



# Interplay of LFV at low-energies and at colliders: impact for new physics scenarios

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JHEP 1010 (2010) 104 & work in progress

## Understanding lepton flavour mixing...

- SM: no  $\nu$ -mass terms; conservation of **neutral** and **charged lepton flavours**
- Implications of neutrino oscillations: **Neutral lepton flavour is violated!**

Neutrinos are massive (very light); **large mixing** in the lepton sector (2010)

$$\Delta m_{\text{sol}}^2 \approx 7.6 \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{12} \approx 0.3$$

$$\Delta m_{\text{atm}}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{23} \approx 0.5$$

$$\sum m_{\nu_i} \lesssim 0.17 \text{ eV (cosm.)}$$

$$\sin^2 \theta_{13} \leq 0.04$$

- Implement mechanism for  $\nu$ -mass generation
- \* **Seesaw mechanism**  $\longleftrightarrow$  If **Majorana**  $\nu$ , a natural **explanation for small**  $m_\nu$   
additional **singlet states**  $N$  ( $\nu_R$ ); new **dynamics**

$$m_\nu \approx \frac{(Y^\nu v)^2}{M_N}$$

$$Y^\nu \sim \mathcal{O}(1) \leftrightarrow M_N \sim \mathcal{O}(10^{15}) \text{ GeV}$$

unreachable / untestable (?)

## Understanding lepton flavour mixing...

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

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

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

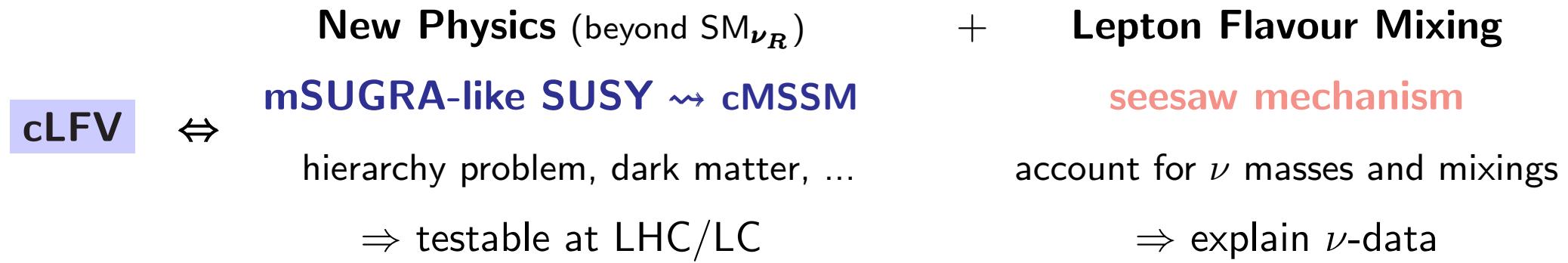
↔ An effective “hint”:  $\text{BR}(\mu \rightarrow e\gamma) = 10^{-11} \times (2 \text{ TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2$   
[SM $_{\nu_R}$ :  $\text{BR}(\mu \rightarrow e\gamma) \sim 10^{-54}$ ]

New Physics (beyond SM $_{\nu_R}$ )	+	Lepton Flavour Mixing
► <b>cLFV</b> $\Leftrightarrow$ $\Lambda \sim \mathcal{O}(\text{TeV})$  (testable at colliders)		non-negligible $\theta_{\ell_i \ell_j}$  (suggested by neutrino mixing)

**charged LFV:** complementary to direct **collider searches** and  $\nu$ -dedicated exps

## cLFV: complementary to collider searches and $\nu$ experiments

- Here: use **low-energy LFV observables** (e.g.  $\text{BR}(\ell_i \rightarrow \ell_j \gamma)$ ) and **high-energy data** (e.g. SUSY kinematical observables at the LHC/LC)  
⇒ Use **cLFV complementarity role** to **disentangle** model of **New Physics**



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

# Flavour in the cMSSM

- **SUSY:** appealing **theoretically** (hierarchy problem, unification of gauge couplings, ...) and **experimentally** (dark matter candidates, TESTABLE at colliders!, ...)

**Minimal SUSY(SM):**  $\mathcal{W}_{\text{MSSM}} = \hat{D}^c Y^d \hat{Q} \hat{H}_1 + \hat{U}^c Y^u \hat{Q} \hat{H}_2 + \hat{E}^c Y^l \hat{L} \hat{H}_1 + \mu \hat{H}_1 \hat{H}_2$

$$\mathcal{L}_{\text{MSSM}}^{\text{soft}} = \mathcal{L}(m_{ij}^{\phi/2}, A_{ij}^f, \dots) \quad \rightsquigarrow \text{SUSY flavour \& CP problem}$$

- Consider **flavour-blind mechanisms** of **SUSY breaking** (e.g. supergravity, etc.)  
⇒ high-scale (GUT) **universality conditions:**  $m_{ij}^{\phi/2} = m_0^2$ ,  $A_{ij}^f = A_0$  (and  $M_i = M_{1/2}$ )

- **cMSSM:** **5 parameters**  $m_0$ ,  $M_{1/2}$ ,  $A_0$ ,  $\tan \beta$  and  $\text{sign}(\mu)$   
only **SM** sources of **flavour and CP violation** ( $Y^f$ )

Embed in the (c)MSSM a mechanism of  $\nu$ -mass generation ...

## Type-I SUSY seesaw

- **cMSSM + 3  $\hat{N}_R$**   $\mathcal{W}_{\text{MSSM}_R}^{\text{lepton}} = \hat{N}^c \mathbf{Y}^\nu \hat{L} \hat{H}_2 + \hat{E}^c Y^l \hat{L} \hat{H}_1 + \frac{1}{2} \hat{N}^c \mathbf{M}_N \hat{N}^c$   
 $Y^\ell = Y_\ell^{\text{diag}}$  and  $M_N = M_N^{\text{diag}}$   
 $-\mathcal{L}^{\text{slepton}} = -\mathcal{L}_{\text{cMSSM}}^{\text{slepton}} + m_0^2 \tilde{\nu}_R \tilde{\nu}_R^* + (A_0 Y^\nu H_2 \tilde{\nu}_L \tilde{\nu}_R^* + B_\nu \tilde{\nu}_R \tilde{\nu}_R + \text{H.c.})$
- $m_\nu = -v_2^2 \mathbf{Y}^\nu \frac{1}{\mathbf{M}_N} \mathbf{Y}^{\nu T}$  **Seesaw equation** (limit  $m_D = Y^\nu v_2 \ll M_N$ )
- $v_2 \mathbf{Y}^\nu = i \sqrt{M_N^{\text{diag}}} \mathbf{R} \sqrt{m_\nu^{\text{diag}}} \mathbf{U}_{\text{MNS}}^\dagger$  (at  $M_N$ )  
[Casas-Ibarra parameterization]  $\left\{ \begin{array}{l} \mathbf{U}_{\text{MNS}}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \varphi_{1,2}) \\ m_\nu^{\text{diag}}(\Delta m_{\text{sol}}^2, \Delta m_{\text{atm}}^2, \sum m_{\nu_i}) \\ M_N^{\text{diag}} \text{ heavy neutrino masses} \\ \mathbf{R}(\theta_i) \text{ 3 complex angles} \end{array} \right.$
- Even for **universal** soft-breaking terms **RGE running of  $Y^\nu$**  ( $M_{\text{GUT}} \rightarrow M_N$ ) induces **flavour-violating** terms in slepton soft-breaking masses  
 $(\Delta m_{\tilde{L}}^2)_{ij} = -\frac{1}{8\pi^2} (3 m_0^2 + A_0^2) (Y^{\nu\dagger} L Y^\nu)_{ij}$      $L = \log(M_{\text{GUT}}/M_N)$   
[Borzumati, Masiero; Hisano; ...]

