Potential of a Linear Collider for Lepton Flavour Violation studies in the SUSY seesaw

António J. R. Figueiredo
CFTP – IST / UTL & LPC-Clermont

based on arXiv:1206.2306 (JHEP 1208 (2012) 138)
with A. Abada, J. C. Romão and A. M. Teixeira

December 3, 2012

Advantages of a LC for studies in lepton physics

- Possible abundant production of new (heavy) L-charged particles
  $\rightarrow$ Leading production mechanism: **primary** (e.g. $\tilde{l}$ in SUSY) vs **cascade decays** at an hadron collider (e.g. $\chi_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp}$)

- **Cleaner events**
  $\rightarrow$ Low particle multiplicity as compared to hadron collider
  $\rightarrow$ Less leptons from hadron and top decays

- Beams easier to polarise with an accuracy $\sim \mathcal{O}(1\%)$
  $\rightarrow$ Possibility of **probing the chiral structure** of new physics
  $\rightarrow$ **Probe lepton flavour mixing** by suppressing the weak charged current bckg (e.g. $e^-_R e^-_R$ beam option)

- Adaptability: If e^+e^-, run in e^-e^- is easy and in general $\sigma(e^-e^- \rightarrow \tilde{l}^- \tilde{l}^-) > \sigma(e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^-)$

Lepton Flavour Violation

LFV sources

- U_{MNS}: Neutrino Oscillations $\Rightarrow$ massive ν_L
- Possibly in new physics models (e.g. slepton soft breaking in SUSY)

High-scale type-I SUSY seesaw
with 3 generations of RH neutrinos superfields

$\rightarrow$ A) ν is Majorana and Y^ν is natural
$\rightarrow$ B) SUSY stabilizes the weak scale
Assumptions on the high-scale SUSY seesaw:

- Avoid SUSY CP and Flavour problems $\Leftarrow$ **cMSSM**
  $\Rightarrow$ Universal soft-breaking masses
  & tri-linear soft-breaking (proportional to Yukawas)

RGE induced lepton flavour violation

$$\textbf{LL sector}: \delta m^2_{\tilde{L}} \propto -Y^{\nu *}\left(\log \frac{M_{GUT}}{M_N}\right) Y^{\nu T}\left(3m_0^2 + A_0^2\right)$$

Slepton flavour mixing proportional to Y^ν

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

LC physics potential studies for SLFV

Past studies in SLFV

- Model independent LL and RR mixing in a e^+e^- collider
  (arXiv:1106.4903 E. Carquín et al [post-LHC 2010])
- Seesaw as origin of LL mixing in a $e^{\pm}e^-$ collider
  (arXiv:hep-ph/0401243, 0310053 F. Deppisch et al [pre-LHC])
- Focused primarily on τ-μ FV motivated by large θ_{atm}

Our analysis

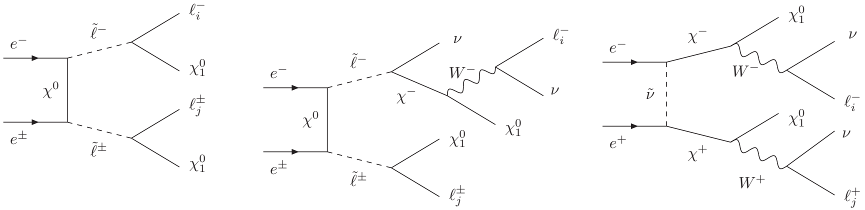
- Address the **potential of beam polarisation for LFV** studies
- **Seesaw as origin** of LL **mixing** with large reactor angle ($\approx 10^{\text{o}}$)
- Focus $\boldsymbol{\mu}$**-**$\boldsymbol{e}$ **FV** and its discovery potential
- Take into account new LFV bounds

$$\text{BR}(\mu \to e\gamma) < 2.4 \times 10^{-12} \text{ (@ 90\% C.L.)}$$

Our analysis

- 2-body sparticle production processes

$$e^+e^- \to \tilde{l}_i^+\tilde{l}_j^-,\chi_A^0\chi_B^0,\chi_A^+\chi_B^-,\tilde{\nu}_i^*\tilde{\nu}_j,\cancel{\tilde{\nu}_i\tilde{\nu}_j}$$
$$e^-e^- \to \tilde{l}_i^-\tilde{l}_j^-,\cancel{\chi_A^-\chi_B^-}$$



