Phenomenology of LFV at low-energies and at the LHC: strategies to probe the SUSY seesaw

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Understanding lepton flavour mixing...

- **Flavour violated** in **neutral leptons** ($\nu_i \leftrightarrow \nu_j$ oscillations)

  What about **charged lepton flavour violation??** $\ell_i \to \ell_j \gamma$, $\ell_i \to 3\ell_j$, ...

  Huge **experimental effort:** **MEG, PRISM/PRIME, SuperB..** ever observable??

$\rightsquigarrow$ An *effective* "hint": $\mathrm{BR}(\mu \to e\gamma) = 10^{-11} \times (2\ \mathrm{TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2$

- cLFV $\Leftrightarrow$ **New Physics** (beyond SM_{ν_R}) $+$ **Lepton Flavour Mixing**

  $\Lambda \sim \mathcal{O}(\mathrm{TeV})$ (testable at LHC) — non-negligible $\theta_{\ell_i \ell_j}$ (suggested by neutrino mixing)

charged LFV: **complementary** to direct **LHC searches** and ν-dedicated exps

cLFV: complementary to LHC searches and ν experiments

- **Here:** use **low-energy LFV observables** (e.g. BR($\ell_i \to \ell_j \gamma$)) and
  high-energy data (e.g. SUSY kinematical observables at the LHC)

$\Rightarrow$ Use **cLFV complementarity role** to **disentangle** model of **New Physics**

		New Physics (beyond SM_{ν_R})	+	Lepton Flavour Mixing
cLFV	$\Leftrightarrow$	**mSUGRA-like SUSY** $\rightsquigarrow$ **cMSSM**		**seesaw mechanism**
		hierarchy problem, dark matter, ...		account for ν masses and mixings
		$\Rightarrow$ testable at LHC		$\Rightarrow$ explain ν-data

- **Probe type-I seesaw** as mechanism of **lepton flavour violation** in the **cMSSM**

cMSSM=constrained Minimal Supersymmetric SM

Type-I SUSY seesaw

- **MSSM + 3 $\hat{N}_R$** $\quad \mathcal{W}^{\text{lepton}}_{\text{MSSM}_R} = \hat{N}^c\, Y^\nu\, \hat{L}\, \hat{H}_2 + \hat{E}^c\, Y^l\, \hat{L}\, \hat{H}_1 + \frac{1}{2}\hat{N}^c\, M_N\, \hat{N}^c$

  $Y^\ell = Y_\ell^{\text{diag}}$ and $M_N = M_N^{\text{diag}}$

  $$-\mathcal{L}^{\text{slepton}} = -\mathcal{L}^{\text{slepton}}_{\text{cMSSM}} + m_0^2 \tilde{\nu}_R\, \tilde{\nu}_R^* + (A_0 Y^\nu H_2\, \tilde{\nu}_L\, \tilde{\nu}_R^* + B_\nu \tilde{\nu}_R\, \tilde{\nu}_R + \text{H.c.})$$

- $m_\nu = -v_2^2\, Y^\nu\, \frac{1}{M_N}\, Y^{\nu T}$ **Seesaw equation** (limit $m_D = Y^\nu v_2 \ll M_N$)

- $v_2 Y^\nu = i \sqrt{M_N^{\text{diag}}}\, R \sqrt{m_\nu^{\text{diag}}}\, U^\dagger_{\text{MNS}}$ (at M_N)

  [Casas-Ibarra parameterization]

  - $U_{\text{MNS}}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \varphi_{1,2})$
  - $m_\nu^{\text{diag}}(\Delta m^2_{\text{sol}}, \Delta m^2_{\text{atm}}, \sum m_{\nu_i})$
  - M_N^{diag} heavy neutrino masses
  - $R(\theta_i)$ 3 complex angles

- Even for **universal** soft-breaking terms **RGE running of** Y^ν $(M_{\text{GUT}} \to M_N)$

  induces flavour-violating terms in slepton soft-breaking masses

  $$(\Delta m^2_{\tilde{L}})_{ij} = -\frac{1}{8\,\pi^2}\,(3\, m_0^2 + A_0^2)\,(Y^{\nu\dagger}\, L\, Y^\nu)_{ij} \qquad L = \log(M_{\text{GUT}}/M_N)$$

  [Borzumati, Masiero; Hisano; ...]

Type-I SUSY seesaw: slepton masses

- **Charged slepton masses** in the **MSSM**$_R$ $\to -\mathcal{L}^{\tilde\ell}_{\text{mass}} \supset \tilde\ell^*_{L,R}\ \boldsymbol{M^2_{\tilde\ell}}\ \tilde\ell_{L,R}$ $\qquad [6\times 6]$

$$\boldsymbol{M^2_{\tilde\ell}} = \begin{bmatrix} LL_{ij} & LR_{ij} \\ (LR)^*_{ji} & RR_{ij} \end{bmatrix} \qquad \text{e.g.} \quad \boldsymbol{M^{ij\,2}_{LL}} = \boldsymbol{m^2_{\tilde L, ij}} + m^2_{\ell\, i} + M^2_Z \cos 2\beta \left(-\tfrac{1}{2} + \sin^2\theta_W\right)$$

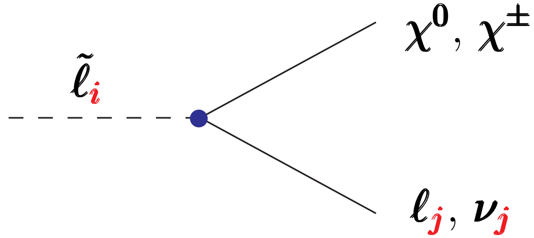
- Under **mSUGRA-inspired GUT universality** conditions:

$$\boldsymbol{m^2_{\tilde L, ij}} = \begin{bmatrix} \boldsymbol{m_0^2} & 0 & 0 \\ 0 & \boldsymbol{m_0^2} & 0 \\ 0 & 0 & \boldsymbol{m_0^2} \end{bmatrix}_{(@M_{\text{GUT}})} \longrightarrow (\boldsymbol{m^2_{\tilde L}})^{\text{EW}}_{ij} = \left(m_0^2 + 0.5\, M^2_{1/2} - m_0^2\, |y|\, (Y^l)^2_{ij}\right) \boldsymbol{\delta_{ij}} + (\Delta m^2_{\tilde L})_{ij}$$

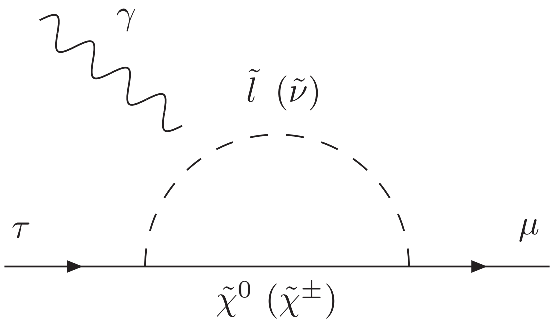
$$(\Delta m^2_{\tilde L})_{ij} \propto \boldsymbol{(Y^{\nu\dagger}\, L\, Y^\nu)_{ij}}$$

