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

Ana M. Teixeira[a], Asmaa Abada[b], António J. R. Figueiredo[c] and Jorge C. Romão[c]

[a]Laboratoire de Physique Corpusculaire, CNRS/IN2P3 – UMR 6533,
Campus des Cézeaux, 24 Av. des Landais, F-63177 Aubière Cedex, France

[b]Laboratoire de Physique Théorique, CNRS – UMR 8627,
Université de Paris-Sud 11, F-91405 Orsay Cedex, France

[c]Centro de Física Teórica de Partículas, Instituto Superior Técnico,
Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

We study the impact of a type-I SUSY seesaw concerning lepton flavour violation (LFV) at low-energies and at the LHC. At the LHC, $\chi_2^0 \to \tilde{\ell}\,\ell \to \ell\,\ell\,\chi_1^0$ decays, in combination with other observables, render feasible the reconstruction of the masses of the intermediate sleptons, and hence the study of $\ell_i - \ell_j$ mass differences. If interpreted as being due to the violation of lepton flavour, high-energy observables, such as large slepton mass splittings and flavour violating neutralino and slepton decays, are expected to be accompanied by low-energy manifestations of LFV such as radiative and three-body lepton decays. We discuss how to devise strategies based in the interplay of slepton mass splittings as might be observed at the LHC and low-energy LFV observables to derive important information on the underlying mechanism of LFV. This contribution summarises part of the work of Ref. [1].

1. MOTIVATION

Extending the Standard Model to accommodate ν data naturally opens the possibility of many other new phenomena. Embedding a type-I seesaw in supersymmetric (SUSY) models provides a unique framework where many theoretical and experimentally shortcomings of the Standard Model can be successfully addressed. Within a type-I SUSY seesaw, even if the soft supersymmetry breaking terms are flavour universal at some high energy unification scale, flavour violation appears at low-energies due to the renormalisation group (RG) evolution of the SUSY soft-breaking parameters, driven by the potentially large and necessarily non-diagonal neutrino Yukawa couplings [2]. Low-energy manifestations of LFV in the framework of the SUSY seesaw include sizeable branching ratios (BR) for radiative decays as $l_i \to l_j \gamma$, three-body decays, $l_i \to 3 l_j$ and sizeable $\mu - e$ conversion rates (CR) in heavy nuclei (for a review, see Ref. [3] and references therein).

At the LHC, processes such as slepton mediated neutralino decays $\chi_2^0 \to \ell_i^\pm\,\ell_j^\mp\,\chi_1^0$ offer a golden laboratory to study lepton flavour violation at higher energies. Three possible signals of LFV can be observed at the LHC: (i) flavoured slepton mass splittings, provided that one can effectively reconstruct slepton masses via observables such as the kinematic end-point of the invariant mass distribution of the leptons coming from the above mentioned cascade decay; (ii) multiple edges in di-lepton invariant mass distributions $\chi_2^0 \to \chi_1^0\,\ell_i^\pm\,\ell_i^\mp$, arising from the exchange of a different flavour slepton $\tilde{l}_j$ (in addition to the left- and right-handed sleptons, $\tilde{l}^i_{L,R}$); (iii) sizeable widths for LFV decay processes like $\chi_2^0 \to \ell_i^\pm\,\ell_j^\mp\,\chi_1^0$.

Our analysis [1] is focused on how the confrontation of slepton mass splittings and of low-energy LFV observables may provide important information about the underlying mechanism of LFV.