Signal: $e^+\mu^- + 2\chi_1^0$

SUSY bckg $\lesssim 5$ fb	B_1 (0τ)	$e^+\mu^- + (\bar{\nu}\nu, 2\bar{\nu}\nu) + 2\chi_1^0$
	B_2 $(\tau{+}0\nu)$	$(e^+\tau^-, \tau^+\mu^-, \tau^+\tau^-) + 2\chi_1^0$
	B_3 $(\tau{+}2\nu)$	$(e^+\tau^-, \tau^+\mu^-) + \bar{\nu}\nu + 2\chi_1^0$
SM bckg $\approx 10^2$ fb	W-strahlung	$W^-(e^+,\tau^+)\nu$, $W^+(\mu^-,\tau^-)\bar{\nu}$
	W-pair	W^+W^-
	τ-pair	$\tau^+\tau^-$

$\to$ Leptonically decaying τs, Ws and Zs

Benchmark spectrum examples

F points (spectrum: slepton > EW gaugino)

- $m_{\tilde{l},\tilde{\nu}} > m_{\chi_2^0,\chi_1^+}$ and $m_{\chi_2^0,\chi_1^+} > m_{\tilde{\tau}_1}$
- Dominant decays:
  - $(\tilde{l}^-,\tilde{\nu}^*) \to \chi_2^0(l^-,\bar{\nu}), \chi_1^-(\nu,l^+), (l^-,\bar{\nu})\chi_1^0$
  - $\chi_1^- \to \tilde{\tau}_1^-\bar{\nu}, W^-\chi_1^0$
  - $\chi_2^0 \to \tilde{\tau}_1^-\tau^+, Z\chi_1^0$

→ Fs have τ-dominated SUSY bckg

C points (spectrum: EW gaugino > slepton)

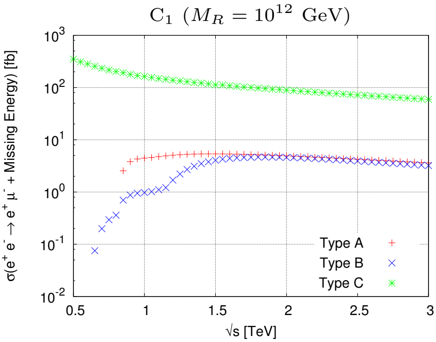
- $m_{\tilde{l},\tilde{\nu}} < m_{\chi_2^0,\chi_1^+}$ and $m_{\chi_1^0} \lesssim m_{\tilde{\tau}_1}$
- Dominant decays:
  - $\chi_1^- \to (\tilde{l}^-\bar{\nu}, \tilde{\nu}^* l^-)$
  - $\chi_2^0 \to \tilde{l}^\pm l^\mp, \tilde{\nu}\bar{\nu}, \tilde{\nu}^*\nu$
  - $(\tilde{l}^-,\tilde{\nu}) \to (l^-,\nu)\chi_1^0$

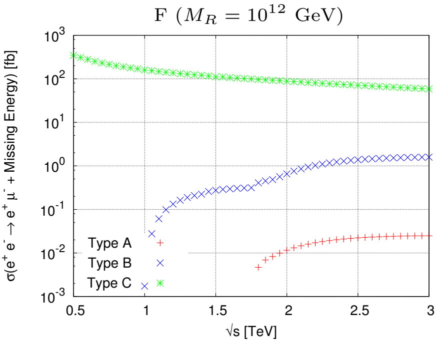
→ Cs have more expected signal compared to Fs:

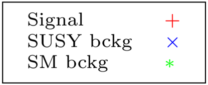
$$\Gamma(\tilde{l})_F > \Gamma(\tilde{l})_C \Rightarrow \mathrm{BR}(\tilde{l} \to l\chi_1^0)_F < \mathrm{BR}(\tilde{l} \to l\chi_1^0)_C$$

e.g. $(\mathrm{BR}(\tilde{e}_L \to e\chi_1^0)_C \;/\; \mathrm{BR}(\tilde{e}_L \to e\chi_1^0)_F)^2 \approx \mathcal{O}(10)$

e^+e^- signal & background







- SM is the main source of bckg
- SUSY bckg dominates (is comparable to) the signal in Fs (Cs)

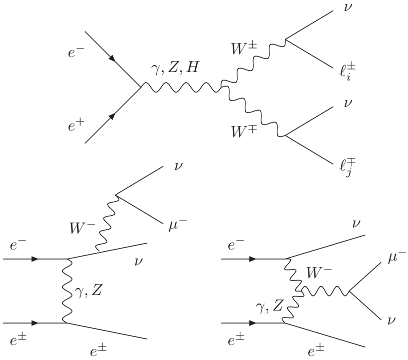
EW Gaugino–Slepton hierarchy can hint on whether:

