Neutrino Physics, Lepton Flavour Violation and the LHC

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Abstract

We will briefly review flavour violation in the lepton sector: starting from neutrino oscillations and their implications, we consider several charged lepton flavour violating observables at high and low energies. We present new physics models and discuss the rôle of the latter in disentangling them. In particular, we show how the interplay of different observables allows to derive important information on the underlying mechanism of lepton flavour violation. As an example, we discuss the impact of a type-I SUSY seesaw concerning lepton flavour violation at low energies and at colliders (LHC and a future Linear Collider).

1 Introduction

Neutrino ($\nu$) oscillation experiments provide indisputable evidence for flavour violation in the neutral lepton sector. This is manifest in leptonic charged currents and, as it occurs for the quark sector, the corresponding amount of flavour violation can be encoded into a mixing matrix, the $U_{\text{PMNS}}$. Nevertheless, oscillation data only adds to the Standard Model’s fermion flavour puzzle: the mixing patterns on the quark and lepton sectors are very different; available data on neutrino masses (mass squared differences and bounds on the absolute mass scale) suggests that if these are to be accommodated via a minimal extension of the Standard Model (SM) by additional right-handed (RH) neutrinos, the Yukawa couplings of the corresponding Dirac mass term ($\sim Y_{\nu L \nu R}$) would be $O(10^{-12})$, rendering even worse the fermion hierarchy puzzle.

In order to accommodate $\nu$ oscillation data, the SM must clearly be extended, and additional degrees of freedom incorporated (RH neutrinos, triplet Higgs, ...). Moreover, should neutrinos be Majorana fermions, new physics (NP) at scales much lighter or far heavier than the electroweak (EW) one can be present. Current experimental (and cosmological) data on neutrino phenomena leaves numerous questions unanswered, such as the hierarchy in the neutrino spectrum, leptonic CP violating phases and their possible rôle in the evolution of the early Universe, unitarity violation in neutrino interactions, non-standard interactions, among many others. Moreover current reactor and accelerator anomalies suggest that there might be extra fermionic gauge singlets (sterile states). This would in turn imply that instead of a 3-neutrino mixing scheme we could have 3+1 (or more)-mixing schemes, and this would have considerable implications on NP models. Possible SM extensions aiming at incorporating massive neutrinos and leptonic mixing will also open
the door to many new phenomena, such as flavour violation in the charged lepton sector (cLFV),
leptonic electric dipole moments, contributions to the muon anomalous magnetic moment, .... The
new states present in these extensions can also give rise to interesting collider signatures.

Other than $\nu$-mixings, there are several observational problems and theoretical caveats sug-
gest ing that NP is indeed required: the former are related to the baryon asymmetry of the Universe
and the need for a dark matter candidate, while among the latter one can mention the hierarchy
problem, the flavour puzzle, or fine-tuning in relation to EW symmetry breaking. There are nu-
merous well motivated and appealing models of NP that aim at addressing these issues, and which
are currently being actively investigated and searched for. Disentangling the NP model and in
particular, probing the underlying mechanism of neutrino mass generation, requires investigating
all available observables, arising from all fronts - high-intensity, high-energy and cosmology - as
well as thoroughly exploring the interplay between them.

Here, we will focus on charged lepton flavour violating observables at low-energies and at
colliders, and we discuss their powerful rôle in shedding light on the NP model. We will begin
by briefly reviewing the effective approach (model-independent) and subsequently consider dif-
ferent SM extensions. Finally, and as an example, we will address in some detail cLFV in the
supersymmetric (SUSY) seesaw.