$\boldsymbol{M^{ij\,2}_{LL,LR} \neq 0 \Rightarrow (M^2_{\tilde\ell})_{ij} \neq 0!}$

$$R^{\tilde\ell\,\dagger}\, M^2_{\tilde\ell}\, R^{\tilde\ell} = \text{diag}(m^2_{\tilde\ell_i}) \qquad \boldsymbol{R^{\tilde\ell} \neq 1!}$$



$\bullet \propto R^{\tilde\ell}_{ij}$



- Expect many interesting **flavour violating** transitions in **charged leptons!**

[“observables” $\propto \boldsymbol{(Y^\nu)^n}$; $Y^\nu \sim \mathcal{O}(1) \Rightarrow \boldsymbol{M_N \sim 10^{15}}$ **GeV**]

One source of flavour violation

- **mSUGRA-like SUSY seesaw: Y^ν unique source of FV**

  (all observables strongly related)

  ⋆ **low-energies:** $l_j \to l_i\gamma$, $l_j \to 3l_i$, $\mu - e$ **in Nuclei**

  ⇒ **large rates potentially observable! (MEG, PRISM/PRIME, ...)**

  ⋆ **high-energies:** study **charged sleptons** from $\chi_2^0 \to \ell^\pm \ell^\mp \chi_1^0$ decays

  ⇒ **possibily sizable** $\tilde{e} - \tilde{\mu}$ **mass differences**, multiple **edges**,

  direct FV decays $\chi_2^0 \to \ell_i \ell_j \chi_1^0$, ...

  [also effective LFV - Buras et al, '09]

- **If LFV indeed observable (large BRs & CR),**

  expect interesting slepton phenomena at the LHC!

  ... strengthen / disfavour seesaw hypothesis !

Slepton mass reconstruction at the LHC

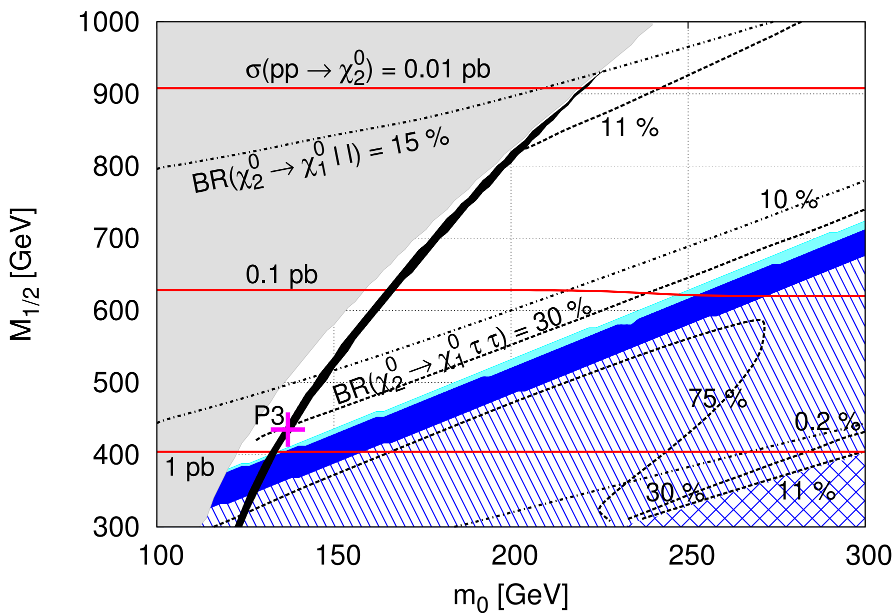
- Focus on **di-lepton invariant mass distributions** from $\chi_2^0 \to \tilde{\ell}_{L,R}\,\ell \to \chi_1^0 \ell\,\ell$

  If **on-shell sleptons** & **isolated** leptons with **large** $p_T > 10$ **GeV**

$$\Rightarrow m_{\ell\ell} = \frac{1}{m_{\tilde{\ell}}}\sqrt{\left(m^2_{\chi_2^0} - m^2_{\tilde{\ell}}\right)\left(m^2_{\tilde{\ell}} - m^2_{\chi_1^0}\right)} \quad \sim \mathbf{0.1\%} \text{ edge precision at LHC}$$

$$\Rightarrow \textbf{infer } \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j) = \frac{|m_{\tilde{\ell}_i} - m_{\tilde{\ell}_j}|}{<m_{\tilde{\ell}_{i,j}}>} \rightsquigarrow \textbf{LHC:} \quad \begin{array}{lcl} \Delta m/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L) & \to & \mathcal{O}(0.1\%) \\ \Delta m/m_{\tilde{\ell}}(\tilde{\mu}_L, \tilde{\tau}_2) & \to & \mathcal{O}(1\%) \end{array}$$

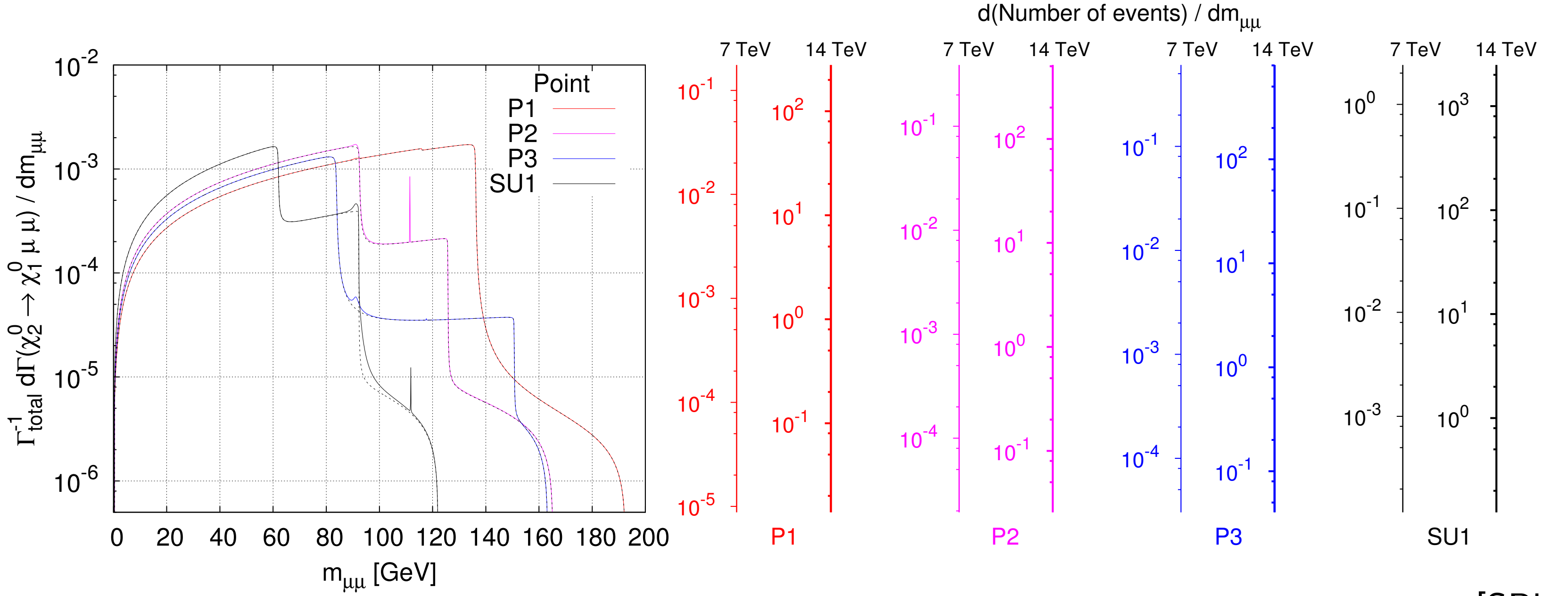
- **cMSSM viability windows:** large χ_2^0 production rates, sizable BR$(\chi_2^0 \to \chi_1^0 \ell\,\ell)$, Ωh^2...