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2. THE SUSY SEESAW

Our analysis is conducted in the framework of the cMSSM extended by three right-handed neutrino superfields, so that the leptonic part of the superpotential is given by $\mathcal{W}^{\text{lepton}} = \hat{N}^c\, Y^\nu\, \hat{L}\, \hat{H}_2 + \hat{E}^c\, Y^l\, \hat{L}\, \hat{H}_1 + \frac{1}{2}\, \hat{N}^c\, M_N\, \hat{N}^c$, where the neutrino Yukawa couplings Y^ν and the Majorana mass M_N matrix are assumed to be diagonal in flavour space ($Y^l = \text{diag}(Y^e, Y^\mu, Y^\tau)$, $M_N = \text{diag}(M_{N_i})$ $i = 1, 2, 3$), without loss of generality. New terms are also added to the soft-SUSY breaking Lagragian, and universality of the soft-SUSY breaking parameters is assumed at some high-energy scale, chosen to be the gauge coupling unification scale $M_X \sim M_{\text{GUT}} \sim 10^{16}$ GeV. In the so-called seesaw limit, one has the usual seesaw equation for the light neutrino masses $m_\nu = -{m_D^\nu}^T M_N^{-1} m_D^\nu$, where $m_D^\nu = Y^\nu\, v_2$ and v_i are the vacuum expectation values of the neutral Higgs scalars, $v_{1(2)} = v\, \cos(\sin)\beta$, with $v = 174$ GeV. A convenient means of parametrizing the neutrino Yukawa couplings, while at the same time allowing to accommodate the experimental data, is given by the Casas-Ibarra parametrization [4], which reads at the seesaw scale M_N

$$Y^\nu v_2 = m_D^\nu \,=\, i \sqrt{M_N^{\text{diag}}}\, R\, \sqrt{m_\nu^{\text{diag}}}\, {U^{\text{MNS}}}^\dagger\,. \quad (1)$$

In Eq. (1) R is a 3×3 complex orthogonal matrix (parametrized by 3 complex angles θ_i), that encodes the possible mixings involving the right-handed neutrinos, in addition to those of the low-energy sector (i.e. U^{MNS}). We use the standard parametrization of the U^{MNS}, with the three mixing angles in the intervals favoured by current best-fit analyses [5].

2.1. Low-energy LFV observables

In the presence of mixings in the lepton sector, Y^ν is clearly non-diagonal in flavour space, and the running from M_X down to the seesaw scale will induce flavour mixing in the otherwise (approximately) flavour conserving SUSY breaking terms. As an example, at low energies the slepton-doublet soft-breaking mass, $m^2_{\tilde{L}}$ (which at the GUT scale is $m^2_{\tilde{L}} = \text{diag}(m_0^2)$) now reads

$$\begin{aligned} (m^2_{\tilde{L}})_{ij} \approx & \;\left(m_0^2 + 0.5 M_{1/2}^2 - m_0^2 |y| (Y^l)^2_{ii}\right) \\ & \qquad + (\Delta m^2_{\tilde{L}})_{ij}\,, \qquad (2) \\ (\Delta m^2_{\tilde{L}})_{ij} \approx & \;-\tfrac{1}{8\,\pi^2}(3 m_0^2 + A_0^2)({Y^\nu}^\dagger L Y^\nu)_{ij}\,, \end{aligned}$$

where $L_{kl} = \log(M_X/M_{N_k})\delta_{kl}$. Hence, slepton mass matrices are non-diagonal, and there is a misalignment between slepton mass and interaction eigenstates. Notice that in the framework of the SUSY seesaw, there is only one source of (s)lepton flavour violation: the neutrino Yukawa couplings, Y^ν.

Flavour violating transitions can occur in the charged slepton sector, giving rise to low-energy LFV observables such as $l_i \to l_j \gamma$, $l_i \to 3 l_j$ and $\mu - e$ conversion in nuclei.

2.2. LFV at the LHC

Within the cMSSM, and in the absence of explicit mixing in the slepton sector, there are only two sources of non-universality for the masses of left- and right-handed sleptons: (i) RGE effects proportional to $(Y^l)^2_{ij}$ (see Eqs. (2)); (ii) LR mixing effects, also proportional to the lepton masses ($m_i^l\, \tan\beta$). Hence, the cMSSM mass differences between the first two families are extremely small implying that, to a large extent, the left- and right-handed selectrons and smuons are nearly degenerate, the mass splitting typically lying at the per mille level.