## Type-I SUSY seesaw: slepton masses

- Charged slepton masses in the  $\text{MSSM}_R \rightarrow -\mathcal{L}_{\text{mass}}^{\tilde{\ell}} \supset \tilde{\ell}_{L,R}^* \mathbf{M}_{\tilde{\ell}}^2 \tilde{\ell}_{L,R}$  [6 × 6]

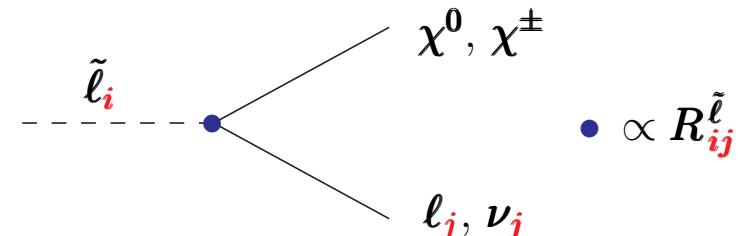
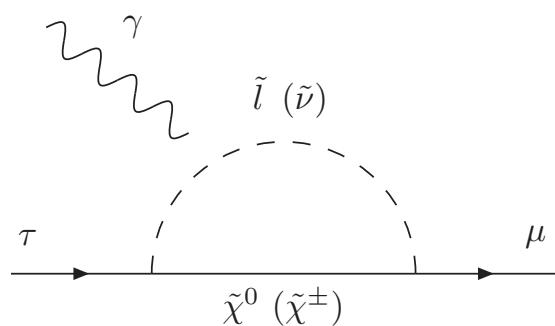
$$\mathbf{M}_{\tilde{\ell}}^2 = \begin{bmatrix} LL_{ij} & LR_{ij} \\ (LR)_{ji}^* & RR_{ij} \end{bmatrix} \quad \text{e.g.} \quad M_{LL}^{ij \ 2} = \mathbf{m}_{\tilde{L},ij}^2 + m_{\ell_i}^2 + M_Z^2 \cos 2\beta \left( -\frac{1}{2} + \sin^2 \theta_W \right)$$

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

$$\mathbf{m}_{\tilde{L}}^2 = \begin{bmatrix} \mathbf{m}_0^2 & 0 & 0 \\ 0 & \mathbf{m}_0^2 & 0 \\ 0 & 0 & \mathbf{m}_0^2 \end{bmatrix}_{(@M_{\text{GUT}})} \longrightarrow (\mathbf{m}_{\tilde{L}}^2)_{ij}^{\text{EW}} = \left( m_0^2 + 0.5 M_{1/2}^2 - m_0^2 |y| (Y^l)_{ij}^2 \right) \delta_{ij} + (\Delta m_{\tilde{L}}^2)_{ij} \quad (\Delta m_{\tilde{L}}^2)_{ij} \propto (Y^{\nu \dagger} L Y^{\nu})_{ij}$$

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

$$R^{\tilde{\ell} \dagger} M_{\tilde{\ell}}^2 R^{\tilde{\ell}} = \text{diag}(m_{\tilde{\ell}_i}^2) \quad R^{\tilde{\ell}} \neq 1!$$



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

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

# One source of flavour violation

- mSUGRA-like SUSY seesaw:  $Y^\nu$  unique source of FV  
(all observables strongly related)
- \* low-energies:  $l_j \rightarrow l_i \gamma$ ,  $l_j \rightarrow 3l_i$ ,  $\mu - e$  in Nuclei  
⇒ large rates potentially observable! (MEG, PRISM/PRIME, ...)
- \* high-energies: study charged sleptons from  $\chi_2^0 \rightarrow \ell^\pm \ell^\mp \chi_1^0$  decays  
⇒ possibly sizable  $\tilde{e} - \tilde{\mu}$  mass differences, multiple edges,  
direct FV decays  $\chi_2^0 \rightarrow \ell_i \ell_j \chi_1^0$ , FV  $\tilde{e}, \tilde{\mu}$  production, ...  
[also effective LFV - Buras et al, '09]
- If LFV indeed observable (large BRs & CR),  
expect interesting slepton phenomena at the LHC/LC!  
... strengthen / disfavour seesaw hypothesis !

## Slepton mass reconstruction at the LHC (LC)

- Focus on **di-lepton invariant mass distributions** from  $\chi_2^0 \rightarrow \tilde{\ell}_{L,R} \ell \rightarrow \chi_1^0 \ell \ell$   
If **on-shell sleptons** & **isolated** leptons with **large  $p_T > 10$  GeV**

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

$$\Rightarrow \text{infer } \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_i, \tilde{\ell}_j) = \frac{|m_{\tilde{\ell}_i} - m_{\tilde{\ell}_j}|}{\langle m_{\tilde{\ell}_{i,j}} \rangle} \rightsquigarrow \text{LHC: } \begin{array}{ll} \Delta m/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L) & \rightarrow \mathcal{O}(0.1\%) \\ \Delta m/m_{\tilde{\ell}}(\tilde{\mu}_L, \tilde{\tau}_2) & \rightarrow \mathcal{O}(1\%) \end{array}$$

- **Linear Collider prospects:** one **order of magnitude** gain in precision ?

Different **methods** to determine  $\tilde{\ell}$ ,  $\chi^0$ ,  $\chi^\pm$  masses; **beam** options/polarization ...