Point	m_0	$M_{1/2}$	A_0	$\tan\beta$
P1	110	528	0	10
P2	110	471	1000	10
P3	137	435	-1000	10
P4	490	1161	0	40
CMS-HM1	180	850	0	10
ATLAS-SU1	70	350	0	10

Proposed cMSSM study points..

Di-muon invariant mass distributions: cMSSM (without seesaw)



[SPheno & Prospino]

Point	$m_{\chi^0_2}$	$m_{\chi^0_1}$	$m_{\tilde{\ell}_L}$	$m_{\tilde{\ell}_R}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\tau}_1}$	$< m_{\tilde{q}} >$	m_h
P1	410	217	374	231	375	224	1064	115.1
P2	356	191	338	212	335	198	963	111.4
P3	342	179	327	218	325	186	877	117.6
ATLAS-SU1	262	140	251	156	254	147	733	111.8

- **Double-triangular distributions:** intermediate $\tilde{\mu}_L$ and $\tilde{\mu}_R$ in $\chi^0_2 \to \chi^0_1 \mu\mu$
- Approximately **superimposed** $\tilde{\ell}_{L,R}$ **edges** for $m_{\mu\mu}$ and m_{ee}: "degenerate" $\tilde{\mu}, \tilde{e}$

LFV at the LHC

- **cMSSM:** nearly **degenerate $\tilde{\mu}, \tilde{e}$** $\quad \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \lesssim \mathcal{O}(10^{-3})$ (small RGE & LR-mixing)

- **Under a** type-I SUSY seesaw (assuming e.g. large $Y^{\nu}_{23,33}$)

$$\Rightarrow \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \approx \frac{1}{2} \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\mu}_L, \tilde{\tau}_2) \approx \frac{1}{2} \left| \frac{(\Delta m^2_{\tilde{L}})_{23}}{(m^2_{\tilde{L}})_{33}} \right| \qquad \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L) \sim \mathcal{O}(10\%)$$

Predominantly **LL effect:** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}^i_L, \tilde{\ell}^j_L) \gg \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}^i_R, \tilde{\ell}^j_R)$

$\Rightarrow$ Correlation BR$(\ell_i \to \ell_j \gamma) \leftrightarrow \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j)$ **[High- low-energy complementarity]**

e.g. $\frac{\text{BR}(\tau \to \mu \gamma)}{\text{BR}(\tau \to \nu_\tau \ell \nu_\ell)} \approx f(\text{EW, mSUGRA})\, L_{33}\, M_{N_3}\, m_{\nu_3}\, \sin 2\theta_{23} \times \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\mu}_L, \tilde{\tau}_2)$

$\Rightarrow$ New edges in di-lepton mass distributions: $\chi^0_2 \to \left\{ \begin{array}{l} \tilde{\ell}^i_L\, \ell_i \\ \tilde{\ell}^i_R\, \ell_i \\ \tilde{\ell}^j_X\, \ell_i \end{array} \right\} \to \chi^0_1\, \ell_i\, \ell_i$

$\Rightarrow$ Possible direct FV in **neutralino and slepton decays:** $\chi^0_2 \to \ell_i\, \ell_j\, \chi^0_1$

LFV at low- and high-energies: strategies to probe seesaw

Working **hypothesis**: mSUGRA-like **cMSSM** and **type-I seesaw**

discovery of **SUSY at LHC** (reconstruction of $\mathcal{L}_{\text{SUSY}}$...)

$\Rightarrow$ **Interplay** of several **low-energy measurements** (θ_{13}, BR, CR)

hint towards SUSY seesaw parameters [Antusch et al$_{|\text{AMT}}$ '06, Arganda et al$_{|\text{AMT}}$ '07]

Furthermore: $\Delta m(\tilde{e}_L, \tilde{\mu}_L)$, $\Delta m(\tilde{\mu}_L, \tilde{\tau}_2)$ within LHC reach, *correlated with*

BR($\mu \to e\gamma$) & CR($\mu - e$, Ti) & BR($\tau \to \mu\gamma$) within **future sensitivity**

$\Rightarrow$ **Intensely explore synergy** of **LFV at low-energies and at the LHC!**

[Abada et al$_{|\text{AMT}}$ '10]

- $\Delta m(\tilde{e}_L, \tilde{\mu}_L)$, $(\tilde{\mu}_L, \tilde{\tau}_2)|_{\text{LHC}}$ and compatible BR$(\mu \to e\gamma)|_{\text{MEG}}$, BR$(\tau \to \mu\gamma)|_{\text{SuperB}}$

  $\Rightarrow$ **strengthen seesaw hypothesis**

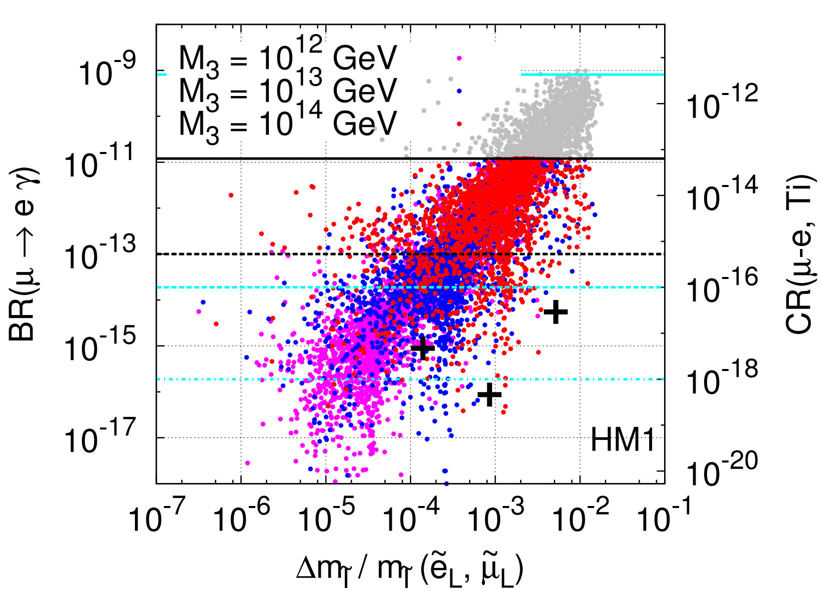
- $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}}$ **excluded by BRs, CR** or **observed BRs/CR** for **negligible Δm**

