}{m}(\tilde{\ell}_i, \tilde{\ell}_j) \sim \mathcal{O}(0.1\%)$

- cLFV decays $\chi_2^0 \to \ell_i^+ \ell_j^- \chi_1^0$

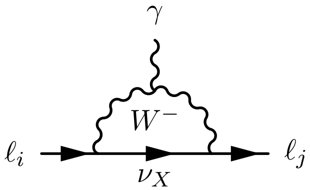
Low energy experiments we currently know and expect (e.g.)

$BR(\mu \to e\gamma)$	$< 2.4 \times 10^{-12}$ (MEG @ PSI, 2011)	10^{-13} (MEG)
$BR(\tau \to \mu\gamma)$	$< 4.5 \times 10^{-8}$ (Belle @ KEKB, 2006)	10^{-9} (SuperB)
$CR(\mu - e, \text{Ti})$	$< 4.3 \times 10^{-12}$ (SINDRUM II @ PSI, 1993)	10^{-16} (Mu2e @ Fermilab) 10^{-18} (PRISM/PRISME @ J-PARC)

SUSY seesaw cLFV (8/11)

- cLFV at low energy: $\mathrm{SM}_{\nu_R} \to$ SUSY seesaw

(SM+neutrino oscillations)



$$\propto \left(U^*_{MNS} \frac{m_\nu^2}{M_W^2} U^T_{MNS} \right)_{ij}$$

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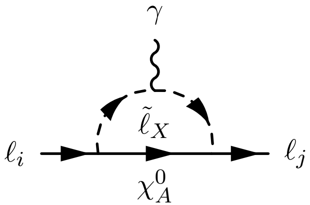

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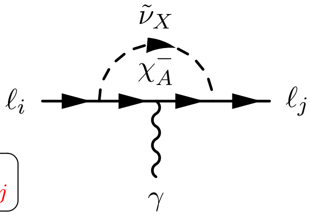

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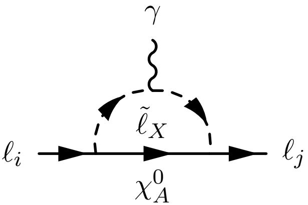

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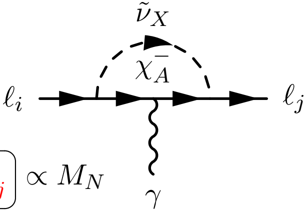

$\boxed{\propto \left(Y^{\nu *} Y^{\nu T}\right)_{ij}} \propto M_N$

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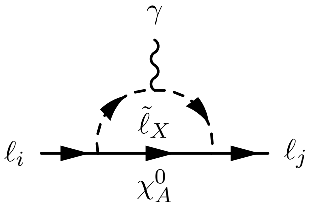

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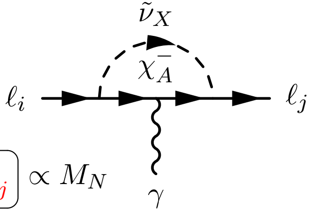

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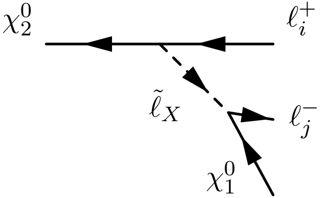
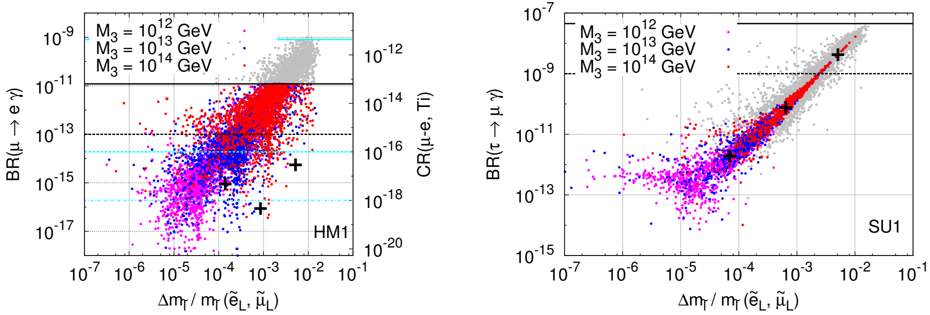
- cLFV at the LHC