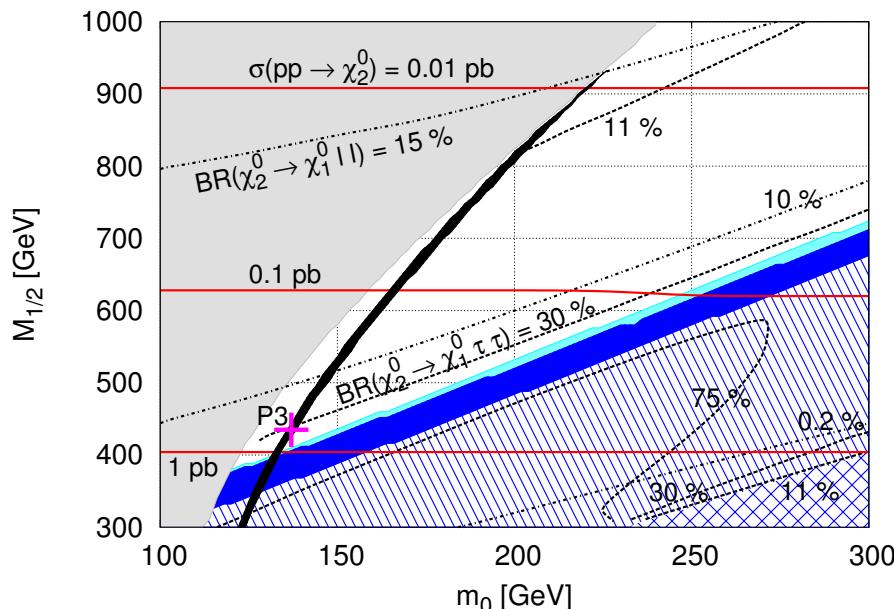
$\Rightarrow$  major **impact** for  $\mathcal{L}^{\text{SUSY}}$  **reconstruction**  $\longleftrightarrow$  **LHC measurements!**

# Slepton mass reconstruction at the LHC (LC)

- cMSSM viability windows: phenomenological viability (th and exp bounds,  $\Omega h^2$ , ...) kinematical requirements (decay chain, hard leptons, etc.) # events (large  $\sigma_{\chi_2^0}^{\text{production}}$ , sizable  $\text{BR}(\chi_2^0 \rightarrow \chi_1^0 \ell \ell)$  ...)

- LHC  $\chi_2^0$  production: squark-decay ( $\tilde{q} \rightarrow \chi_2^0 q$ ), direct ( $pp \rightarrow \chi_2^0 X$ ),  $\tilde{g}\tilde{g}$  mode

$$\textbf{P3} \rightsquigarrow \sigma(pp \rightarrow \chi_2^0) \sim 60 \text{ (800)} \text{ fb} [\sqrt{s} = 7 \text{ (14)} \text{ TeV}]$$



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

Proposed cMSSM study points..

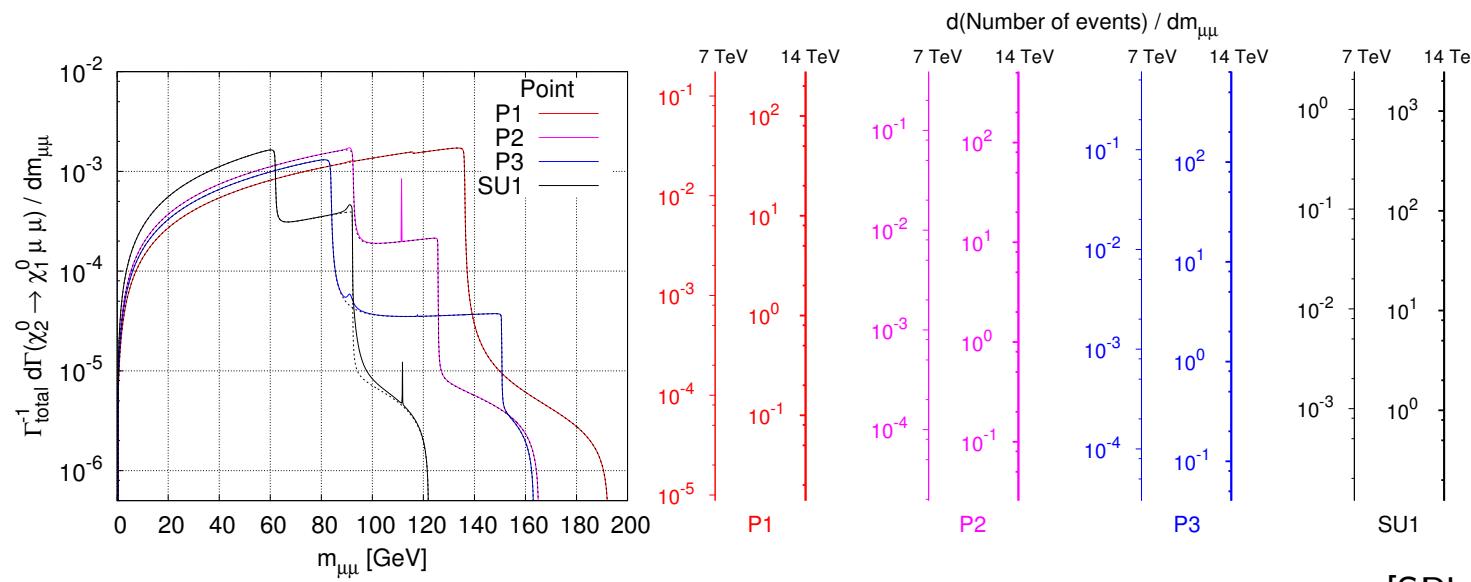
- LC  $\chi_2^0$  production: direct ( $e^+ e^- \rightarrow \chi_i^0 \chi_j^0$ ) [ $s$ -channel  $Z$  and  $t, u$ -channel  $\tilde{l}$  ]

$$\textbf{P3} \rightsquigarrow \sigma(e^+ e^- \rightarrow \chi_2^0) \sim 80 \text{ fb} [\sqrt{s} = 1 \text{ TeV}]$$

$$\textbf{SU1} \rightsquigarrow \sigma(e^+ e^- \rightarrow \chi_2^0) \sim 160 \text{ (25)} \text{ fb} [\sqrt{s} = 1 \text{ TeV (500 GeV)}]$$

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

► LHC:



[SPheno & Prospino]

Point	$m_{\chi_2^0}$	$m_{\chi_1^0}$	$m_{\tilde{\ell}_L}$	$m_{\tilde{\ell}_R}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\tau}_1}$	$\langle m_{\tilde{q}} \rangle$	$m_h$
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  $\chi_2^0 \rightarrow \tilde{\mu}_{L,R} \mu \rightarrow \chi_1^0 \mu \mu$
- Approximately **superimposed**  $\tilde{\ell}_{L,R}$  **edges** for  $m_{\mu\mu}$  and  $m_{ee}$ : “**degenerate\tilde{\mu}, \tilde{e}**
- **LC:** only light spectra accessible... more precise measurements!