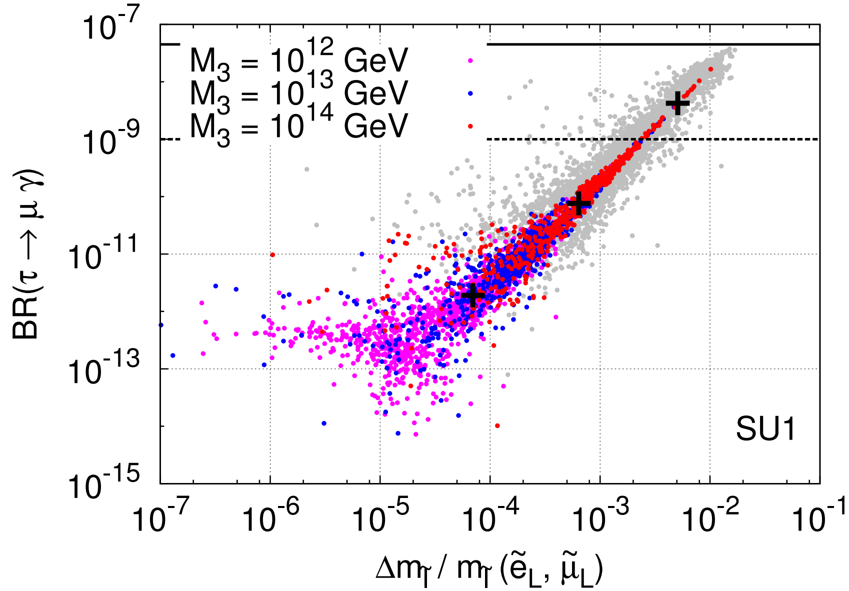
  $\Rightarrow$ **suggests distinct** (or additional) **source of flavour violation**

LFV at low- and high-energies: general overview

mSUGRA: CMS point HM1 {180, 850, 0, 10, +1} **and ATLAS point SU1** {70, 350, 0, 10, +1}

Seesaw: general R (vary $|\theta_i|, \arg\theta_i \in [-\pi,\pi]$), $M_{N_3} = 10^{12,13,14}$ GeV; $\theta_{13} = 0.1^\circ$





If type-I seesaw indeed at work and **SUSY** $\sim$ **HM1, SU1** (mSUGRA):

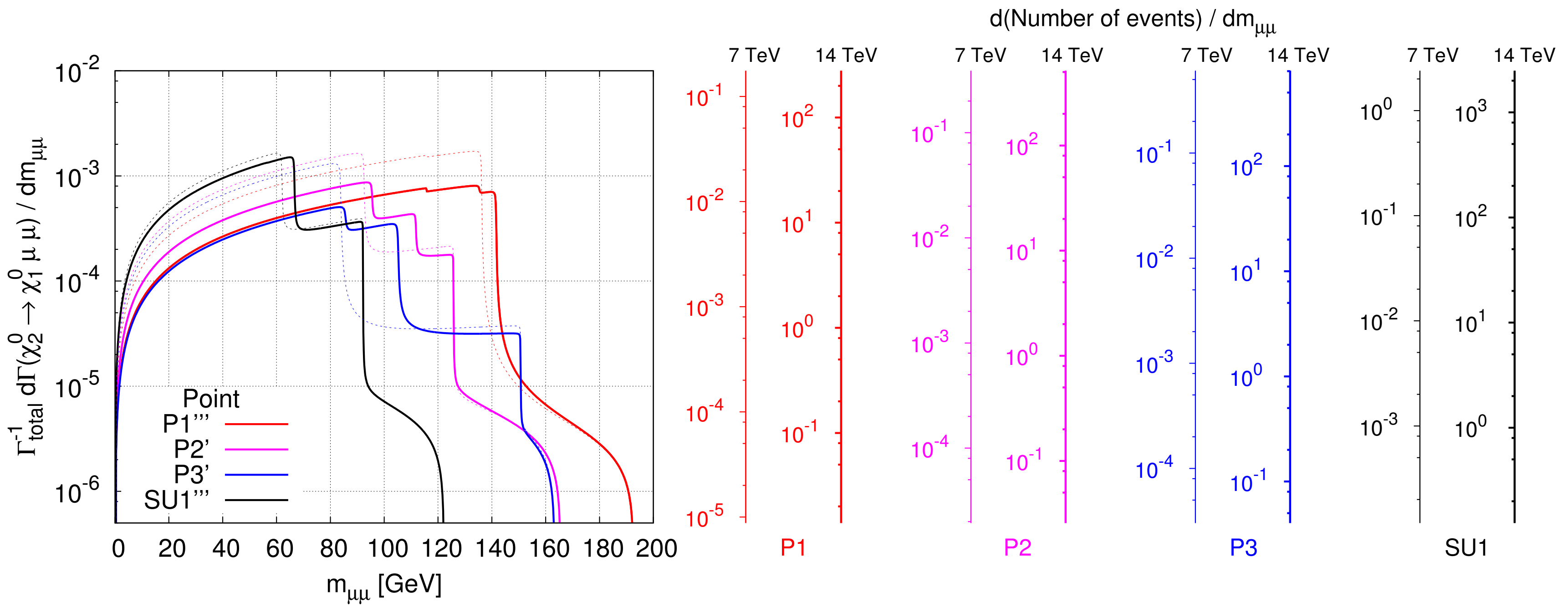
- **LFV observables within experimental reach;** $\Delta m|_{\text{SU1}} \lesssim \Delta m|_{\text{HM1}}$
- **HM1:** $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim 0.1 - 1\% \rightsquigarrow$ **BR**$(\mu \to e\gamma)|_{\text{MEG}}$
- **SU1:** $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim 0.1 - 1\% \Rightarrow$ **BR**$(\tau \to \mu\gamma) \gtrsim 10^{-9}$ **(SuperB)**

$\Rightarrow$ Hint towards scale of new physics ($M_{N_3} \gtrsim 10^{13}$ GeV)

LFV at the LHC: di-lepton distributions in χ_2^0 decays

Impact of **type-I SUSY seesaw** for **di-lepton distributions** $\chi_2^0 \to \tilde{\ell}^i_{L,R}\,\ell_i \to \chi_1^0\,\ell_i\,\ell_i$

Seesaw: $R = 1$, $P'^{(\prime\prime\prime)}_{M_N} = \{10^{10},\, 5\times 10^{10}\,(10^{12}),\, 5\times 10^{13}\,(10^{15})\}$ GeV, $\theta_{13} = 0.1°$



▶ **Displaced** $m_{\mu\mu}$ and m_{ee} **edges** $(\tilde{\ell}_L) \Leftrightarrow$ **sizable** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$ [⇝ flavour non-universality (?)]