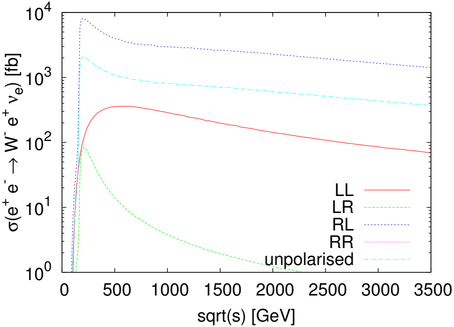
- signal is smaller than the SUSY bckg
- existence of $\sqrt{s}$ window w/ very small SUSY bckg (vs signal)

Polarisation: maximize significance

- Flavour mixing in the LL sector & $e^{\pm}e^{-} \to e^{\pm}\mu^{-}$ $\boxed{\Rightarrow \text{initial } e^{-} \to e^{-}_{L}}$
- And to minimize W-strahlung $\boxed{\Rightarrow \text{initial } e^{+} \to e^{+}_{L}}$
- $e^{+}e^{-} \to W^{+}W^{-}$ suppression:
  s-channel with $e^{+}_{L}e^{-}_{L}$ or $e^{+}_{R}e^{-}_{R}$ and t-channel with $e^{+} \to e^{+}_{L}$

$$\boxed{\Rightarrow \sigma(e^{+}_{L}e^{-}_{L} \to W^{+}W^{-}) \simeq 0}$$





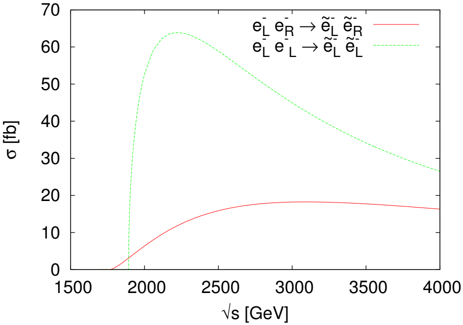
Polarisation: maximize significance

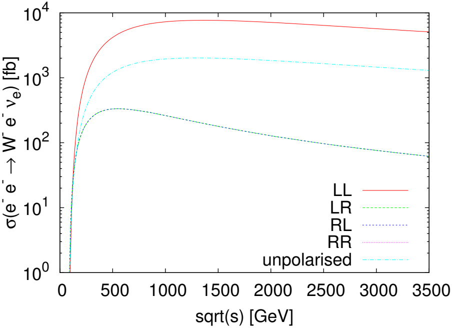
What about the other e^- in e^-e^-?

- $e_L^- e_L^-$ maximizes the signal (w/o suppressing W-strahlung bckg)
- $e_L^- e_R^-$ minimizes the W-strahlung while reducing the signal

$$\sigma(e_L^- e_L^- \to \text{signal}) \approx 2 \times \sigma(e_L^- e_R^- \to \text{signal}) \left(\frac{\sigma(e_L^- e_L^- \to \tilde{e}_L^- \tilde{e}_L^-)}{\sigma(e_L^- e_R^- \to \tilde{e}_L^- \tilde{e}_R^-)} \right)$$

$e_L^- e_L^-$ vs $e_L^- e_R^-$ significance: depends on $\sqrt{s}$





C$_1$: $e_L^+ e_L^-$ beam option

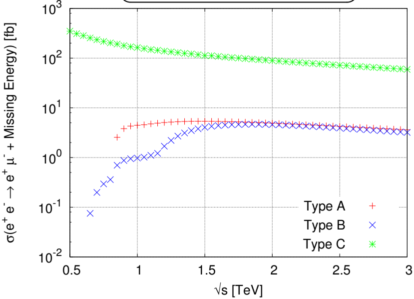
Dominant SUSY bckg sources (ordered by threshold)

1. ~~$\tilde{\tau}_1^+ \tilde{\tau}_1^-$~~
2. ~~$\tilde{\tau}_2^+ \tilde{\tau}_2^-$~~, $\tilde{e}_R^+ (\tilde{\ell}_L^-, \tilde{\tau}_2^-)$ (FV)
3. ~~$\chi_1^+ \chi_1^-$~~, ~~$\chi_2^0 \chi_2^0$~~