## LFV at high energies ( $\chi_2^0$ decay chain)

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

► Under a type-I SUSY seesaw (assuming e.g. large  $Y_{32,33}^\nu$ )

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

Predominantly  **$LL$  effect:**  $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_L^i, \tilde{\ell}_L^j) \gg \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\ell}_R^i, \tilde{\ell}_R^j)$

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

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

$\Rightarrow$  New edges in di-lepton mass distributions:  $\chi_2^0 \rightarrow \begin{cases} \tilde{\ell}_L^i \ell_i \\ \tilde{\ell}_R^i \ell_i \\ \tilde{\ell}_X^j \ell_i \end{cases} \rightarrow \chi_1^0 \ell_i \ell_i$

$\Rightarrow$  Possible direct FV in neutralino and slepton decays:  $\chi_2^0 \rightarrow \ell_i \ell_j \chi_1^0$

# 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  $\mathcal{L}_{\text{SUSY}}\dots$ )

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

**hint towards SUSY seesaw parameters** [Antusch et al<sub>|AMT</sub> '06, Arganda et al<sub>|AMT</sub> '07]

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

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

⇒ **Intensely explore synergy of LFV at low-energies and at the LHC!**

[Abada et al<sub>|AMT</sub> '10]

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

⇒ **strengthen seesaw hypothesis**

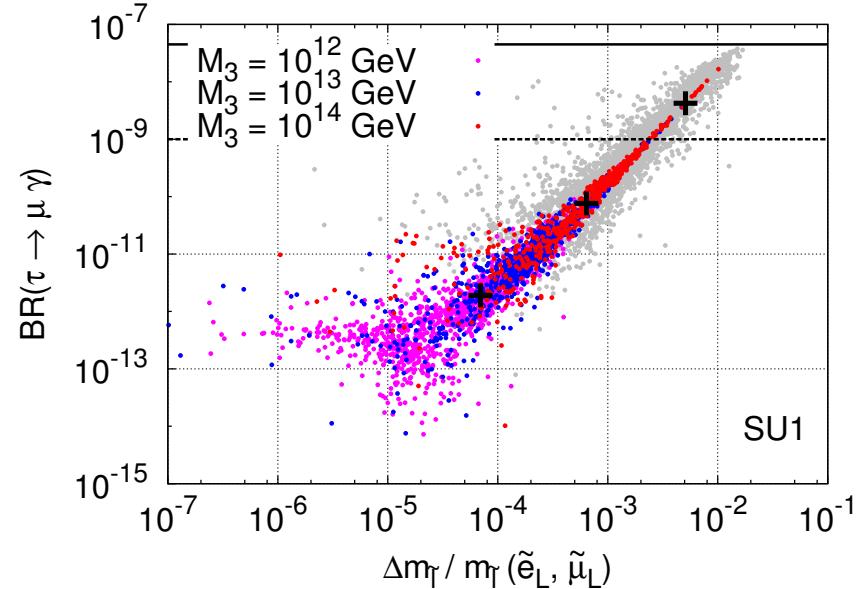
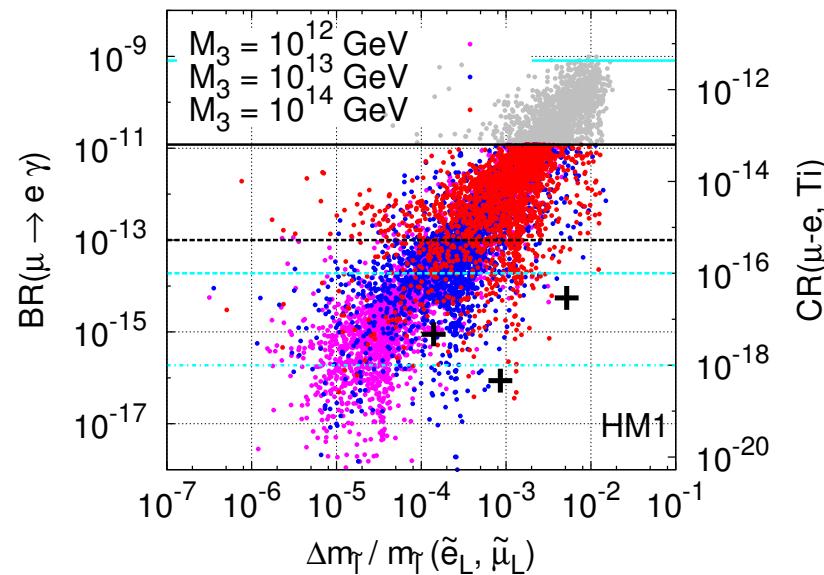
►  $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}}$  excluded by BRs, CR or observed BRs/CR for **negligible  $\Delta m$**

⇒ **suggests distinct** (or additional) **source of flavour violation**

# LFV at low- and high-energies: general overview

**cMSSM:** 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;  $\theta_{13} = 0.1^\circ$



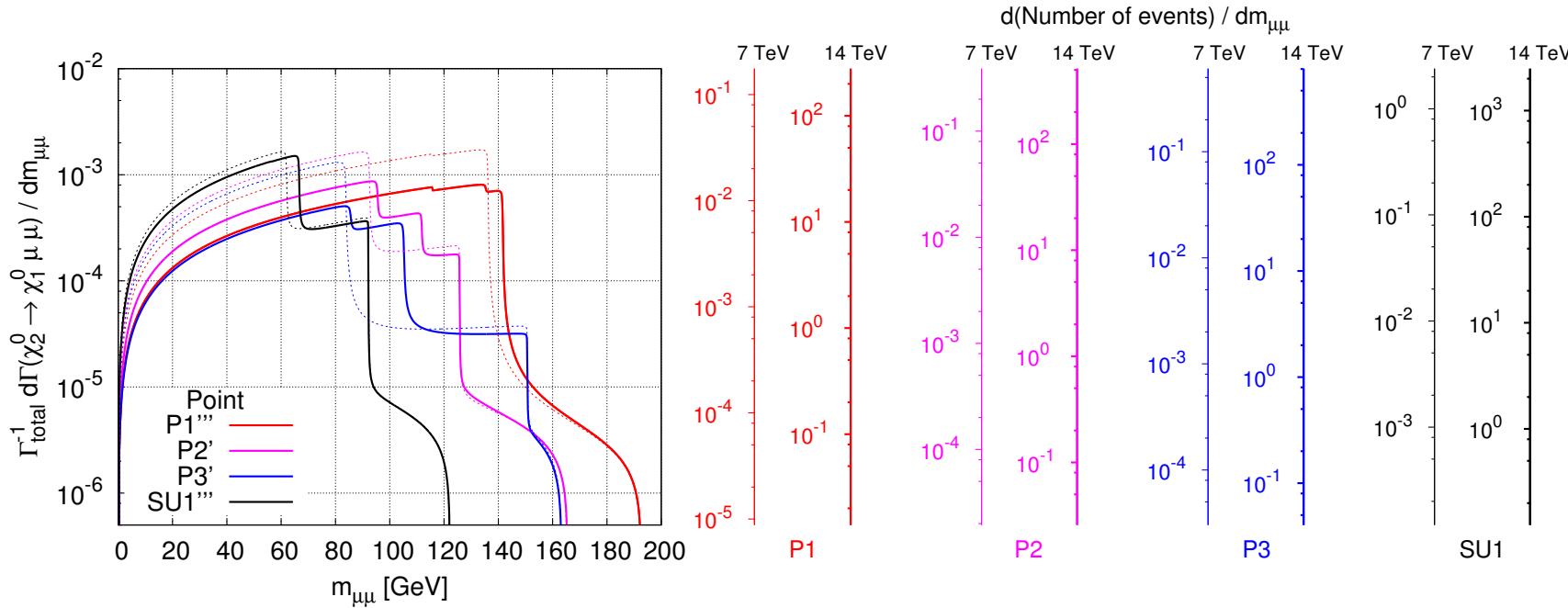
If type-I seesaw indeed at work and **SUSY  $\sim$  HM1, SU1** (cMSSM):