2 cLFV observables

In the SM, as it was originally formulated (massless $\nu$), cLFV processes are strictly forbidden.
With massive $\nu$’s (no assumption being made on the mechanism of $\nu$ mass generation), cLFV
processes are suppressed by the tiny $\nu$ masses (GIM-like suppression): for example, the branching
ratio (BR) of the $\mu \to e\gamma$ decay, schematically depicted in Fig. 1(a), is given by

$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2,$$

and using known oscillation parameters ($U = U_{PMNS}$ the leptonic mixing matrix) [2], one finds
$BR(\mu \to e\gamma) \lesssim 10^{-54}$, thus unaccessible to present and future experiments! In contrast with
flavour violation in the hadronic sector, where phenomena such as neutral meson mixings and
rare decays can be successfully explained by the SM, cLFV signals indisputably the presence of
new physics. Indeed, the additional particle content and the new flavour dynamics present in many
extensions of the SM may give contributions to cLFV processes such as radiative (e.g. $\mu \to e\gamma$)
and three-body decays (e.g. $\mu \to eee$), so that the observation of such processes would provide an
unambiguous signal of NP, see Fig. 1(b).

![Radiative decays](image1.png)

Figure 1: Radiative decays $\ell_i \to \ell_j \gamma$: (a) in the SM ($m_\nu \neq 0$), in NP models (b) and in SUSY models (c).
So far, no signal of cLFV has been observed, even though the searches for rare leptonic
decays have been an important part of the experimental program for several decades. Currently,
the search for manifestations of cLFV constitutes the goal of several experiments exclusively
dedicated to look for signals of rare lepton decay processes. Equally interesting LFV observables
are $\mu - e$ conversion in heavy nuclei: although significant improvements are expected regarding
the experimental sensitivity to $\mu \to e\gamma (< 10^{-13})$ [3], the most challenging experimental prospects
arise for the CR($\mu - e$) in heavy nuclei such as titanium or gold. The possibility of improving the
sensitivities to values as low as $\sim 10^{-18}$ renders this observable an extremely powerful probe of
LFV in the muon-electron sector. In Table 1, we briefly survey some of the current bounds for
the different cLFV processes, as well as the future experimental sensitivity.

| LFV process | Present bound | Future sensitivity |
|-------------|---------------|--------------------|
| BR($\mu \to e\gamma$) | $5.7 \times 10^{-13}$ | $6 \times 10^{-14}$ |
| BR($\tau \to e\gamma$) | $3.3 \times 10^{-8}$ | $10^{-9}$ |
| BR($\tau \to \mu\gamma$) | $4.4 \times 10^{-8}$ | $10^{-9}$ |
| BR($\mu \to 3e$) | $1.0 \times 10^{-12}$ | $\sim 10^{-16}$ |
| BR($\tau \to 3e$) | $2.7 \times 10^{-8}$ | $2.3 \times 10^{-10}$ |
| BR($\tau \to 3\mu$) | $2.1 \times 10^{-8}$ | $8.2 \times 10^{-10}$ |
| CR($\mu - e$, Ti) | $4.3 \times 10^{-12}$ | $\mathcal{O}(10^{-18})$ |
| CR($\mu - e$, Au) | $7 \times 10^{-13}$ | $\mathcal{O}(10^{-16})$ |

Table 1: Present bounds and future sensitivities for several LFV observables.

In addition to low-energy experiments, there are also searches for cLFV at high-energies: the
presence of new flavour violating physics can be directly signaled via the LFV production and/or
decays of heavy states (which must be nevertheless sufficiently light to be produced at the LHC
or a future Linear Collider). Moreover, data from LHCb is also expected to directly constrain
LFV (as well as lepton number violation) in meson and in tau-lepton decays.

In the absence of cLFV and other signals, one could constraint the parameter space of NP
models (scale, couplings, ...) and this may directly probe the neutrino mass generation mechanism.
On the other hand, if cLFV is indeed observed, then one should compare the signal with peculiar
features of a given model (predictions of observables, patterns of correlations between observables).
A possibility to address these NP scenarios is to use the effective approach and study a given
(cLFV) observable in a model independent way.