In the SUSY seesaw, the radiative corrections introduced by the neutrino Yukawa couplings induce both flavour conserving and flavour violating contributions to the slepton soft masses: in addition to generating LFV effects, the new terms proportional to Y^ν will also break the approximate universality of the first two generations. An augmented mixing between $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$ translates into larger mass splittings for the mass eigenstates. In particular, as noticed in [6], large mixings involving the third generation can lead to sizeable values of the mass splitting between slepton mass eigenstates, while avoiding the stringent BR($\mu \to e\gamma$) constraint. In the latter case (i.e. large $Y^\nu_{32,33}$), the mass splittings between left-handed sleptons of the first two generations are given by

$$\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{e}_L,\tilde{\mu}_L) = \frac{|m_{\tilde{e}_L} - m_{\tilde{\mu}_L}|}{\langle m_{\tilde{\ell}_{e,\mu}}\rangle} \approx \frac{1}{2}\,\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\mu}_L,\tilde{\tau}_2) \approx \frac{1}{2}\left|\frac{(\Delta m^2_{\tilde{L}})_{23}}{(m^2_{\tilde{L}})_{33}}\right|, \quad (3)$$

and can be sizeable, well within the expected sensitivity of the LHC [7]. Furthermore, notice that in the framework of the SUSY seesaw, large slepton mass splittings only emerge for the left-handed sleptons ($\tilde{\mu}_R$ and $\tilde{e}_R$ remain approximately degenerate).

In the cMSSM, the decays of the χ_2^0 into a di-lepton final state $\chi_2^0 \to \ell_i^{\pm}\,\ell_i^{\mp}\,\chi_1^0$ are flavour conserving, implying that if measurable, the kinematical edges of a di-lepton mass distribution, $m_{\ell_i\ell_i}$ necessarily lead to the reconstruction of intermediate sleptons of the same flavour, $\tilde{\ell}^i_{L,R}$.

SUSY models violating strict lepton flavour symmetry may leave distinct imprints on the di-lepton mass distribution, depending on whether the soft-breaking slepton terms are non-universal (but flavour conserving) or truly flavour-violating. In the first case, the most significant effect will be a visible displacement of the kinematical edges in each of the di-lepton distributions: for instance, the edge corresponding to $\tilde{e}_L$ in m_{ee} will not appear at the same values as that of $\tilde{\mu}_L$ in $m_{\mu\mu}$, implying that $m_{\tilde{e}_L} \neq m_{\tilde{\mu}_L}$. The second case will lead to far richer imprints: in addition to a relative displacement of the $\tilde{\ell}^i_X$ in the corresponding $m_{\ell_i\ell_i}$ distributions, the most striking effect is the appearance of new edges in a di-lepton mass distribution: provided there is a large flavour mixing in the mass eigenstates (and that all the decays are kinematically viable), one can have $\chi_2^0 \to \{\tilde{\ell}^i_L\,\ell_i, \tilde{\ell}^i_R\,\ell_i, \tilde{\ell}^j_X\,\ell_i\} \to \chi_1^0\,\ell_i\,\ell_i$ so that in addition to the two $\tilde{\ell}^i_{L,R}$ edges, a new one would appear due to the exchange of $\tilde{\ell}^j_X$.

Having a unique source of flavour violation implies that the high-energy LFV observables, $\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}(\tilde{\ell}_i,\tilde{\ell}_j)$, are strongly correlated with the low-energy ones (BRs and CR). In the absence of a direct means of testing the SUSY seesaw, the interplay of these sets of observables may allow to either strengthen the seesaw hypothesis, or even disfavour the seesaw (thus suggesting additional or even distinct sources of flavour violation).

Table 1
mSUGRA benchmark points selected for the LFV analysis: m_0, $M_{1/2}$ (in GeV) and A_0 (in TeV), and $\tan\beta$ ($\mu > 0$). HM1 and SU1 are LHC CMS- and ATLAS-proposed benchmark points [8].

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

3. RESULTS

3.1. Slepton mass reconstruction

The identification of the several high-energy LFV observables at the LHC implies that several requirements must be met. First of all, the spectrum must be such that the decay chain $\chi_2^0 \to \tilde{\ell}\ell \to \chi_1^0\ell\ell$, with intermediate real (on-shell) sleptons, is allowed; secondly, the outgoing leptons should be sufficiently hard: $m_{\chi_2^0} - m_{\tilde{\ell}_L,\tilde{\tau}_2} > 10$ GeV; moreover, the χ_2^0 production rates, and the BR($\chi_2^0 \to \chi_1^0\ell\ell$) must be large enough to ensure that a significant number of events is likely to be observed at the LHC.