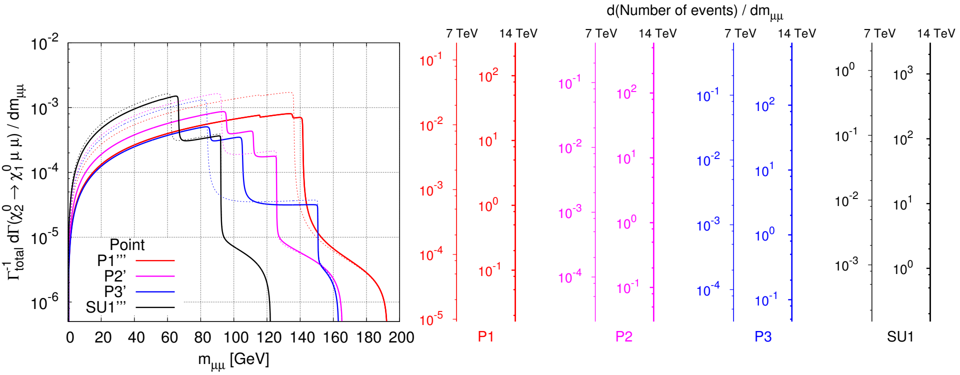


SMS and low energy cLFV interplay (9/11)



- HM1: If slepton mass splittings (SMS) are observed at LHC $\Rightarrow$ MEG should observe $\mu \to e\gamma$ & $M_3 \approx 10^{14}$ GeV (dependent on θ_{13})
- HM1: Given $\theta_{13} \approx 9^o$, observation of SMS would be incompatible with present bounds on $BR(\mu \to e\gamma)$!
- SU1: Tight correlation between SMS and low energy cLFV

Edges in leptonic invariant mass distributions (10/11)



- Two mass eigenstates ⇒ 2-edges

$$\chi_2^0 \to \tilde{\mu}^{\pm}_{L,R}\mu^{\mp} \to \mu^{\pm}\mu^{\mp}\chi_1^0$$

- 3-edges ⇒ (in)direct evidence of sleptonic cLFV

$$\chi_2^0 \to \begin{pmatrix} \tilde{\mu}^{\pm}_{L,R} \\ \tilde{\tau}^{\pm}_2 \end{pmatrix} \mu^{\mp} \to \mu^{\pm}\mu^{\mp}\chi_1^0$$

Conclusions (11/11)

Assuming minimal supergravity inspired SUSY breaking + the standard natural seesaw

- A tight correlation exists between low energy cLFV within future sensitivity and potentially observable slepton mass splittings at the LHC
- Multiple edges in flavour conserving di-leptonic invariant mass distribution already allow to hint towards sizable charged (s)lepton flavour violation

We have also conducted a similar analysis for the type-III
Work in progress: prospects for the SUSY seesaw in a e^+e^- or e^-e^- Linear Collider

Backup Slides

Point	m_0 (GeV)	$M_{1/2}$ (GeV)	A_0 (TeV)	$\tan\beta$
P1	110	528	0	10
P2	110	471	1	10
P3	137	435	-1	10
P4	490	1161	0	40
P5-HM1	180	850	0	10
P6-SU1	70	350	0	10

Table: mSUGRA benchmark points selected for the LFV analysis: m_0, $M_{1/2}$ (in GeV) and A_0 (in TeV), as well as $\tan\beta$. For all points we take $\mu > 0$. Points P5-HM1 and P6-SU1 are LHC CMS- and ATLAS-proposed benchmark points.