3 cLFV: the effective approach

In the SM, lepton number is an accidental symmetry due to the gauge group and particle con-
tent. The generation of $\nu$ masses exclusively using the SM field content requires adding non-
renormalisable operators of dimension 5 (or higher), that break lepton number, to the SM La-
grangian. Independent of the model, the only possible $d = 5$ operator is the Weinberg operator,
$\delta L^{d=5} = \frac{1}{2} c_{a\beta}^{d=5} (\bar{\ell}_L \tilde{\Phi}^a) (\tilde{\phi}^a \ell_R)$, where $\ell_L$ stands for the lepton doublets and and $\tilde{\phi}$ is
related to the SM Higgs doublet. The coefficient $c_{d=5}$ is a matrix of inverse mass dimension, which
is not invariant under $B - L$, and is thus a source of Majorana $\nu$ masses.

Among the dimension 6 operators (second order in an $1/M$ expansion, $M$ being the scale of
NP), one finds four-fermion operators responsible for cLFV processes. The breaking of lepton
number, as required by Majorana $\nu$ masses, then provides a natural link between neutrino mass generation and cLFV. The effective Lagrangian then reads
\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{M} c^{d=5} \mathcal{O}^{d=5} + \frac{1}{M^2} c^{d=6} \mathcal{O}^{d=6} + \cdots ,
\]
(2)
where the NP, valid at the scale $M$ is encoded in the coefficients, $c^{d>4}$.

In the case of a minimal extension of the SM by heavy fields, it can be shown that one can only have three types of basic seesaw mechanisms, depending on the nature of the new heavy fields: right-handed neutrinos (type I), heavy scalars (type II) or fermionic triplets (type III), as depicted in Fig. 2. It is important to notice that all these mechanisms can be embedded into larger frameworks such as grand unified theories (GUTs), SUSY and extra dimensions.

![Image](image_url)

**Figure 2:** Seesaw mechanisms: (a) singlet fermion, (b) triplet fermion and (c) triplet scalar exchange.

In the case of a fermionic (type I or III) seesaw, the heavy propagator is expanded as $\frac{1}{D^2 - M^2} \sim -\frac{1}{M} - \frac{1}{M^2} D^2 + \cdots$. The first term induces a $d = 5$ scalar operator, which flips chirality and generates a $\nu$-mass term. The second term ($\sim 1/M^2$) preserves chirality and induces a correction to the kinetic terms of the light fields. The coefficients $c^{d=6} \propto \frac{1}{M^2}$ are suppressed compared to those associated to the $d = 5$ operator, $c^{d=5} \propto \frac{1}{M}$. The situation is different in the case of heavy scalar triplets, since the scalar propagator expands as $\frac{1}{D^4 - M^4} \sim -\frac{1}{M^4} - \frac{D^2}{M^4} + \cdots$, implying that the $d = 5$ operator already scales as $1/M^2$. In the case of the type I and III seesaws, $c^{d=5} = Y^T N Y_N$, $Y_N$ being the Yukawa couplings to the Higgs field and $M_N$ the heavy fermion masses. Accommodating $\nu$ data with natural coefficients ($c^{d=5} \sim O(1)$), implies $M_N \sim 10^{15}$ GeV, intriguingly close to GUT scale. However, the scale of NP can be lowered to $\sim 1$ TeV if one allows for couplings as small as the charged lepton ones. In the case of a scalar triplet, $c^{d=5} \propto Y_\Delta \mu_\Delta / M^2_\Delta$; the scale $\mu_\Delta$ can be directly related to the smallness of $m_\nu$, thus allowing to have $M_\Delta \sim$ TeV with natural Yukawa couplings.

Since such a $d = 5$ operator is characteristic to all models with Majorana $\nu$, the coefficient $c^{d=5}$ does not allow to discriminate among the different models. In order to do so, one must either produce the heavy mediators or call upon the low-energy effects of the different $d = 6$ operators. There is a large number of such operators but here we will only focus on those inducing cLFV processes. On Table 2 we list the $d = 6$ cLFV operators as well as the corresponding coefficient for each type of seesaw and, for comparison, the $d = 5$ coefficient.