- ▶ LFV observables within experimental reach:  $\Delta m|_{\text{SU1}} \lesssim \Delta m|_{\text{HM1}}$
- ▶ **HM1:**  $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim 0.1 - 1\% \rightsquigarrow \text{BR}(\mu \rightarrow e\gamma)|_{\text{MEG}}$
- ▶ **SU1:**  $\Delta m(\tilde{e}_L, \tilde{\mu}_L)|_{\text{LHC}} \sim 0.1 - 1\% \Rightarrow \text{BR}(\tau \rightarrow \mu\gamma) \gtrsim 10^{-9}$  (**SuperB**)  
 $\Rightarrow$  Hint towards scale of new physics ( $M_{N_3} \gtrsim 10^{13}$  GeV)

# LFV at the LHC: di-lepton distributions in $\chi_2^0$ decays

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

**Seesaw:**  $R = 1$ ,  $P_{M_N}'^{(''')}$  =  $\{10^{10}, 5 \times 10^{10} (10^{12}), 5 \times 10^{13} (10^{15})\}$  GeV,  $\theta_{13} = 0.1^\circ$

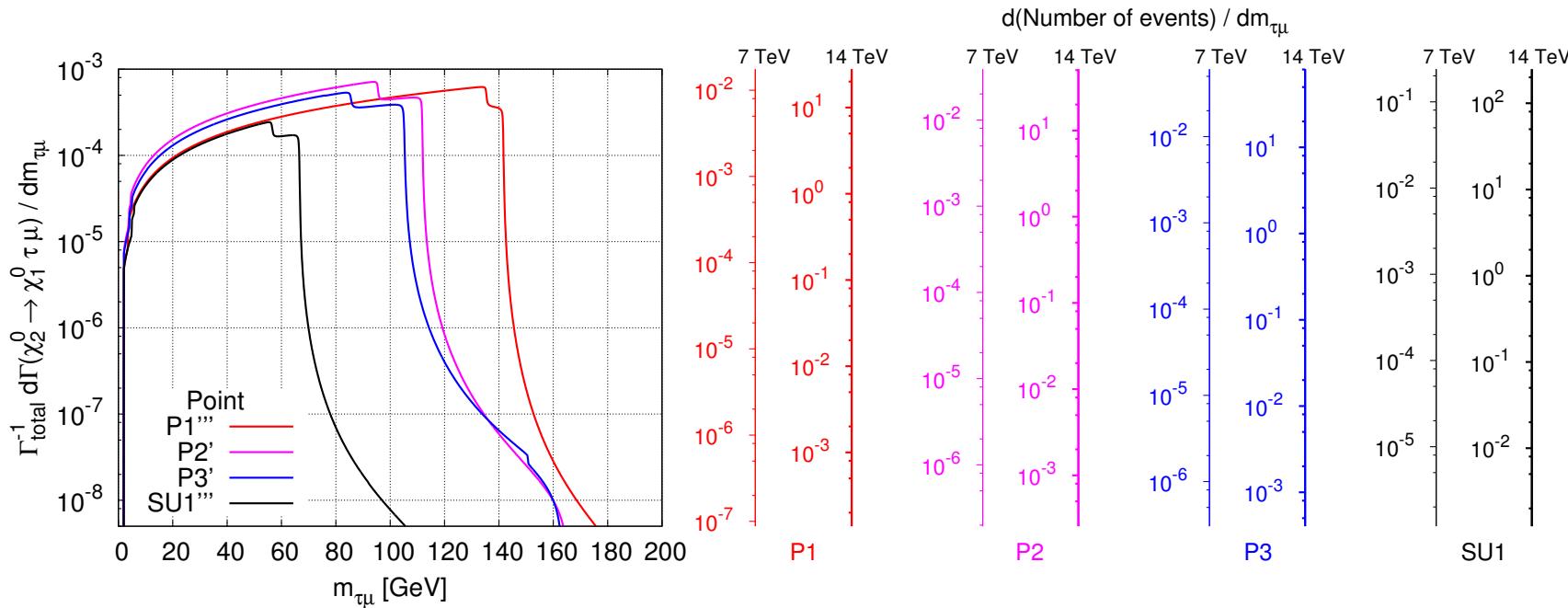


- Displaced  $m_{\mu\mu}$  and  $m_{ee}$  edges ( $\tilde{\ell}_L$ )  $\Leftrightarrow$  sizable  $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$  [ $\rightsquigarrow$  flavour non-universality (?)]
- Appearance of new edge in  $m_{\mu\mu}$ : intermediate  $\tilde{\tau}_2$  [ $\rightsquigarrow$  flavour violation!]
- LFV at the LHC:  $\chi_2^0 \rightarrow \tilde{\tau}_2 \mu \rightarrow \chi_1^0 \mu \mu$