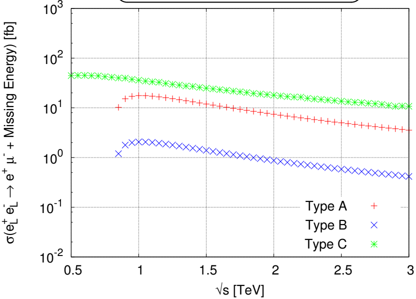
$M_R = 10^{12}$ GeV

Signal	+
SUSY bckg	×
SM bckg	*

Unpolarised beams

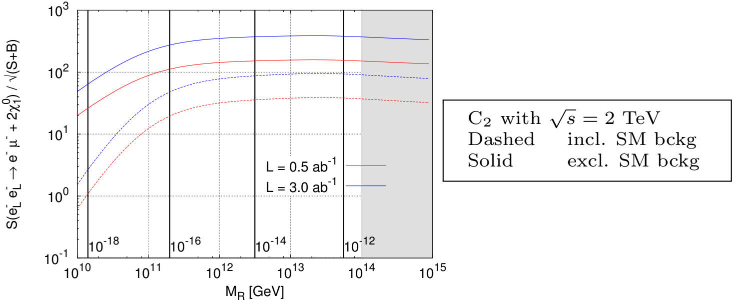


LL polarised beams



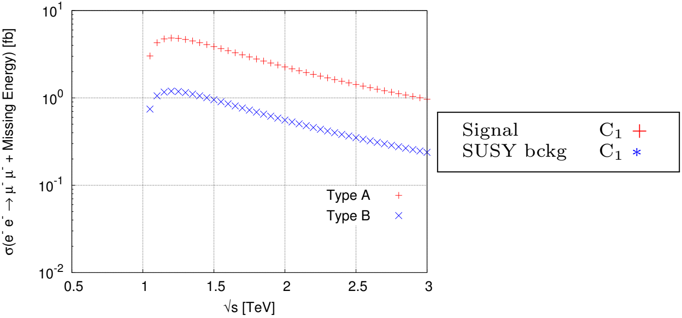
- Signal & SUSY bckg sources: $e_L^+ e_L^- \to \tilde{e}_R^+ \tilde{l}_L^- \to e^+ (\mu^-, \tau^-) \, 2\chi_1^0$
- Signal vs SUSY bckg difference: $\tilde{e}_L$–$\tilde{\mu}_L$ mix $\approx$ $\tilde{e}_L$–$\tilde{\tau}_L$ mix
  $\Rightarrow \sigma(e_L^+ e_L^- \to \text{SUSY bckg}) / \sigma(e_L^+ e_L^- \to \text{signal}) \approx \mathrm{BR}(\tau \to \mu \bar{\nu} \nu)$

Signal significance and seesaw scale



- If $\boldsymbol{M_R}$ **is high** and the **SUSY** spectrum is **accessible @ LC**: **$\boldsymbol{\mu}$-$\boldsymbol{e}$ cLFV can be discovered**
- If **$\boldsymbol{\mu}$-$\boldsymbol{e}$ cLFV** is indeed **discovered** at LC: **hint on $\boldsymbol{M_R}$** (provided the seesaw is the unique source of cLFV)
- If **$\boldsymbol{\mu}$-$\boldsymbol{e}$ cLFV** at LC is **sizable**: **BR($\boldsymbol{\mu \to e\gamma}$) observable** @ future low energy cLFV experiments

Muonic $\Delta L = 2$ LFV



- Signal smaller than $e^-e^- \to e^-\mu^-$ (competitive with $e^+e^- \to e^+\mu^-$)
- Suppress W-strahlung bckg: $e^-e^- \to W^-W^-\nu\nu \to \mu^-\mu^- 2(\bar{\nu}\nu)$ becomes the main SM bckg $\approx \mathcal{O}(1)$ fb
- SUSY bckg from $\tilde{e}_R^-\tilde{l}_L^-$ is suppressed
- **Profit** from excellent **muon tagging** and **reconstruction efficiencies**
- **Very clean signal**