From a symmetry point of view, it is natural to have large $c^{d=6}$ coefficients, since the $d = 6$ operators preserve $B - L$, in contrast with the $d = 5$ operator. For example, in the type II seesaw, the dimensionfull $\mu_\Delta$ coefficient, which is directly related to the smallness of $m_\nu$, does not affect the dimension 6 operator. However, decoupling the $d = 5$ and $d = 6$ coefficients is not possible in the fermionic seesaw (see Table 2).

In the effective approach (for a review, see [14]), the observables can be written in terms of effective parameters, encoding the flavour mixing generated by the model, which remains valid up
Effective Lagrangian

\[ L_{\text{eff}} = c_i O_i \]

Table 2: Dimension 6 operators (and coefficients) responsible for cLFV and corresponding \( d = 5 \) coefficients.

| Model                  | \( c^{d=5} \)          | \( c^{d=6} \)          | \( O^{d=6} \)          |
|------------------------|-------------------------|-------------------------|-------------------------|
| Fermionic Singlet (type I) | \( Y_T \frac{1}{M_N} Y_N \) | \( Y_N \frac{1}{M_N} \) | \( \ell_{\alpha \beta} \phi \) |
| Scalar Triplet (type II)  | \( 4Y_\Delta \frac{1}{M_\Delta} \) | \( \Delta \alpha \beta \) | \( \ell_{\alpha \beta} \phi \) |
| Fermionic Triplet (type III) | \( Y_T \frac{1}{M_\Sigma} Y_\Sigma \) | \( \Sigma \alpha \beta \) | \( \ell_{\alpha \beta} \phi \) |

A signal from MEG (Table 1) i.e. \( 10^{-14} \lesssim \text{BR}(\mu \rightarrow e\gamma) \lesssim 10^{-13} \) will put constraints on \( \Lambda \), depending on the size of the couplings: assuming natural values of \( Y_\Delta \sim 1 \) implies that \( 15 \text{ TeV} < \Lambda < 50 \text{ TeV} \), while for \( Y_\Delta \sim 10^{-2} \), \( \text{BR}(\mu \rightarrow e\gamma) \) within MEG reach would lead to \( 0.15 \text{ TeV} < \Lambda < 0.5 \text{ TeV} \). If the triplet mass is of the order of the TeV, then one could expect some signals at the LHC, like the production of doubly charged Higgs triplet decaying into same sign leptons (a striking signal, clean from any SM background). Collider signatures depend on the different parameters of the model and so far, negative LHC searches have already allowed to constrain the parameter space of this model \( [15] \); moreover the existing synergy between high- and low-energy observables also allows to infer information on the neutrino mass spectrum and CP violating phases \( [16] \).

4 cLFV and new physics

Depending on the \( \nu \) mass generation mechanism, one can have very different scenarios of cLFV at low-energies. Whichever NP is called upon to explain the origin of (Majorana) \( \nu \) masses and mixings, whether or not it is sufficiently large to generate observable cLFV strongly depends on two main ingredients: the scale of NP (not necessarily the scale of the seesaw mediator) and the amount of mixing present in the lepton sector parametrized by an effective mixing \( \theta_{ij} \) (\( U^{PMNS} \) and additional mixings).

There are several classes of well-motivated extensions of the SM, aiming at overcoming both its theoretical and experimental shortcomings. These models can either offer new explanations for the smallness of \( m_\nu \) (e.g. through a geometrical suppression mechanism, as is the case of large extra dimensions, or then R-parity violation in the case of SUSY models), or onto them one can embed a seesaw mechanism. In addition, these extensions can provide new sources of LFV \( [17] \).

In general, the low-energy cLFV observables can be significantly enhanced when compared to the minimal seesaw\(^1\).