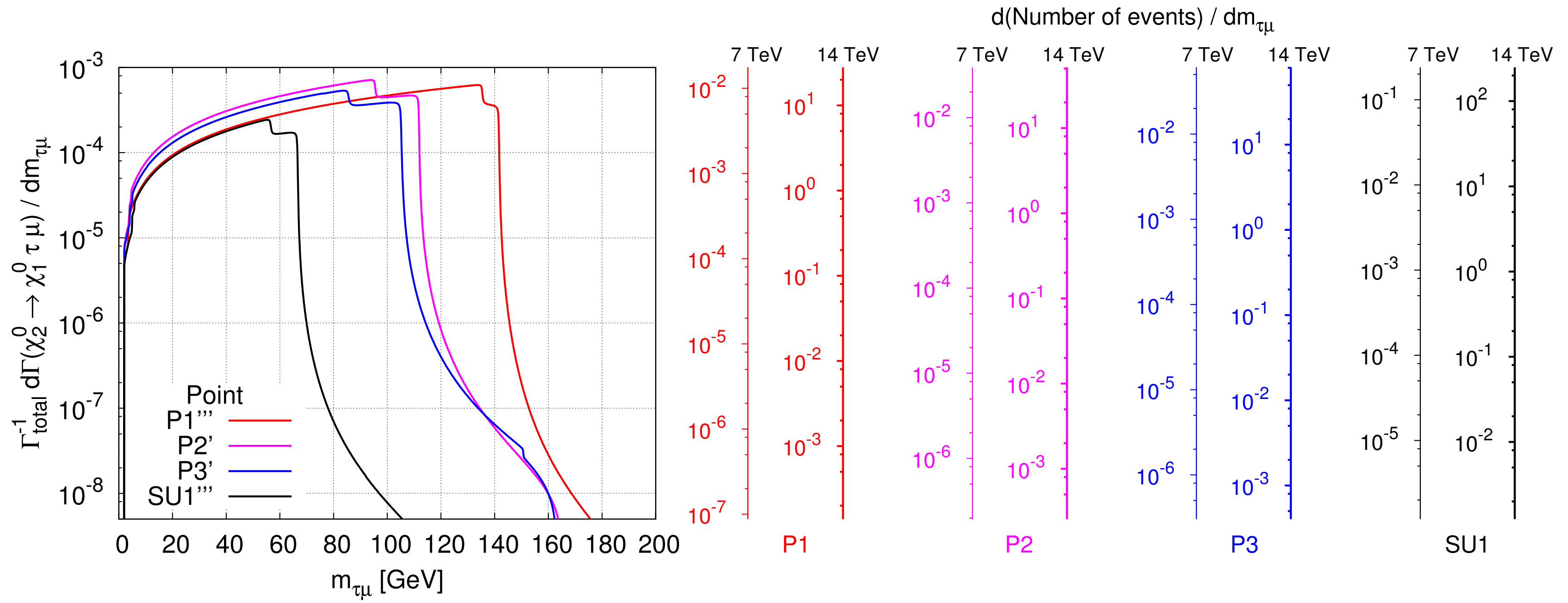
▶ Appearance of **new edge** in $m_{\mu\mu}$: **intermediate** $\tilde{\tau}_2$ [⇝ flavour **violation!**]

▶ **LFV at the LHC:** $\chi_2^0 \to \tilde{\tau}_2\,\mu \to \chi_1^0\,\mu\,\mu$

LFV at the LHC: flavour violating χ_2^0 decays

Impact of **type-I SUSY seesaw** for **di-lepton distributions** $\chi_2^0 \to \tilde{\ell}^j_{L,R}\,\ell_i \to \chi_1^0\,\ell_i\,\ell_j$

Seesaw: $R = 1$, $P'^{('''))}_{M_N}$ $=\{10^{10},\, 5\times10^{10}\,(10^{12}),\, 5\times10^{13}\,(10^{15})\}$ GeV, $\theta_{13} = 0.1°$



- Opposite-sign, **different flavour final state** di-leptons (τ, μ, etc)
- **Lepton flavour violated** in χ_2^0 and $\tilde{\ell}$ **decays!**
- **LFV at the LHC: e.g. $\chi_2^0 \to \tilde{\tau}_2\,\mu \to \chi_1^0\,\tau\,\mu$, $\chi_2^0 \to \tilde{\mu}_L\,\tau \to \chi_1^0\,\tau\,\mu$**

Interplay of high- and low-energy LFV: what can we learn?

cMSSM: no FV in lepton sector, approximately **degenerate** $\tilde{e} - \tilde{\mu}$

Type-I SUSY seesaw to account for neutrino masses and mixings:

⋆ **sizable** $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$, $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\mu}_L, \tilde{\tau}_2)$ (within **LHC** sensitivity)

⋆ new edges in **di-lepton distributions**

⋆ **correlation** of **high-** and **low-energy** LFV observables [e.g. **BR vs** $\Delta m_{\tilde{\ell}}$]

Impact of possible **scenarios of experimental data**

[**synergy** of **BRs, CR**$|_{\text{low-energy}}$ and $\Delta m(\tilde{e}, \tilde{\mu})|_{\text{LHC}}$; **large** RR splittings$|_{\text{LHC}}$; ...]

$\Rightarrow$ **substantiate** seesaw hypothesis (eventually hinting towards new physics scale)

$\Rightarrow$ **disfavour** a type-I seesaw as the (only) **source of flavour violation**