The above requirements impose strong constraints on the cMSSM parameters (i.e. on m_0, $M_{1/2}$, A_0 and $\tan\beta$). In [1], the cMSSM parameter space was thouroughly investigated, leading to the identification of regions where the slepton masses could be successfully reconstructed. This study allowed to identify several benchmark points (to which two LHC ones were added), which were used in the numerical studies.

If such events are indeed observable, and successfully reconstructed, one expects a 0.1% precision in the measurement of the kinematical edges of the di-lepton invariant mass distributions [9,10], $m_{\ell\ell} = \frac{1}{m_{\tilde{\ell}}}\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\chi_1^0})}$. In turn, this will allow to infer the slepton mass differences with a precision of $\sim 10^{-4}$ for a $\tilde{e} - \tilde{\mu}$ relative mass difference [7]; in our analysis we adopted a more conservative view, assuming maximal sensitivities of $\mathcal{O}(0.1\%)$ for $\Delta m_{\tilde\ell}/m_{\tilde\ell}(\tilde e,\tilde\mu)$ and $\mathcal{O}(1\%)$ for $\Delta m_{\tilde\ell}/m_{\tilde\ell}(\tilde\mu,\tilde\tau)$.

3.2. LFV at low and high energies

In the framework of the cMSSM (without a seesaw mechanism), the dilepton invariant mass distribution ($\ell = e,\mu$) for the study points of Table 1 leads to double triangular distributions (except for point P1), with superimposed edges corresponding to the exchange of left- and right-handed selectrons and smuons [1]. The numerical scans of the parameter space further confirm that in the cMSSM both $\Delta m_{\tilde\ell}/m_{\tilde\ell}(\tilde e_L,\tilde\mu_L)$ and $\Delta m_{\tilde\ell}/m_{\tilde\ell}(\tilde e_R,\tilde\mu_R)$ lie in the range $10^{-7} - 10^{-3}$.

Even in the most minimal implementation of the seesaw, assuming that all flavour mixing in Y^ν is only stemming from the x U^{MNS} mixing matrix (i.e. taking the conservative limit $R = 1$ in Eq. 1), the left-handed slepton mass splittings are much larger than in the cMSSM, with values as large as $\mathcal{O}(10\%)$. Very large splittings are associated with heavy seesaw scales (in particular, M_{N_3}) and/or large, negative values of A_0. Aside from the perturbativity bounds on Y^ν, the most important constraints on the seesaw parameters arise from the non-observation of LFV processes: since both flavour violating BRs and slepton mass splittings originate from the same unique source (Y^ν), compatibility with current bounds, in particular on BR($\mu \to e\gamma$) and BR($\tau \to \mu\gamma$), may preclude sizeable values for the slepton mass splittings[1]. This unique synergy is instrumental in devising a strategy to test the SUSY seesaw via the interplay of high- and low-energy observables.

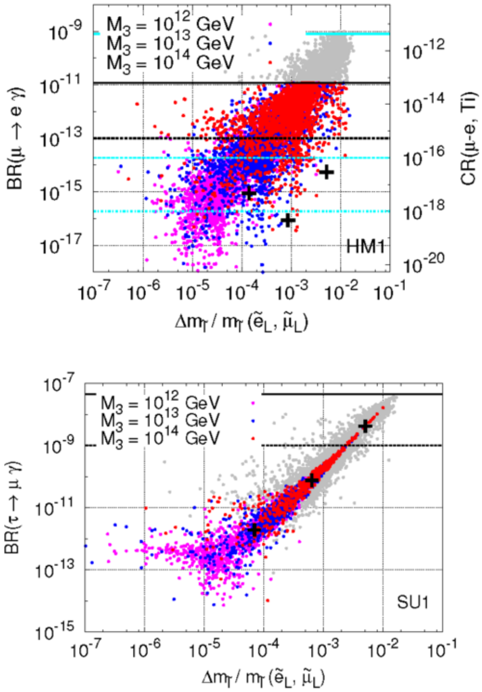

Figure 1. Upper panel: BR($\mu \to e\gamma$) as a function of the $\tilde e_L - \tilde\mu_L$ mass difference, for seesaw variations of point HM1. On the secondary right y-axis, the corresponding predictions of CR($\mu - e$, Ti). Lower pannel: BR($\tau \to \mu\gamma$) as a function of the $\tilde e_L - \tilde\mu_L$ mass difference, for seesaw variations of point 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. We take the Chooz angle to be $\theta_{13} = 0.1°$, and the remaining parameters were set as $M_{N_1} = 10^{10}$ GeV, $M_{N_2} = 10^{11}$ GeV, with the complex R matrix angles being randomly varied as $|\theta_i| \in [0,\pi]$, and $\arg(\theta_i) \in [-\pi,\pi]$.