# LFV at the LHC: flavour violating $\chi_2^0$ decays

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

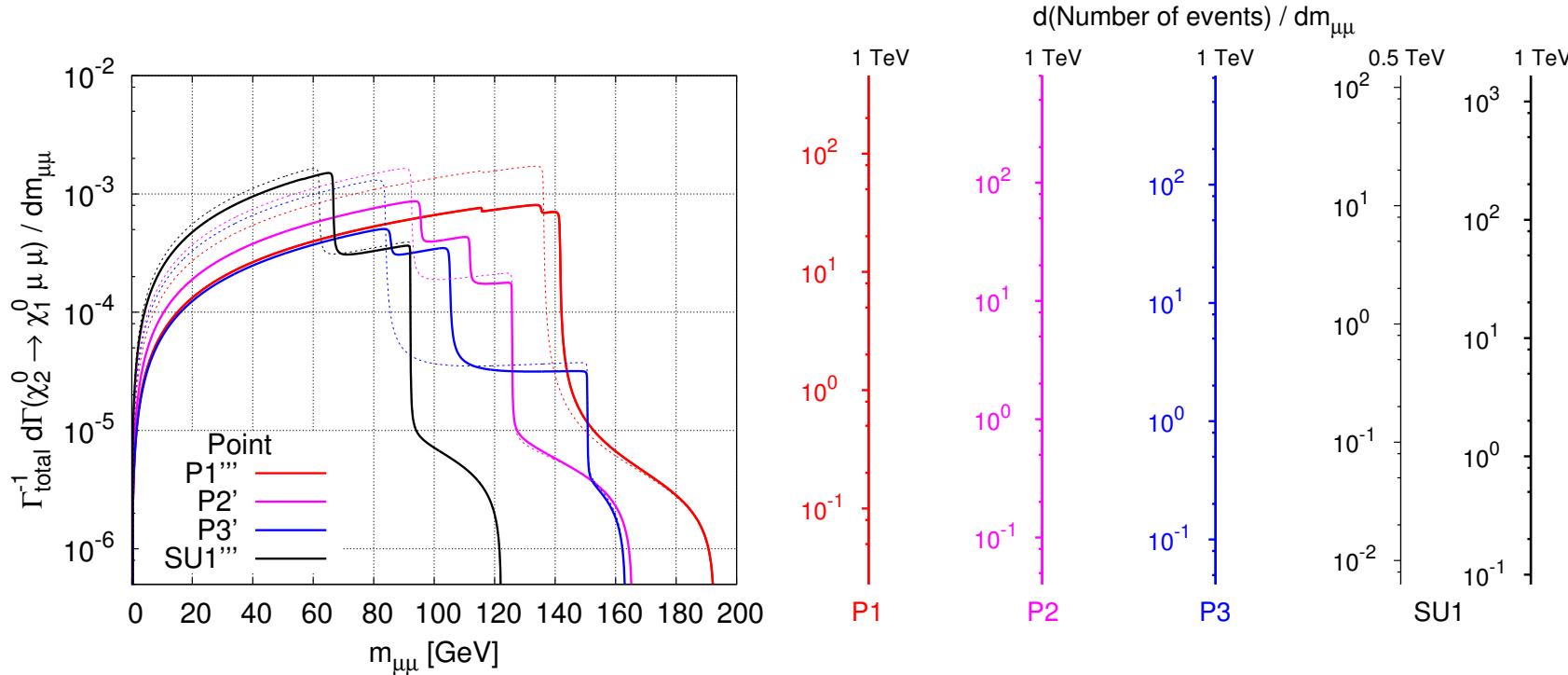
**Seesaw:**  $R = 1$ ,  $P_{M_N}'^{(''')}$  =  $\{10^{10}, 5 \times 10^{10} (10^{12}), 5 \times 10^{13} (10^{15})\}$  GeV,  $\theta_{13} = 0.1^\circ$



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

## LFV at the LC ( $e^+e^-$ ): LFV from $\chi_2^0$ decays

- Analogous to LHC-analysis: displaced & new edges, LFV  $\chi_2^0$  &  $\tilde{\ell}$  decays



- At LC: better resolution in mass determination; sharper edges; ...  
⇒ e.g. explore regimes of smaller  $\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L, \tilde{\mu}_L)$ , ...
- Cover high-energy counterpart for sensitivity ranges of low-energy experiments  
⇒ fully explore correlation of high- and low-energy LFV observables

# LFV at the LC: direct $\tilde{\ell}$ production

- Direct  $\tilde{\ell}$  production in  $e^+e^-$ ; flavour violated in  $\tilde{\ell}$ -production and decay

[Hisano et al., Majerotto et al., Deppisch et al., ...]

$$\Rightarrow e^+e^- \rightarrow \tilde{\ell}_m \tilde{\ell}_k \rightarrow \ell_i^- \chi_1^0 \ell_j^+ \chi_1^0 \quad [s\text{-channel } Z \text{ and } t,u\text{-channel } \chi^0]$$

**ATLAS-SU1:**  $\#(e^+e^- \xrightarrow{\chi_2^0} \mu^+ \mu^- \chi_1^0 \chi_1^0) \sim 10^4$  (700)     $\sqrt{s} = 1\text{TeV}$  (500 GeV)  
 $\#(e^+e^- \xrightarrow{\chi_2^0} \tau^\pm \mu^\mp \chi_1^0 \chi_1^0) \sim 1500$  (100)     $\mathcal{L} = 1000$  (500)  $\text{fb}^{-1}$

- Direct  $\tilde{\ell}$  production in  $e^-e^-$ : a golden channel for LFV??

$$\Rightarrow e^-e^- \rightarrow \tilde{\ell}_m \tilde{\ell}_k \rightarrow \ell_i^- \chi_1^0 \ell_j^- \chi_1^0 \quad [t,u\text{-channel Majorana } \chi^0 \text{ exchange}]$$

⇒ possible event  $e^-e^- \rightarrow \mu^- \mu^- + \text{missing } E$     signal of LFV!

⇒ clean signal - backgrounds? .. none from FC SUSY ...

other **New Physics** | $_{\Delta L=2}$  (e.g.  $\Delta_{(s)}^{--}$ ,  $\Delta_{(t)}^0$ ), ...

work in progress...

# 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/LC sensitivity)
- ★ **new edges** in **di-lepton distributions**
- ★ **new, clean events** at LC in **LFV  $e^- e^-$ ?**
- ★ **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|<sub>low-energy</sub>** and  $\Delta m(\tilde{e}, \tilde{\mu})|_{\text{collider}}$ ; **large RR** splittings|<sub>collider</sub>; ...]
- ⇒ **substantiate seesaw hypothesis** (eventually hinting towards new physics scale)
- ⇒ **disfavour** a **type-I seesaw** as the (only) **source of flavour violation**