Additional slides

LFV formulae: slepton masses

$$M_{LL}^{ij\,2} = m^2_{\tilde{L},ij} + v_1^2 \left(Y^{l\,\dagger}\, Y^l\right)_{ij} + M_Z^2 \cos 2\beta \left(-\frac{1}{2} + \sin^2\theta_W\right) \delta_{ij} \,,$$

$$M_{RR}^{ij\,2} = m^2_{\tilde{E},ij} + v_1^2 \left(Y^l\, Y^{l\,\dagger}\right)_{ij} - M_Z^2 \cos 2\beta \sin^2\theta_W\, \delta_{ij} \,,$$

$$M_{LR}^{ij\,2} = v_1 \left({A_l}^{\dagger}\right)_{ij} - v_2\, \mu\, {Y^{l}}^{\dagger}_{ij} \,, \quad M_{RL}^{ij\,2} = \left(M_{LR}^{ji\,2}\right)^* \,,$$

$$(M^2_{\tilde{\nu}})_{ij} = m^2_{\tilde{L},ij} + \frac{1}{2} M_Z^2 \cos 2\beta\, \delta_{ij} \,.$$

$$(m^2_{\tilde{L}})_{ij} = \left(m_0^2 + 0.5\, M^2_{1/2} - m_0^2\, |y|\, (Y^l)^2_{ij}\right) \delta_{ij} + (\Delta m^2_{\tilde{L}})_{ij} \,,$$

$$(m^2_{\tilde{E}})_{ij} = \left(m_0^2 + 0.15\, M^2_{1/2} - 2\; m_0^2\, |y|\, (Y^l)^2_{ij}\right) \delta_{ij} + (\Delta m^2_{\tilde{E}})_{ij} \,,$$

$$|y| \approx \frac{1}{8\pi^2} \left(3 + \frac{A_0^2}{m_0^2}\right) \log\left(\frac{M_X}{m_{\mathsf{SUSY}}}\right)$$

$$(\Delta m^2_{\tilde{L}})_{ij} = -\frac{1}{8\,\pi^2} (3\, m_0^2 + A_0^2)\, (Y^{\nu\,\dagger}\, L\, Y^\nu)_{ij} \,,$$

$$(\Delta A_l)_{ij} = -\frac{3}{16\,\pi^2} A_0\, Y^l_{ij}\, (Y^{\nu\,\dagger}\, L\, Y^\nu)_{ij} \,,$$

$$(\Delta m^2_{\tilde{E}})_{ij} = 0 \;;\; L_{kl} \equiv \log\left(\frac{M_X}{M_{N_k}}\right) \delta_{kl} \,.$$

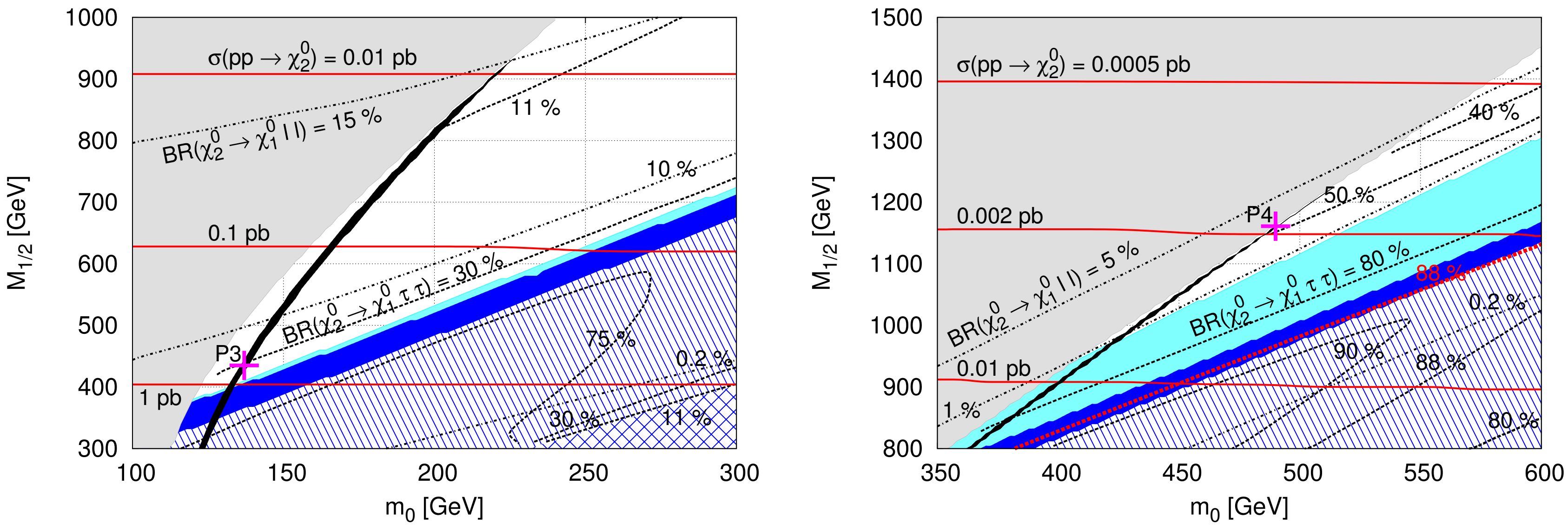
Mass splitting formulae

$$\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j) \approx \frac{1}{2m_{\tilde{\ell}}^2} \left| \frac{m_i^2 \, (A_0 - \mu \tan\beta)^2}{0.35 M_{1/2}^2 + M_Z^2 \cos 2\beta(-1/2 + 2\sin^2\theta_W) \, + (\Delta m_{\tilde{L}}^2)_{ii}} \pm 2 \, |(\Delta m_{\tilde{L}}^2)_{ij}| \right| ,$$

$$\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j) \; \approx \left| \frac{(\Delta m_{\tilde{L}}^2)_{ij}}{(m_{\tilde{L}}^2)} \right| .$$

$$\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\mu}_L, \tilde{\tau}_2) \; \approx \; \frac{1}{8\pi^2} \, \frac{L_{33} \, M_{N_3}}{v^2 \sin^2\beta} \, \frac{3m_0^2 + A_0^2}{m_0^2 + 0.5 M_{1/2}^2} \left| \sum_{ij} U_{2i}^{\mathsf{MNS}} U_{3j}^{\mathsf{MNS}\,*} R_{3i}^* R_{3j} \sqrt{m_{\nu_i} m_{\nu_j}} \right| .$$

cMSSM parameter space for $\chi_2^0 \to \ell\ell\chi_1^0$ decays



$m_0 - M_{1/2}$ plane (in GeV), for $A_0 = -1$ TeV and $\tan\beta = 10$ (left); the same but with $A_0 = 0$ and $\tan\beta = 40$ (right). In both figures, the shaded region on the left is excluded due to the presence of a charged LSP. The full black region corresponds to a WMAP compatible χ_1^0 relic density. Likewise, on the dashed region on the bottom, the spectrum does not fulfil the kinematical requirements described in the text: the solid regions correspond to having $m_{\chi_2^0} < m_{\tilde{\ell}_L} + 10$ GeV (cyan), $m_{\chi_2^0} < m_{\tilde{\tau}_2} + 10$ GeV (blue), $m_{\chi_2^0} < m_{\tilde{\ell}_L, \tau_2}$ (dashed blue), and $m_{\chi_2^0} < m_{\tilde{\tau}_1} + m_\tau$ (blue crosses). The centre (white) region denotes the parameter space obeying the "standard window" constraints. The dotted and dashed lines respectively denote isosurfaces for BR($\chi_2^0 \to \chi_1^0 \ell\ell$) and BR($\chi_2^0 \to \chi_1^0 \tau\tau$). Full red lines denote the contours of χ_2^0 production cross sections. Crosses (pink) correspond to benchmark points P3 and P4