If the LHC measures a given mass splitting, predictions can be made regarding the associated LFV BRs (for an already reconstructed set of mSUGRA parameters). Comparison with current bounds (or possibly an already existing BR measurement) may allow to derive some hints on the underlying source of flavour violation: a measurement of a slepton mass splitting of a few percent, together with a measurement of a low-energy observable (in agreement to what could be expected from the already reconstructed SUSY spectrum) would constitute two signals of LFV that could be simultaneously explained through one common origin - a type-I seesaw mechanism. On the

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[1] This is in contrast with other scenarios of (effective) flavour violation in the slepton sector where the different off-diagonal elements of the slepton mass matrix can be independently varied [6].

other hand, two conflicting situations may occur: (i) a measurement of a mass splitting associated to LFV decays experimentally excluded; (ii) observation of LFV low-energy signal, and (for an already reconstructed SUSY spectrum) approximate slepton mass universality. These scenarios would either suggest that non-universal slepton masses or low-energy LFV would be due to a mechanism other than such a simple realisation of a type-I seesaw (barring accidental cancellations or different neutrino mass schemes). For instance, a simple explanation for the first scenario would be that the mechanism for SUSY breaking is slightly non-universal (albeit flavour conserving).

To illustrate this interplay, we conduct a general scan over the seesaw parameter space. In Fig. 1 we display different low-energy LFV observables as a function of the $\tilde{e}_L - \tilde{\mu}_L$ mass difference, and choose for this overview of the SUSY seesaw the LHC points HM1 and SU1.

As can be seen from the upper panel of Fig. 1, if a SUSY type-I seesaw is indeed at work, and θ_{13} has been constrained to be extremely small, a measurement of $\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L)$ between 0.1% and 1%, in association with a reconstructed sparticle spectrum similar to HM1, would be accompanied (with a significant probability) by the observation of $\mathrm{BR}(\mu \to e\gamma)$ at MEG [11] (and we notice here that, even for very large values of M_{N_3}, the constraints on the parameter space from $\mathrm{BR}(\mu \to e\gamma)$ would preclude the observation of a $\tau \to \mu\gamma$ transition for an HM1-like spectrum).

Although LHC production prospects have to be taken into account, when compared to HM1, SU1 offers a less promising framework for the observation of sizable mass splittings at the LHC (unless a precision of around 10^{-3} for $\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L)$ can indeed be achieved). However the most interesting lepton flavour signature of SU1 is related to its potential to induce large $\mathrm{BR}(\tau \to \mu\gamma)$, within the future sensitivity of SuperB [12]: a measurement of $\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L) \sim 0.1\%{-}1\%$ at the LHC would imply $\mathrm{BR}(\tau \to \mu\gamma) \gtrsim 10^{-9}$, and would hint towards a heavy seesaw scale, $M_{N_3} \gtrsim 10^{13}$ GeV.