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\(^1\) For a discussion on observable cLFV signals in TeV-scale type I seesaw and Higgs triplet models, see e.g. \( [18] \).
For instance, in the framework of enlarged Higgs sectors (as is the case of Little Higgs models [20]), new couplings between SM leptons, new “mirror” fermions and heavy gauge bosons are sources of cLFV, being also at the origin of $m_\nu \neq 0$; this leads to scenarios of strongly correlated cLFV observables. However, such models require a sizable fine-tuning of the parameters as they typically induce excessively large contributions to low-energy cLFV observables.

Another class of models generating non-trivial lepton flavour structures is associated to the displacement of SM fermions along extra dimensions (scenarios with either large flat [21] or small warped [22] extra dimensions). For example, in the case of RS warped extra dimensions, compatibility with $\text{BR}(\mu \to e\gamma)$ imposes that the mass of the Kaluza-Klein excitations be $M_{KK} \gtrsim 30$ TeV, thus beyond present LHC reach. Possible ways out include non-geometrical flavour structures, or an increase of the gauge symmetry [23].

Non-constrained SUSY extensions of the SM introduce new sources of LFV through (generic) soft-breaking SUSY terms, giving rise to flavour violating neutral and charged lepton-slepton vertices. Even if independent of the mechanism of neutrino mass generation, these sources induce sizable contributions to different cLFV observables (for a recent comparative discussion see [24]).

From these examples it is clear that NP models can predict (or accommodate) extensive ranges for the cLFV observables. Thus, in order to disentangle the underlying model of LFV, one has to explore the peculiar features (correlations of observables, etc.) of each model. This can be illustrated, as done in [25], by the following comparison of ratios of different low-energy cLFV observables for models such as Little Higgs (with T-parity), MSSM (Higgs or dipole dominance) and 4th generation, as can be seen in Table 3.

| ratio | LHT | MSSM (dipole) | MSSM (Higgs) | SM4 |
|-------|-----|---------------|--------------|-----|
| BR(μ→eee) | 0.02...1 | $\sim 6 \times 10^{-3}$ | $\sim 6 \times 10^{-3}$ | 0.06...2.2 |
| BR(μ→eγ) | 0.04...0.4 | $\sim 1 \times 10^{-2}$ | $\sim 1 \times 10^{-2}$ | 0.07...2.2 |
| BR(τ→μμμ) | 0.04...0.4 | $\sim 2 \times 10^{-3}$ | 0.06...0.1 | 0.06...2.2 |
| BR(τ→eμμ) | 0.04...0.3 | $\sim 2 \times 10^{-3}$ | 0.02...0.04 | 0.03...1.3 |
| BR(τ→eγ) | 0.04...0.3 | $\sim 1 \times 10^{-2}$ | $\sim 1 \times 10^{-2}$ | 0.04...1.4 |
| BR(τ→eeε) | 0.8...2 | $\sim 5$ | 0.3...0.5 | 1.5...2.3 |
| BR(τ→μμμ) | 0.7...1.6 | $\sim 0.2$ | 5...10 | 1.4...1.7 |
| CR(μTi→eTi)/BR(μ→eγ) | $10^{-3}...10^2$ | $\sim 5 \times 10^{-3}$ | 0.08...0.15 | $10^{-12}...26$ |

Table 3: Comparison of various ratios of observables in the LHT model, the MSSM without and with significant Higgs contributions, and the SM with 4 generations. Table taken from [25].

For example, should observations be made of LFV tau-decays, leading to a ratio $\text{BR}(\tau \to 3\mu)/\text{BR}(\tau \to \mu e\epsilon)$ of $O(1)$, this would disfavour both MSSM cases when compared to the LHT model (see Table 3). Many other such correlations between low-energy cLFV observables could be considered; furthermore, the interplay between low- and high-energy observables (as those that can be studied in colliders) can be also explored. In order to illustrate this, we will focus on the specific case of the SUSY seesaw.

and [19] and references therein.
5 Probing the SUSY seesaw

The (type I) SUSY seesaw consists of embedding a seesaw mechanism in the framework of SUSY models, which are taken to be flavour conserving, so that the Yukawa couplings are the unique source of flavour violation. Flavour violation in the $\nu$ sector is transmitted to the charged one via radiative effects involving the $\nu$ Yukawa couplings, $Y^\nu$. Even under the assumption that the SUSY breaking mechanism is flavour conserving, renormalisation effects (RGE) can induce a sufficiently large amount of flavour violation as to account for sizable cLFV rates [26]. This implies that all cLFV observables will be strongly related.