Point	M_{N_1} (GeV)	M_{N_2} (GeV)	M_{N_3} (GeV)	θ_{13}
P′	10^{10}	5×10^{10}	5×10^{13}	0.1°
P″	10^{10}	10^{12}	5×10^{12}	1°
P‴	10^{10}	10^{12}	10^{15}	0.1°

Table: Seesaw benchmark points. For the remaining parameters we have taken $R = 1$, and $\varphi_1 = \varphi_2 = \delta = 0$.

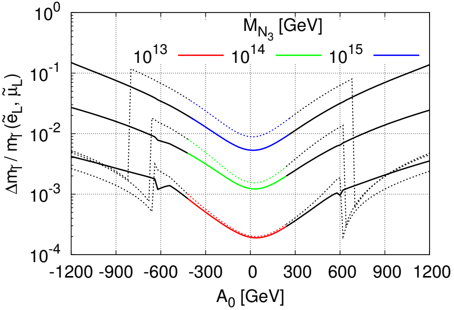


Figure: Comparison between "real" (dashed lines) and "effective" (full) slepton mass differences ($\tilde{e}_L - \tilde{\mu}_L$), normalised to the average $\tilde{e}_L, \tilde{\mu}_L$ mass, as a function of A_0 (in GeV). We have considered $R = 1$, $\theta_{13} = 0.1°$, $M_{N_1} = 10^{10}$ GeV, $M_{N_2} = 10^{11}$ GeV, taking three distinct values for $M_{N_3} = 10^{13}$ GeV (red), $M_{N_3} = 10^{14}$ GeV (green) and $M_{N_3} = 10^{15}$ GeV (blue). The mSUGRA parameters have been set as for point P1 (except for $|A_0| \leq 1.2$ TeV). Black lines denote points excluded due to the violation of at least one experimental and/or observational constraint.

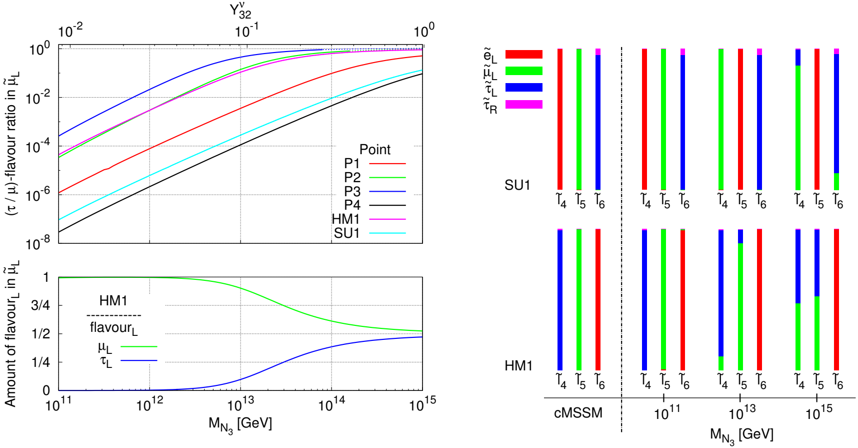


Figure: On the left, τ/μ flavour ratio in $\tilde{\mu}_L$ mass eigenstate as a function of M_{N_3} (in GeV). For the mSUGRA benchmark points of Table 1, we set $R = 1$, $\theta_{13} = 0.1^\circ$ (with $\delta = \varphi_{1,2} = 0$), and take $M_{N_1} = 10^{10}$ GeV, $M_{N_2} = 10^{11}$ GeV. On the upper axis we display the values of Y^ν_{32}. The secondary panel illustrates $|R^{\tilde{l}}_{5\mu_L}|^2$ and $|R^{\tilde{l}}_{5\tau_L}|^2$ for the same M_{N_3} interval. On the right we depict the flavour content of the 3 heavier mass eigenstates: red - $\tilde{e}_L$, green - $\tilde{\mu}_L$, blue (magenta) - $\tilde{\tau}_{L(R)}$, for P5-HM1 and P6-SU1, illustrating both the cMSSM case (on the far left) and the type-I seesaw, for three values of M_{N_3} (with the remaining seesaw parameters as before).