Benchmark points: production and decay

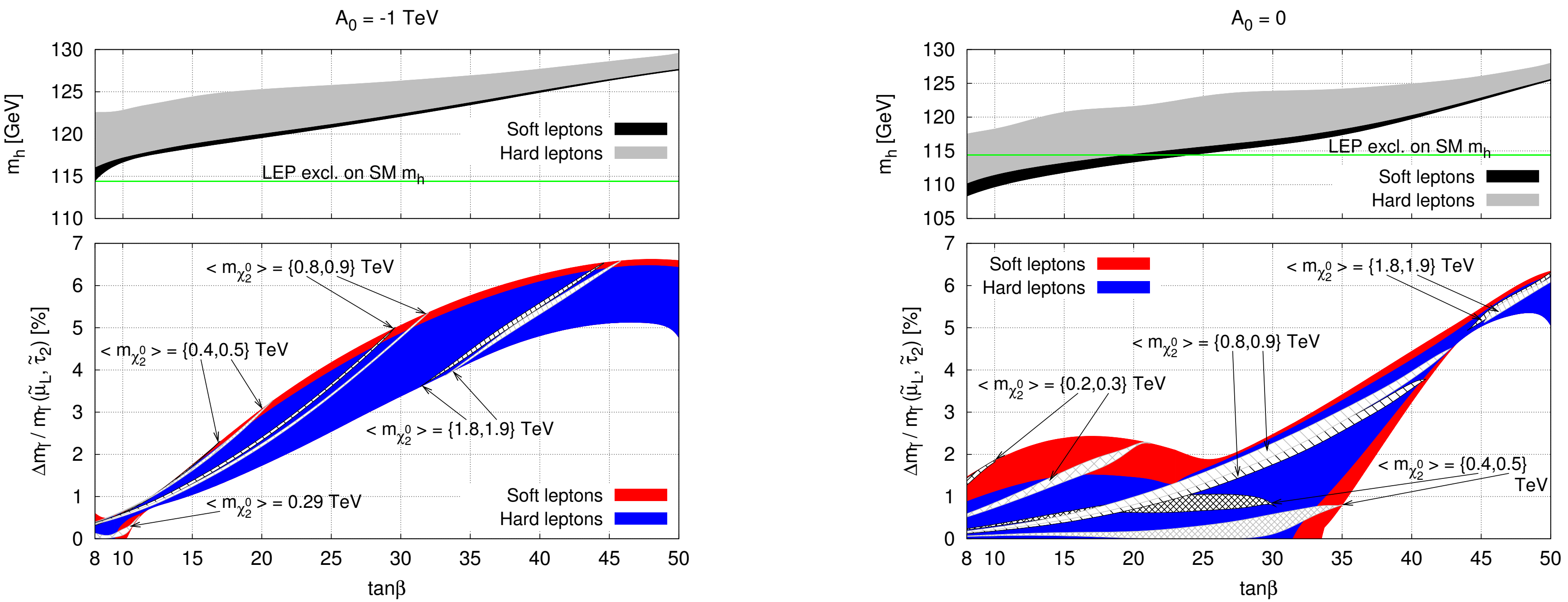
Point	$\sigma(pp \to \tilde{\chi}_2^0)$ (fb)		$\sigma(pp \to \tilde{\chi}_2^0\,\tilde{\chi}_2^0)$ (fb)	
	7 TeV	14 TeV	7 TeV	14 TeV
P1	17.5	278.7	1.0	19.1
P2	38.8	513.9	2.2	32.6
P3	60.6	806.9	3.8	52.1
P4	0.04	1.87	~ 0.00	0.13
P5-HM1	0.57	16.50	0.02	1.24
P6-SU1	239.0	2485.8	15.1	158.0

$\ell_i\,\ell_i$	$\tilde{l}_X^i$	BR($\chi_2^0 \to \tilde{l}_X^i l_i \to l_i l_i \chi_1^0$) (%)					
		P1	P2	P3	P4	P5-HM1	P6-SU1
$\tau\tau$	$\sum_{\tilde{l}}$	15.2	19.2	30.2	1.7	9.4	25.6
	$\tilde{\tau}_2$	7.9	7.6	4.0	1.7	9.4	2.4
	$\tilde{\tau}_1$	7.3	11.6	26.2	—	—	23.2
$\mu\mu$	$\sum_{\tilde{l}}$	12.6	8.7	6.1	3.1	15.2	6.5
	$\tilde{\mu}_L$	12.2	7.3	5.8	3.0	15.1	4.6
	$\tilde{\mu}_R$	0.4	1.4	0.3	0.1	6.5×10^{-2}	1.9
ee	$\sum_{\tilde{l}}$	12.5	8.7	6.0	3.0	15.3	6.5
	$\tilde{e}_L$	12.2	7.3	5.8	3.0	15.2	4.6
	$\tilde{e}_R$	0.3	1.4	0.2	3.2×10^{-2}	5.7×10^{-2}	1.9

(i) Production cross sections for at least one χ_2^0, $\sigma(pp \to \tilde{\chi}_2^0)$ (in fb), and exactly two χ_2^0, $\sigma(pp \to \tilde{\chi}_2^0\,\tilde{\chi}_2^0)$ (in fb), for the benchmark points, with $\sqrt{s} = 7$ TeV and 14 TeV.

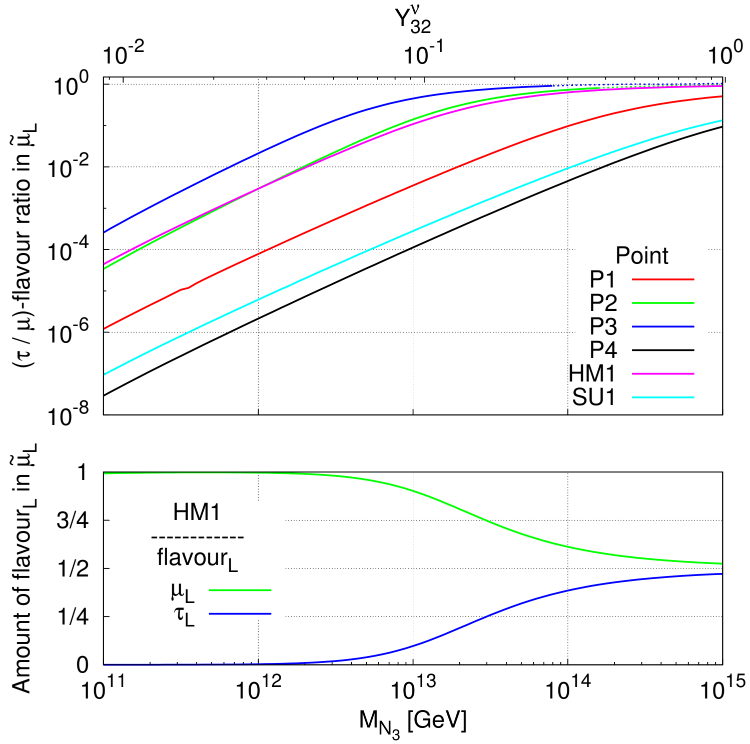
(ii) Branching ratios BR($\chi_2^0 \to \tilde{l}_X^i l_i \to l_i l_i \chi_1^0$) (in %) for a given di-lepton final state, isolating specific intermediate sleptons and summing over all exchanged (slepton) states.

