Lepton flavour violation and neutrino physics: beyond the Standard Model

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If observed, charged lepton flavour violation is a clear sign of new physics - beyond the Standard Model minimally extended to accommodate neutrino oscillation data. After a brief review of several charged lepton flavour violation observables and their current experimental status, we consider distinct extensions of the Standard Model which could potentially give rise to observable signals, focusing on the case of models in which the mechanism of neutrino mass generation is the common source of neutral and charged lepton flavour violation.

1 Introduction

Three major observations cannot find an explanation in the Standard Model (SM); these include the baryon asymmetry of the Universe (BAU), the lack of a viable dark matter (DM) candidate and finally, neutrino oscillations.

Leptonic mixings and massive neutrinos offer a true gateway to many new experimental signals or deviations from SM predictions in the lepton sector; among others, these include charged lepton flavour violation (cLFV). The most minimal extension of the SM allowing to accommodate $\nu$ oscillation data consists in the addition of right-handed neutrinos ($\nu_R$) while preserving the total lepton number, thus giving rise to Dirac masses for the neutral leptons. In such a framework, individual lepton numbers are violated (as encoded in the lepton mixing matrix, $U_{PMNS}$), and cLFV transitions such as $\mu \to e\gamma$ can occur, being mediated by $W^\pm$ bosons and massive neutrinos. However, and due to the tiny values of light neutrino masses, the associated rate is extremely small, $\text{BR}(\mu \to e\gamma) \sim \mathcal{O}(10^{-54})$, lying beyond the reach of any future experiment. Thus, the observation of a cLFV process would necessarily imply the existence of new physics degrees of freedom (beyond minimal extensions via massive Dirac neutrinos).

At present, many cLFV observables are being searched for in numerous facilities; after a brief summary of the current status of the experimental searches, we consider the impact of SM extensions regarding cLFV. An interesting class of models is that in which cLFV arises from the mechanism of $\nu$-mass generation: among the several models successfully accounting for and explaining $\nu$-data, many offer the possibility to further address the BAU via leptogenesis, and/or succeed in putting forward viable DM candidates, or even ease certain theoretical puzzles of the SM. In particular, we will summarise the prospects for cLFV observables of several appealing seesaw realisations.

aPCCF RI 16-05
2 cLFV observables and facilities: brief overview

Other than $\nu$-oscillations (by themselves signalling flavour violation in the neutral lepton sector), lepton flavour violation can be searched for in a number of rare decays and transitions, both at high-intensities and at high-energies\(^8\). Current searches have already put stringent bounds on these rare processes, and the next generation of experiments is expected to further improve them\(^2\).

A number of cLFV observables emerges in association with the so-called muonic channels. Radiative cLFV muon decays, $\mu^+ \rightarrow e^+ \gamma$, have been searched for since the 1940s; the event signature consists of back-to-back coincident positron-photon pairs, with a well-defined energy ($E_e = E_\gamma = m_\mu/2$). There are prompt and accidental backgrounds to the process: while the former are related with SM-allowed radiative muon decays ($\mu \rightarrow e\nu_\mu \nu_\gamma$), and scale proportional to the rate of the stopped muons, $R_\mu$, the latter include coincidences of photons (from SM-allowed radiative decays, or in flight $e^+ e^-$ annihilation) with a positron from Michel decays, and typically scale with $R_\mu^2$. The current bound on these decays is $\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ (MEG, 2016). In the future, MEG II should be able to bring down the sensitivity to $6 \times 10^{-14}$.

Three-body cLFV muon decays, $\mu^+ \rightarrow e^+ e^- e^+$, are also a privileged channel to look for new physics. The event signature is associated with a final state composed of three charged particles, coincident and arising from a common vertex. Likewise, there are physics and accidental backgrounds, the latter being the dominant ones. The current bound $\text{BR}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ (SINDRUM, 1988) is expected to be ameliorated in the near future by the Mu3e experiment ($10^{-15}$, possibly $10^{-16}$ if a very high-intensity muon beam is available).

Muonic atoms also offer a rich laboratory to study cLFV - these are 1s bound states which are formed when a $\mu^-$ is stopped in a target. The muon can then decay via SM-allowed processes (decay in orbit, nuclear capture, ...) or, in the presence of new physics, undergo cLFV transitions. An example is that of the neutrinoless $\mu - e$ conversion, $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$: the rate of the (coherent) process typically increases with the atomic number, being maximal for $30 \leq Z \leq 60$. The event signature consists of a single mono-energetic electron, whose energy (albeit target-dependent) lies close to 100 MeV, being thus easily distinguishable from the energy of electrons arising from the Michel spectrum of free $\mu$ decays. This is a clean process, which only has physics backgrounds (e.g. muon decay in orbit) suffering to a minor extent from beam purity issues, cosmic rays, ... The best limit has been obtained for Gold nuclei, $\text{CR}(\mu - e, \text{Au}) < 7 \times 10^{-13}$; in the future, several collaborations plan to significantly improve the sensitivity to $\mu - e$ conversion, and these include DeeMe - $\text{CR}(\mu - e, \text{SiC}) < 5 \times 10^{-14}$, Mu2e - $\text{CR}(\mu - e, \text{Al}) < 10^{-17}$, COMET Phase I (II) - $\text{CR}(\mu - e, \text{Al}) < 10^{-15}(10^{-17})$, and ultimately PRISM/PRIME - $\text{CR}(\mu - e, \text{Ti}) < 10^{-18}$.