At high energies, such as at the LHC, neutralino decays are an excellent laboratory to study cLFV in the slepton sector: among the many possible observables associated with $\chi^0_2 \rightarrow \tilde{\ell}^\pm_1 \ell^\mp_j$ decays, one can have sizable flavoured slepton mass splittings, new edges in dilepton invariant mass distributions and explicit flavour violating final states. At a future Linear Collider, and in addition to the above observables, one can also study cLFV in the $e^\pm e^- \rightarrow e^\pm \mu^-$ processes, profiting from the possibility of beam polarization (especially important in reducing charged current LFV background); moreover, the $e^- e^- \rightarrow \mu^- \mu^-$ channel might provide a truly golden channel for cLFV.

5.1 cLFV at LHC and interplay with low-energy cLFV observables

At the LHC, wino-like neutralino decays into same flavour, opposite sign dileptons plus missing $E_T$ allow to study cLFV from dilepton mass distributions. The observables thus considered can also be correlated with low-energy cLFV, and strategies can be devised to probe the underlying mechanism of flavour violation in the lepton sector.

For a flavour conserving framework (for example, the constrained Minimal Supersymmetric SM, cMSSM), and provided that the SUSY spectrum renders the decays kinematically viable, one has the following decay chain for a wino-like neutralino: $\chi^0_2 \rightarrow \tilde{\ell}^\pm_{L,R} \ell^\mp \rightarrow \chi^0_1 \ell^\mp_i \ell^\pm_i$, mediated by sleptons which are dominated by the flavour component of the final state lepton. The associated dilepton invariant mass distributions, $m_{ee}$ and $m_{\mu\mu}$, exhibit two edges, corresponding to intermediate left- and right-handed selectrons and smuons, respectively. The comparison of the $m_{ee}$ and $m_{\mu\mu}$ distributions will further reveal that the edges are approximately superimposed, corresponding to degenerate sleptons of the first two generations. This can be inferred from the dotted lines in Fig. 3 taken from [27]. The impact of the SUSY seesaw is visible in the full lines of Fig. 3. Firstly, let us mention that should we now compare $m_{ee}$ and $m_{\mu\mu}$ distributions we would verify that the edges corresponding to the left-handed sleptons no longer coincide, which directly signals that there will be a non-negligible slepton mass splitting ($\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}(\tilde{e}_L, \tilde{\mu}_L)$), which can be as large as a few %. More striking is the appearance of a third edge in $m_{\mu\mu}$ - this provides clear and indisputable evidence that a different flavour slepton (in this case $\tilde{\tau}_2$) has mediated the decay, and signals cLFV in slepton production and decay.

If a type I SUSY seesaw is indeed at work, then the different observables are expected to be correlated. Studying the interplay of different high- and low-energy observables thus allows to test the underlying hypothesis of type I seesaw embedded into the cMSSM (or any other flavour-blind SUSY breaking model). This is illustrated on Fig. 4 where we display BR($\mu \rightarrow e\gamma$) (with information on the corresponding ranges for $\mu - e$ conversion in Ti nuclei on the secondary y-axis), as well as BR($\tau \rightarrow \mu\gamma$), all as a function of the slepton mass splittings. The measurement of flavoured mass splittings at the LHC, compatible with an observation of BR($\mu \rightarrow e\gamma$) and/or BR($\tau \rightarrow \mu\gamma$) would clearly strengthen the seesaw hypothesis, hinting towards the scale of NP; conversely, splittings corresponding to an amount of cLFV already excluded by low-energy observables, or the
Figure 3: Evidence of cLFV at high-energies from dimuon invariant mass distributions: \( \text{BR}(\chi_2^0 \rightarrow \mu \mu \chi_1^0) \) as a function of \( m_{\mu \mu} \) for different SUSY seesaw spectra; a third edge reveals that \( \tilde{\tau} \) also mediated the neutralino decays, in addition to the \( \tilde{\mu}_{L,R} \) characteristic of the flavour-conserving cMSSM case (dotted lines). Secondary y-axes denote the expected number of events for \( \sqrt{s} = 7 \) (14) TeV, with \( \mathcal{L} = 1 \) (100) fb\(^{-1}\).