3.3. LFV at the LHC: χ_2^0 decays

In the upper panel of Fig. 2, we display the $\mathrm{BR}(\chi_2^0 \to \mu\,\mu\,\chi_1^0)$ as a function of the di-muon invariant mass $m_{\mu\mu}$ for different SUSY seesaw points (see [1]), comparing the distributions with those of the cMSSM. As is manifest from Fig. 2, the impact of the seesaw at the level of the dimuon mass distributions is quite spectacular, particularly in the appearance of a third edge in most of the benchmark points considered. With the exception of the seesaw variation of point P1, all other distributions now exhibit the edge corresponding to the presence of an intermediate $\tilde{\tau}_2$, implying that the decay occurs via $\chi_2^0 \to \tilde{\tau}_2\mu \to \mu\,\mu\,\chi_1^0$. For instance, for point P2′, the $\mathrm{BR}(\chi_2^0 \to \mu\mu\chi_1^0)$ via intermediate $\tilde{\mu}_L$, $\tilde{\mu}_R$ and $\tilde{\tau}_2$ are 2.6%, 1.1% and 1.6%, respectively. Interestingly, the fact that the SUSY seesaw leads to increased mass splittings only for the left-handed sleptons might provide another potential fingerprint for this mechanism of LFV. Compiling all the data collected throughout our numerical analysis, we have found that the maximal splitting between right-handed smuons and selectrons is $\left.\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}(\tilde{\mu}_R, \tilde{e}_R)\right|_{\max} \approx 0.09\%$ (while within the SUSY seesaw $\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}(\tilde{\mu}_L, \tilde{e}_L)$ could easily reach values of a few %). Should the LHC measure mass splittings between right-handed sleptons of the first two families that are significantly above the 0.1% level, this could provide important indication that another mechanism of FV should be at work: among the many possibilities, a likely hypothesis would be the non-universality of the slepton soft-breaking terms.

Finally, we display in the lower panel of Fig. 2 the prospects for direct flavour violation in χ_2^0 decays: in addition to the possibility of having staus in the intermediate states, one can also have opposite-sign, different flavour final state dileptons. In particular, one can have $\chi_2^0 \to \mu\tau\chi_1^0$, with a non-negligible associated branching ratio. For $\sqrt{s} = 14$ TeV and $\mathcal{L} = 100\ \mathrm{fb}^{-1}$, the expected number of events (without background analysis nor detector simulation) is $\mathcal{O}(10^3)$.

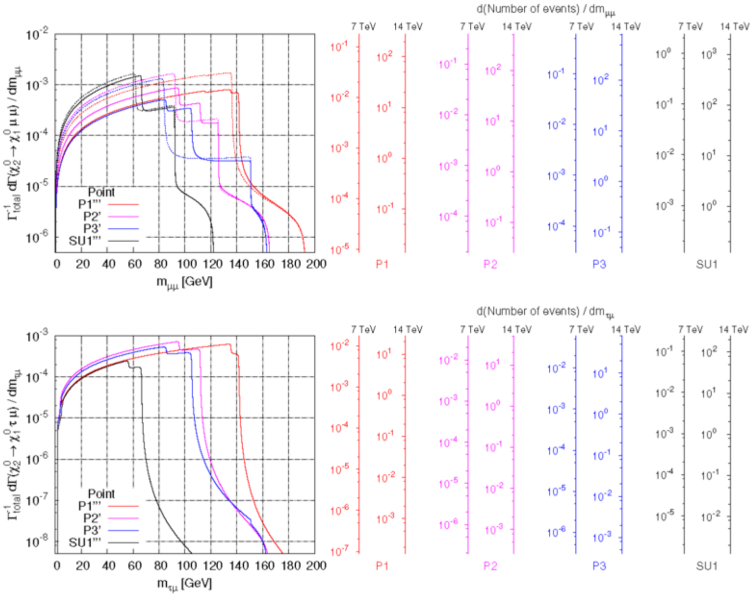

Figure 2. Upper panel: BR($\chi_2^0 \to \mu\mu\chi_1^0$) as a function of the di-muon invariant mass $m_{\mu\mu}$ (in GeV), with dotted lines corresponding to the corresponding cMSSM case; lower panel: BR($\chi_2^0 \to \mu\tau\chi_1^0$) as a function of the di-lepton invariant mass $m_{\tau\mu}$ (in GeV). We consider different realisations of SUSY seesaw points: P1$'''$ (red), P2$'$ (pink), P3$'$ (blue) and SU1$'''$ (black). Secondary 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}.

4. CONCLUDING REMARKS

We have discussed that if the seesaw is indeed the source of both neutrino masses and leptonic mixings, and also accounts for low-energy LFV observables within future sensitivity reach, interesting slepton phenomena are expected to be observed at the LHC: in addition to the mass splittings, the most striking effect will be the possible appearance of new edges in di-lepton mass distributions. From the comparison of the predictions for the two sets of observables (high and low energy) with the current experimental bounds and future sensitivities, one can either derive information about the otherwise unreachable seesaw parameters, or disfavour the type-I SUSY seesaw as the unique source of LFV. A complete analysis can be found in Ref. [1].

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