Conclusions

- New physics beyond the SM can provide sources of LFV (other than neutrino oscillations)
- Study potential of LC in discovering and probing new physics (focus on μ-e FV)
- SUSY seesaw induced **μ-e cLFV is discoverable for an LC-accessible SUSY spectrum**, $\mathcal{L} = 0.5\ \text{ab}^{-1}$ and a sufficiently high seesaw scale
- cLFV studies @ LC can **probe SUSY seesaw** (if unique source of cLFV)
- e^-e^- beam option has better discovery prospects than e^+e^-
- $e^-e^- \to \mu^-\mu^-$ offers a cleaner cLFV signal than $\to e^-\mu^-$
- **Beam polarisation**: **instrumental** to suppress SUSY and SM bckg [$e^+_L e^-_L$, $e^-_L e^-_R$, $e^-_L e^-_L$: preferred options]

Backup Slides

cMSSM benchmark points

	C_1	C_2	F'	F
m_0 (GeV)	150	200	600	750
$M_{1/2}$ (GeV)	727.9	949.2	667.0	872.1
$\tan\beta$	10	10	52	52
A_0 (GeV)	0	0	0	0
sign(μ)	1	1	1	1

Table: Representative points used in the numerical analysis.

Benchmark spectra

	C_1	C_2	F'	F
χ_1^0	303.7	401.1	279.9	370.6
χ_2^0	574.2	756.9	530.3	700.9
χ_3^0	-882.3	-1114.7	-786.5	-993.9
χ_4^0	893.5	1124.4	797.5	1003.8
$\chi_1^\pm$	574.4	757.1	530.5	701.1
$\chi_2^\pm$	893.8	1124.5	798.3	1004.2
$(\tilde{\nu}_e)_L$	504.2	657.9	742.4	943.3
$(\tilde{\nu}_\mu)_L$	503.9	657.6	651.0	830.0
$(\tilde{\nu}_\tau)_L$	502.1	655.2	741.8	942.5
$\tilde{e}_R$	314.4	409.7	650.3	817.6
$\tilde{e}_L$	510.7	662.9	747.0	946.9
$\tilde{\mu}_R$	314.4	409.7	649.5	816.6
$\tilde{\mu}_L$	509.9	662.6	746.5	946.3
$\tilde{\tau}_1$	306.5	401.1	383.6	495.8
$\tilde{\tau}_2$	510.6	661.4	672.8	847.4

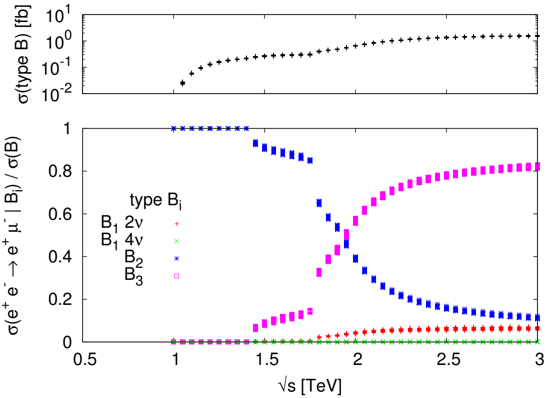
Table: Slepton, neutralino and chargino mass spectrum (in GeV) for the points of Table 1.

F: SUSY background

F

1. $\tilde{\tau}_1^+\tilde{\tau}_1^-$ 2. $\chi_1^+\chi_1^-$, $\chi_2^0\chi_2^0$
3. $\underline{\tilde{e}_R^+\tilde{e}_L^-}$ 4. $\underline{\tilde{\nu}_e^*\tilde{\nu}_e}$, $\underline{\tilde{e}_L^+\tilde{e}_L^-}$