- **(s)lepton** physics & **LFV** also want a **Linear Collider !**

## **Additional slides**

## LFV formulae: slepton masses

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

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

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

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

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

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

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

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

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

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

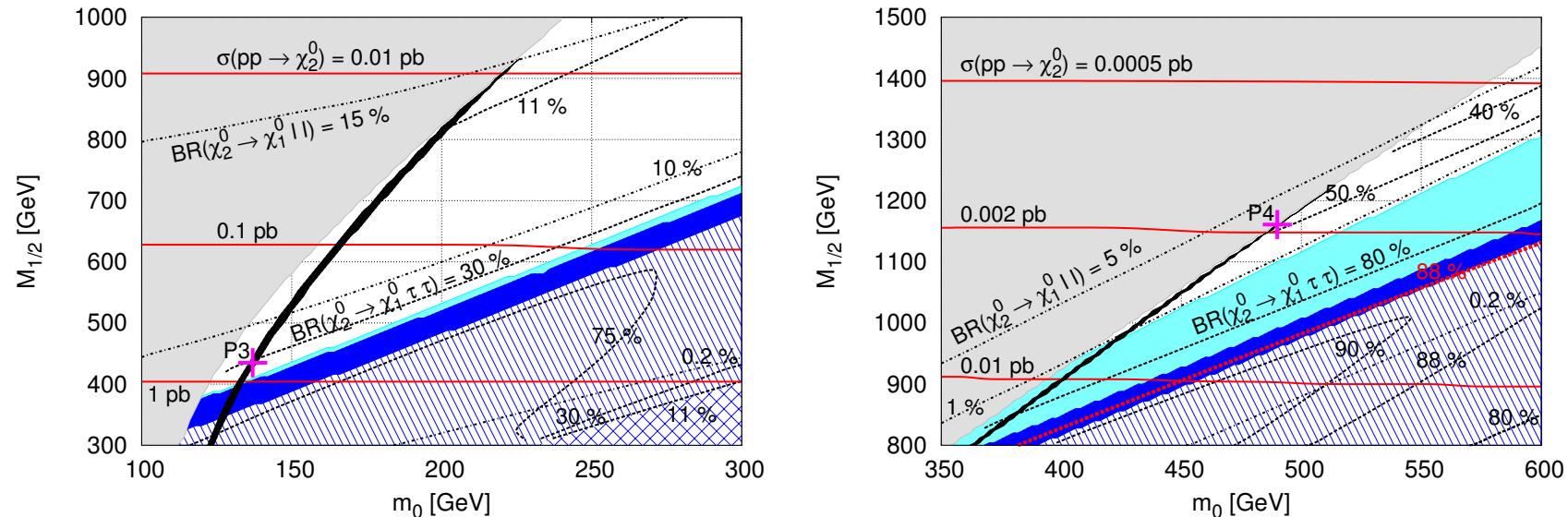
## Mass splitting formulae

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

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

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

# cMSSM parameter space for $\chi_2^0 \rightarrow \ell\ell\chi_1^0$ 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  $\chi_1^0$  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  $\text{BR}(\chi_2^0 \rightarrow \chi_1^0 \ell\ell)$  and  $\text{BR}(\chi_2^0 \rightarrow \chi_1^0 \tau\tau)$ . Full red lines denote the contours of  $\chi_2^0$  production cross sections. Crosses (pink) correspond to benchmark points P3 and P4

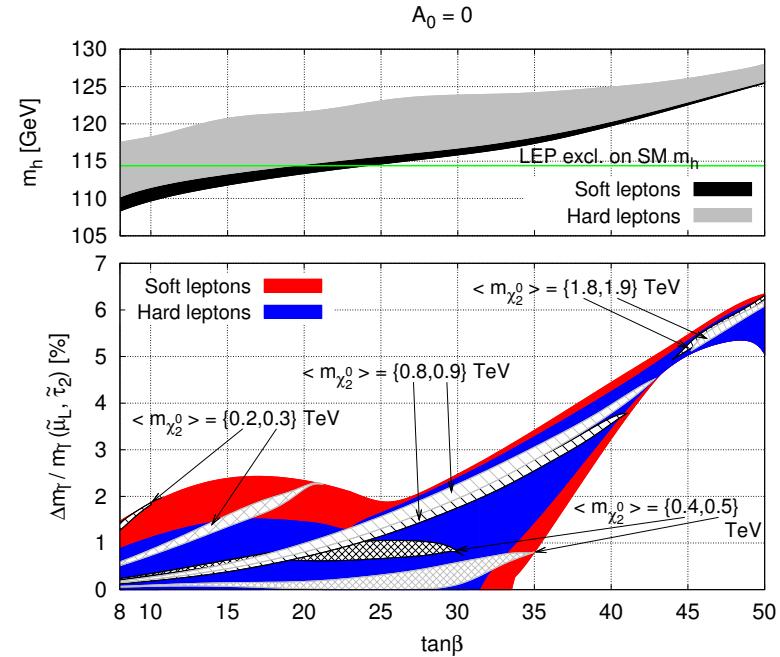
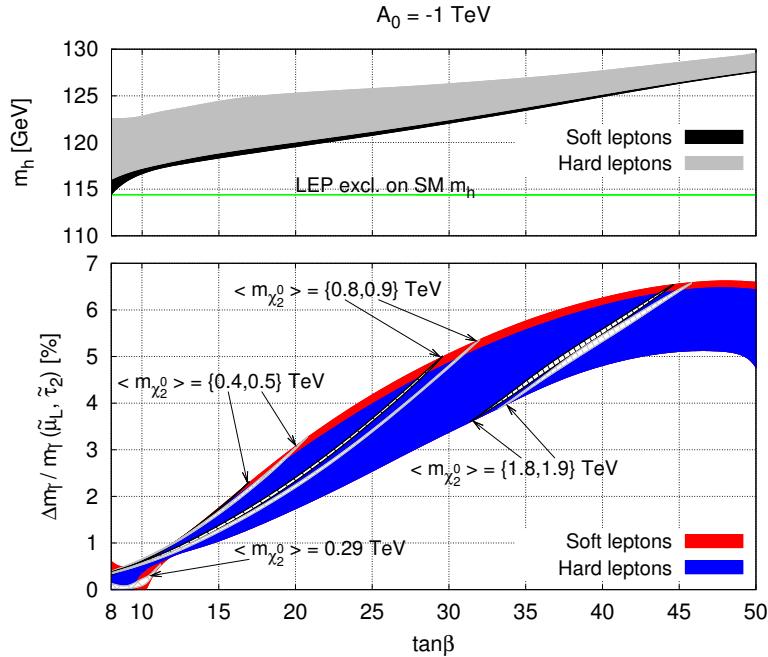
## Benchmark points: production and decay

Point	$\sigma(pp \rightarrow \tilde{\chi}_2^0)$ (fb)		$\sigma(pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0)$ (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	$\sim 0.00$	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( $\chi_2^0 \rightarrow \tilde{l}_X^i l_i \rightarrow l_i l_i \chi_1^0$ ) (%)					
		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	$6.5 \times 10^{-2}$	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	$3.2 \times 10^{-2}$	$5.7 \times 10^{-2}$	1.9