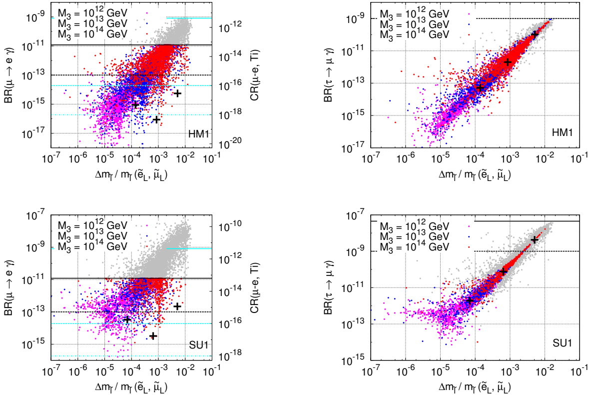


Figure: Upper left (right) panel: BR($\mu \to e\gamma$) (BR($\tau \to \mu\gamma$)) on the left y-axis as a function of the mass difference $\tilde{e}_L - \tilde{\mu}_L$, normalised to the average $\tilde{e}_L, \tilde{\mu}_L$ mass, for seesaw variations of point P5-HM1. We display the corresponding predictions of CR($\mu - e$, Ti) on the secondary right y-axis. Lower panels: same as above, but for point P6-SU1. Horizontal lines denote the corresponding current bounds/future sensitivities. The distinct coloured regions correspond to three different values of $M_{N_3} = \{10^{12},\ 10^{13},\ 10^{14}\}$ GeV. The remaining parameters were set as $M_{N_1} = 10^{10}$ GeV, $M_{N_2} = 10^{11}$ GeV, $\theta_{13} = 0.1°$ and the complex R matrix angles have been randomly varied as $|\theta_i| \in [0, \pi]$, and $\arg(\theta_i) \in [-\pi, \pi]$. The crosses correspond to the different seesaw benchmark points: from smaller to larger mass splittings one has HM1″ (SU1″), HM1′ (SU1′), HM1‴ (SU1‴), for the upper (lower) panels.

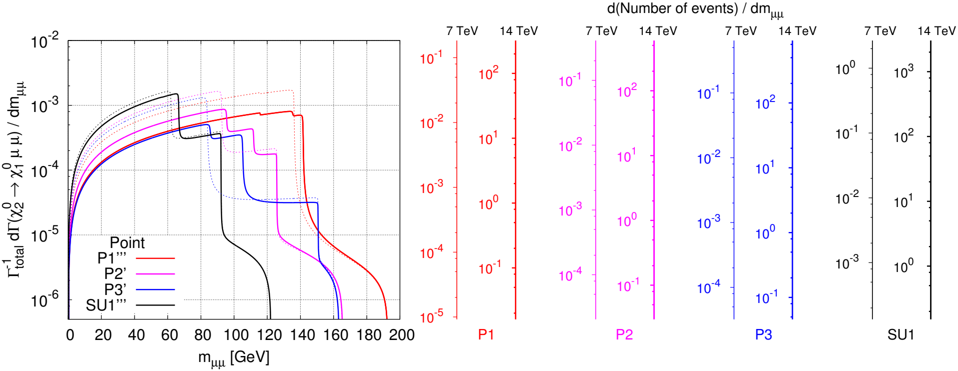


Figure: BR($\chi_2^0 \to \mu\mu\chi_1^0$) as a function of the di-muon invariant mass $m_{\mu\mu}$ (in GeV) for different SUSY seesaw points (see Tables 1 and 2). Upper panel: P1′′′ (red), P2′ (pink), P3′ (blue) and P6-SU1′′′ (black). Dotted (coloured) lines denote in both panels the curves for the corresponding cMSSM case. Secondary (right) y-axes denote the corresponding expected number of events for $\sqrt{s} = 7$ TeV and 14 TeV, respectively with $\mathcal{L} = 1$ fb^{-1} and $\mathcal{L} = 100$ fb^{-1}.