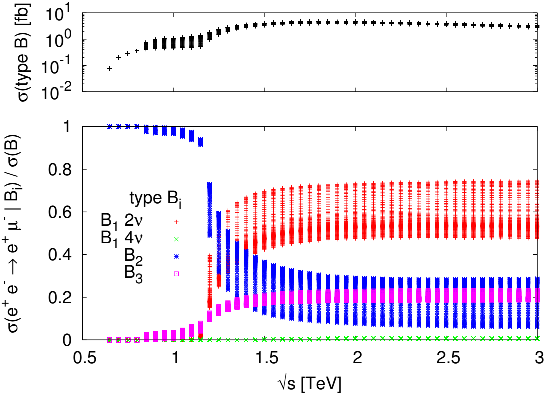
→ F has τ-dominated SUSY bckg



C_1 SUSY background

C_1

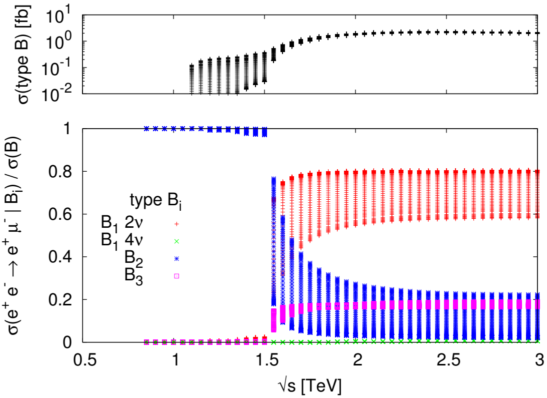
1. $\tilde{\tau}_1^+ \tilde{\tau}_1^-$
2. $\tilde{\tau}_2^+ \tilde{\tau}_2^-$, $\tilde{e}_R^+ (\tilde{\ell}_L^-, \tilde{\tau}_2^-)$ (FV) $\nearrow (\tau^- \chi_1^0, \tilde{\tau}_1^- Z)$
3. $\underline{\chi_1^+ \chi_1^-}$, $\underline{\chi_2^0 \chi_2^0}$



C_2 SUSY background

C_2 ($\tilde{\tau}_1$ exits the detector w/o decaying)

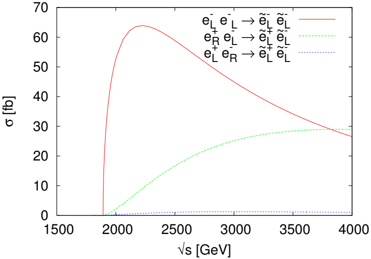
1. $\tilde{e}_R^+(\tilde{\ell}_L^-, \tilde{\tau}_2^-)$ (FV)
2. $\chi_2^0\chi_1^0(\to \tau^+\tau^- 2\chi_1^0)$
3. $\tilde{\tau}_2^+\tilde{\tau}_2^-$
4. $\underline{\chi_1^+\chi_1^-}$, $\underline{\chi_2^0\chi_2^0}$



LC physics potential studies

Polarisation studies (see e.g. arXiv:hep-ph/9803319)

- Polarisation with threshold scans to determine slepton mass (sensitiveness $\propto d\sigma/ds$ near threshold: β vs β^3)



  (other: $e^+e^- \to \chi_1^+\chi_1^-$, $e^-\gamma \to \tilde{\nu}_e\chi_1^-$, ...)

- Charged and neutral **slepton mass determination**: constrain $\mathbf{tan}\,\boldsymbol{\beta}$ ($m^2_{\tilde{\nu}} - m^2_{\tilde{l}_L} = M_W^2 \cos 2\beta$ @ tree-level)
- Constrain the **exchanged particle mass** with accuracy $\propto |d\sigma/dm|$
- **Probe lepton flavour mixing** by suppressing the weak charged current bckg using $e^-_R e^-_R$ beam option

High-scale SUSY seesaw at low energy

(m_ν, after EWSB, from the unique dimension five operator)

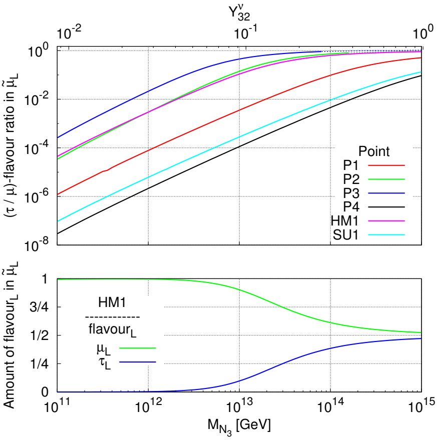
- Higher dimension operators quite suppressed by naturalness requirements on Y^ν
- Deviation from mSUGRA-inspired flavour-blindness @ GUT due to RGE induced effects

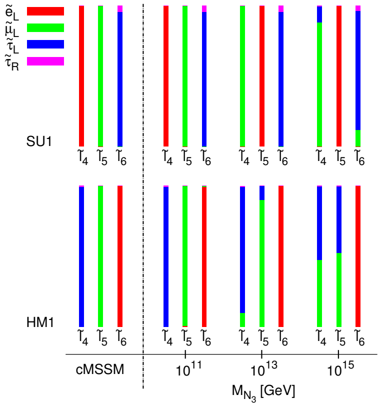
$$\textbf{LL sector}: \ \delta m^2_{\tilde{L}} \propto -Y^{\nu *} \left(\log \frac{M_{GUT}}{M_N} \right) Y^{\nu T} \left(3m_0^2 + A_0^2 \right)$$

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





(arXiv:1007.4833 A. Abada et al)

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