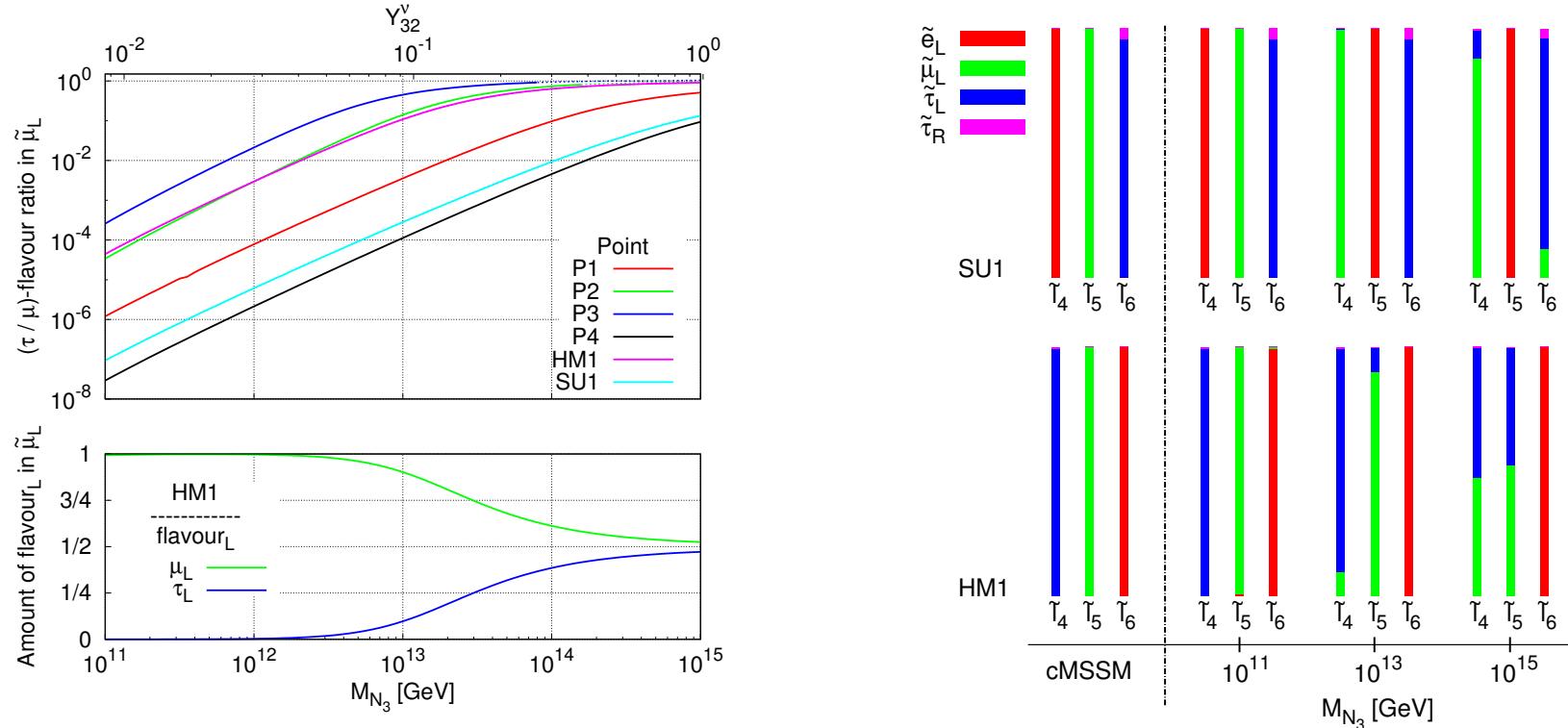
- (i) Production cross sections for at least one  $\chi_2^0$ ,  $\sigma(pp \rightarrow \tilde{\chi}_2^0)$  (in fb), and exactly two  $\chi_2^0$ ,  $\sigma(pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0)$  (in fb), for the benchmark points, with  $\sqrt{s} = 7$  TeV and 14 TeV.
- (ii) Branching ratios  $BR(\chi_2^0 \rightarrow \tilde{l}_X^i l_i \rightarrow l_i l_i \chi_1^0)$  (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,  $A_0 = -1, 0, 1 \text{ TeV}$ ). 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).

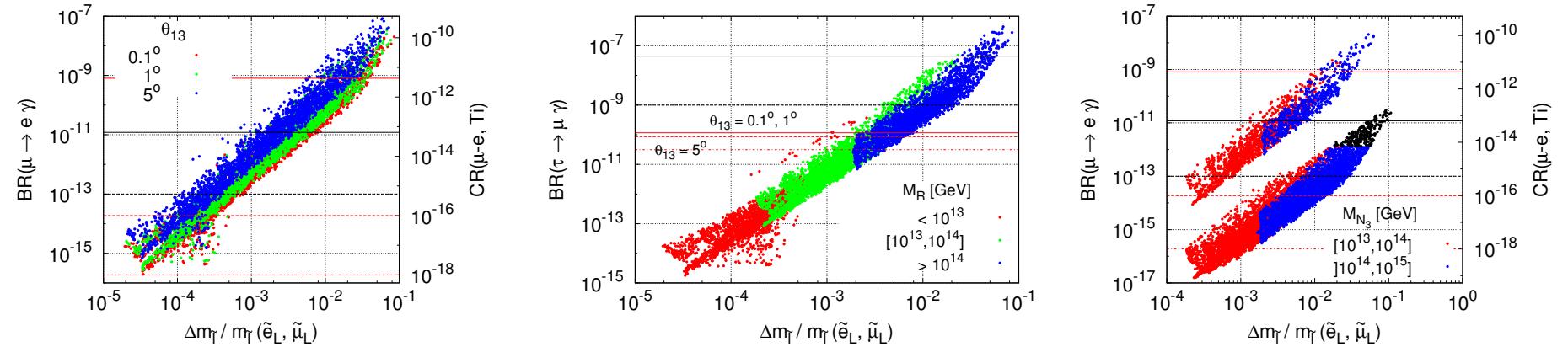
# Quasi-degenerate flavour content: effective mass splitting



On the left,  $\tau/\mu$  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  $Y_{32}^\nu$ . The secondary panel illustrates  $|R_{5\mu_L}^{\tilde{l}}|^2$  and  $|R_{5\tau_L}^{\tilde{l}}|^2$  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.

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

# Degenerate right-handed neutrinos



First (second) panel:  $\text{BR}(\mu \rightarrow e\gamma)$  ( $\text{BR}(\tau \rightarrow \mu\gamma)$ ) 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  $\text{CR}(\mu - e, Ti)$  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  $R = 1$ ,  $\theta_{13} = 0.1^\circ, 1^\circ, 5^\circ$  (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  $\theta_{13}$  ( $M_R$ ). 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.