Figure 4: Probing the SUSY seesaw via the synergy of low and high energy cLFV observables: on the left \( \text{BR}(\mu \rightarrow e \gamma) \) as a function of \( \delta m_{\tilde{\ell}_L - \tilde{\mu}_L} \) mass difference, with corresponding predictions of CR(\( \mu - e, \tilde{\ell} \)) displayed on the secondary right y-axis; on the right \( \text{BR}(\tau \rightarrow \mu \gamma) \) vs. \( \Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}(\tilde{\ell}_L, \tilde{\mu}_L) \). Horizontal lines denote the corresponding current bounds/future sensitivities.

Observation of low-energy cLFV for negligible slepton mass splittings would point towards distinct (or additional) sources of flavour violation. For an updated analysis, see [28].

5.2 cLFV at Linear Colliders

A detailed study of cLFV at a future Linear Collider (LC) was conducted in [29]. When compared to the LHC, a LC offers the possibility of direct slepton production, thus giving access to the slepton sector for shorter SUSY decay chains. In particular, the following processes were studied,

\[
e^+ e^- \rightarrow \begin{cases} e^+ \mu^- + 2 \chi_1^0 \\ e^+ \mu^- + 2 \chi_1^0 + (2,4) \nu \\ e^+ \mu^- + (2,4) \nu \end{cases} \quad e^- e^- \rightarrow \begin{cases} e^- \mu^- + 2 \chi_1^0 \\ e^- \mu^- + 2 \chi_1^0 + (2,4) \nu \\ e^- \mu^- + (2,4) \nu \end{cases}
\]

| Process | Signal | SUSY bkg | SM\(m_\mu\) bkg |
|---------|--------|----------|----------------|
| \( e^+ e^- \rightarrow \) | | | |
| \( e^- e^- \rightarrow \) | | | |

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corresponding to the SUSY seesaw signal, SUSY and SM$_{\nu}$ backgrounds (bkg), respectively. As can be seen in Fig. 5 (left), provided that the seesaw scale is not excessively low, one can have sizable cross sections for $e^- e^- \rightarrow e^- \mu^-$, above 1 fb (the SM bkg is expected to be disentangled via appropriate cuts, due to the different topology and nature of the missing energy).

Figure 5: On the left, cross section for $e^- e^- \rightarrow e^- \mu^-$ as a function of the seesaw scale, $M_R$; on the right $\sigma(e^- e^- \rightarrow \mu^- \mu^-)$ as a function of the c.o.m. energy, for different SUSY seesaw spectra.

In Fig. 5 (right) we depict the $e^- e^- \rightarrow \mu^- \mu^-$ channel as a function of the centre of mass energy ($\sqrt{s}$). Provided that $\sqrt{s}$ is sufficiently high, the signal clearly dominates over the SUSY background (the SM one being negligible). As can be seen, this channel offers a clean probe of the Majorana nature of the exchanged neutral superparticle (neutralino) in the $t$-channel, and can become a truly golden channel to probe the neutrino mass generation mechanism.