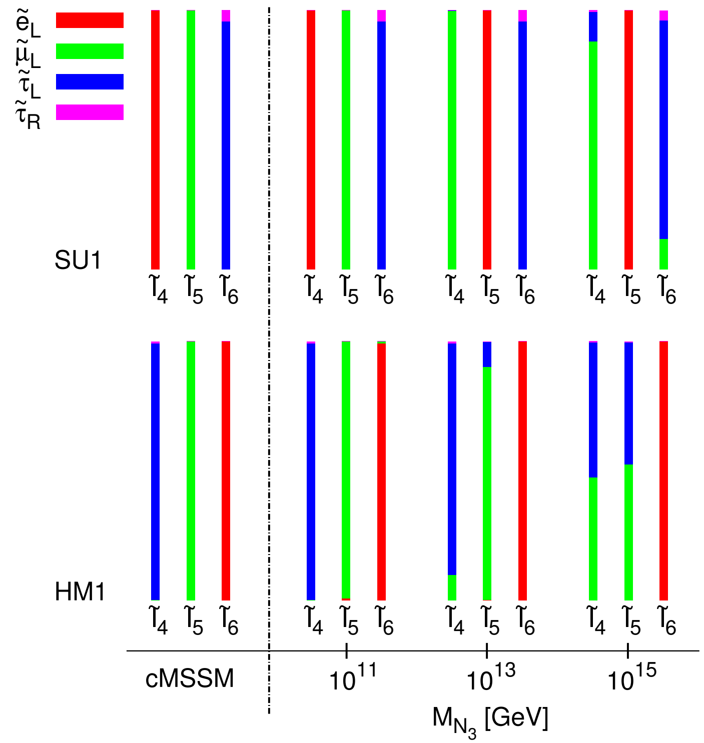
cMSSM mass splittings: overview



Mass difference $\tilde{\mu}_L - \tilde{\tau}_2$ (normalised to the average $\tilde{\mu}_L, \tilde{\tau}_2$ masses) in the cMSSM as a function of $\tan\beta$, for different values of A_0 (from top to bottom, $A_0 = -1, 0, 1$ TeV). The subplots above each panel denote the corresponding variation of m_h. The different solid regions correspond to hard (blue, gray) or soft (red, black) leptons in the final state. Inset are bands corresponding to different regimes for $m_{\chi_2^0}$ (in TeV).

Quasi-degenerate flavour content: effective mass splitting

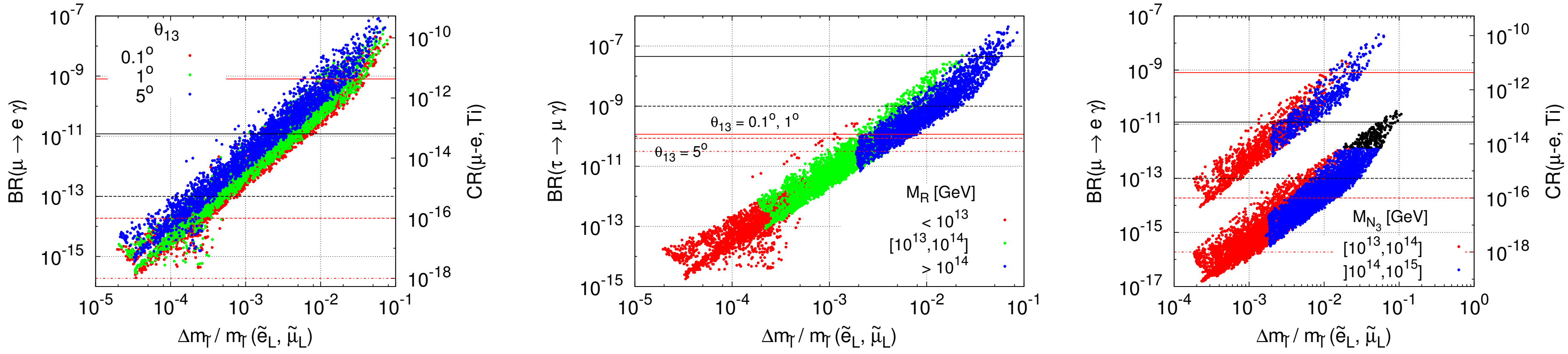




On the left, τ/μ flavour ratio in $\tilde{\mu}_L$ mass eigenstate as a function of M_{N_3} (in GeV). $R = 1$, $\theta_{13} = 0.1^\circ$ and take $M_{N_1} = 10^{10}$ GeV, $M_{N_2} = 10^{11}$ GeV. On the upper axis we display the values of Y^ν_{32}. The secondary panel illustrates $|R^{\tilde{l}}_{5\mu_L}|^2$ 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.

$$m_i^{(\text{eff})} \equiv \sum_{X=\tilde{\tau}_2,\tilde{\mu}_L,\tilde{e}_L} m_{\tilde{l}_X} \left(|R^{\tilde{l}}_{X i_L}|^2 + |R^{\tilde{l}}_{X i_R}|^2\right) \;, \qquad \left(\frac{\Delta m}{m}\right)^{(\text{eff})}(\tilde{l}_i, \tilde{l}_j) \equiv \frac{2\,|m_i^{(\text{eff})} - m_j^{(\text{eff})}|}{m_i^{(\text{eff})} + m_j^{(\text{eff})}} \,.$$

Degenerate right-handed neutrinos



First (second) 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. We display the corresponding predictions of CR($\mu - e$, Ti) on the right y-axis. Leading to the scan, we set $\tan\beta = 10$, and the remaining mSUGRA parameters were randomly varied (with $|A_0| \lesssim 1$ TeV, satisfying the "standard window" constraint and requiring consistency with the dark matter and Higgs boson mass bounds). For the seesaw parameters we have taken $R = 1$, $\theta_{13} = 0.1^\circ$, 1°, 5° (with $\delta = \varphi_{1,2} = 0$), and $M_{N_1} = M_{N_2} = M_{N_3} = M_R$ being varied as 10^{12} GeV $\lesssim M_R \lesssim 10^{15}$ GeV. In the upper left (right) panel colour code denotes different regimes of θ_{13} (M_R). Third panel: comparison of degenerate (region with higher BR) and hierarchical (region with lower BR) spectrum. Same scan as before, but now taking only $\theta_{13} = 0.1^\circ$ and 10^{13} GeV $\lesssim M_R \lesssim 10^{15}$ GeV.