6 Conclusions

Neutrino oscillation data clearly suggests the existence of NP beyond the SM. However, the actual underlying mechanism of neutrino mass generation and lepton flavour violation remains unclear. Here, we have argued that cLFV observables are a privileged means to address these issues. In particular, the interplay between observables allows to probe different extensions of the SM. For certain frameworks, as is the case of the SUSY seesaw, the possible correlation between low and high-energy cLFV observables (with the latter being studied at colliders such as the LHC or a future LC) may provide a unique tool to test the source of LFV, further hinting on the typical scale of the mechanism of neutrino mass generation.

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References

[1] S. T. Petcov, Sov. J. Nucl. Phys. 25 (1977) 340 [Yad. Fiz. 25 (1977) 641] [Erratum-ibid. 25 (1977) 698] [Erratum-ibid. 25 (1977) 1336].

[2] J. Beringer et al. [Particle Data Group Collaboration], Phys. Rev. D 86 (2012) 010001.

[3] J. Adam et al. [MEG Collaboration], arXiv:1303.0754 [hep-ex].

[4] A. M. Baldini et al., arXiv:1301.7225 [physics.ins-det].

[5] B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 104 (2010) 021802 arXiv:0908.2381 [hep-ex].

[6] B. Meadows et al., arXiv:1109.5028 [hep-ex].

[7] U. Bellgardt et al. [SINDRUM Collaboration], Nucl. Phys. B 299 (1988) 1.

[8] A. Blondel et al., arXiv:1301.6113 [physics.ins-det].

[9] K. Hayasaka et al., Phys. Lett. B 687 (2010) 139 arXiv:1001.3221 [hep-ex].

[10] C. Dohmen et al. [SINDRUM II. Collaboration], Phys. Lett. B 317 (1993) 631.

[11] R. J. Barlow, Nucl. Phys. Proc. Suppl. 218 (2011) 44.

[12] W. H. Bertl et al. [SINDRUM II Collaboration], Eur. Phys. J. C 47 (2006) 337.

[13] Y. G. Cui et al. [COMET Collaboration], KEK-2009-10.

[14] A. Abada et al., JHEP 0712 (2007) 061 arXiv:0707.4058 [hep-ph].

[15] A. Melfo et al. Phys. Rev. D 85 (2012) 055018 arXiv:1108.4416 [hep-ph].

[16] J. Garayoa and T. Schwetz, JHEP 0803 (2008) 009 arXiv:0712.1453 [hep-ph].

[17] M. Raidal et al., Eur. Phys. J. C 57 (2008) 13 arXiv:0801.1826 [hep-ph] and references therein.

[18] D. N. Dinh and S. T. Petcov, JHEP 1309 (2013) 086 arXiv:1308.4311 [hep-ph].

[19] R. Alonso et al., JHEP 1301 (2013) 118 arXiv:1209.2679 [hep-ph].

[20] M. Blanke et al., Acta Phys. Polon. B 41 (2010) 657 arXiv:0906.5454 [hep-ph].

[21] N. Arkani-Hamed, M. Schmaltz, Phys. Rev. D 61 (2000) 033005 arXiv:hep-ph/9903417.

[22] T. Gherghetta and A. Pomarol, Nucl. Phys. B 586 (2000) 141 arXiv:hep-ph/0003129.

[23] A. M Iyer and S. K Vempati, Phys. Rev. D 86 (2012) 056005 arXiv:1206.4383 [hep-ph].

[24] M. Arana-Catania et al, Phys. Rev. D 88 (2013) 015026 arXiv:1304.2783 [hep-ph].

[25] A. J. Buras et al., JHEP 1009 (2010) 104 arXiv:1006.5356 [hep-ph].

[26] F. Borzumati and A. Masiero, Phys. Rev. Lett. 57 (1986) 961.
[27] A. Abada et al., JHEP 1010 (2010) 104 [arXiv:1007.4833 [hep-ph]].

[28] A. J. R. Figueiredo and A. M. Teixeira, arXiv:1309.7951 [hep-ph].

[29] A. Abada et al., JHEP 1208 (2012) 138 [arXiv:1206.2306 [hep-ph]].