Another interesting observable consists in the cLFV decay of a muonic atom into a pair of electrons, $\mu^- e^- \rightarrow e^- e^-$; the Coulomb interaction between the muon and the electron wave functions leads to an enhancement of the associated decay rate, which can scale proportionally to $(Z-1)^3$ - or even stronger, for large $Z$ atoms (suggesting that experimental setups with Lead or Uranium atoms could be considered). This is a “new” observable, which could be included in the Physics Programme of COMET, and also be studied at Mu2e.

Due to its larger mass, decays of the tau lepton offer numerous channels in which to search for cLFV. Taus can be pair-produced in $e^+ e^-$ collisions, and events are divided into two hemispheres: one is devoted to tagging tau leptons relying on SM decays (such as $\tau \rightarrow \nu_\tau \nu_\tau e^+$), while the other is used to search for rare cLFV decays. Purely leptonic cLFV processes include radiative decays ($\tau \rightarrow \ell \gamma$) and three body final states ($\tau \rightarrow \ell_i \ell_j \ell_k$). Event signatures are established on criteria for the invariant mass and the total energy of the final state (e.g. $E_{3\ell} - \sqrt{3}/2 \sim 0$, $M_{3\ell} \sim m_\tau$). Contrary to radiative decays, which are plagued by both physical and accidental backgrounds, the three-body $\tau$ decays do not suffer from irreducible backgrounds. At present, the bounds for the different channels lie around $10^{-8}$; future prospects, which include a SuperB or a Tau-Charm

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\(^8\)For dedicated reviews, see\(^1\).
factory, are expected to improve the current sensitivities to $10^{-9}$ ($10^{-10}$) for radiative (3-body) decays. Semi-leptonic tau decays offer further possibilities to look for cLFV (as well as lepton number violation or even baryon number violation); a summary of the upper limits on many of the latter channels can be found in Fig. 1.

Abundant data on leptonic and semi-leptonic meson decays has further allowed to constrain many cLFV decay modes. As an example, we quote here some of the current limits\(^5\): $\text{BR}(K_L \to \mu e) < 4.7 \times 10^{-12}$, $\text{BR}(K^+ \to \pi^+ \mu^+ e^-) 2.1 < \times 10^{-11}$, $\text{BR}(D^0 \to \mu e) < 1.5 \times 10^{-8}$ and $\text{BR}(B \to \mu e) < 2.8 \times 10^{-9}$.

Finally, cLFV can also be manifest in the decays of SM bosons, such as $Z \to \ell_i \ell_j$, for which recent LHC bounds have already started superseeding previous LEP bounds\(^5\); likewise, the impressive amount of Higgs states produced in both LHC runs has also allowed to study and constrain very rare cLFV decay modes such as $H \to \mu \tau$. Should new physics states be produced at the LHC, one can naturally look for their cLFV decays, possibly induced by new flavour-violating interactions (although the properties of the final states, and the experimental signatures, are strongly model-dependent).

### 3 cLFV and New Physics models

Interpreting experimental data on cLFV observables - be it in the form of a possible measurement or improved bounds - requires an underlying theoretical framework: new physics models can lead to “observable” cLFV introducing new sources of lepton flavour violation, as well as new operators at the origin of the flavour violating processes.

A first, model-independent approach consists in parametrising cLFV interactions by means of higher-order non-renormalisable (dimension $d > 4$) operators. The new low-energy effective Lagrangian can be written as $\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \sum_{n\geq 1} C_{ij}^{4+n} \Lambda^{-n} \mathcal{O}_{ij}^{4+n}$, in which $\Lambda$ denotes the scale of new physics, and $\mathcal{C}$, $\mathcal{O}$ the effective couplings and operators, with the former corresponding to complex matrices in flavour space. Contrary to the unique dimension-five Weinberg operator (common to all models with Majorana neutrino masses), there exists a large number of dimension-six operators, whose low-energy effects include cLFV. Regarding the cLFV dimension-six operators, these can be loosely classified as dipole, four-fermion and scalar/vector operators.

In order to constrain the new physics scale and the amount of flavour violation thus introduced, the cLFV observables can be cast (at leading order) in terms of combinations of $C_{ij}^{6}$, and $\Lambda^{-2}$; simple, natural hypothesis on one allow to infer constraints on the other. Table 1 (adapted from\(^6\)) collects some bounds on the scale of new physics (derived under the hypothesis of natural, $\mathcal{O}(1)$, effective couplings) and on the size of the new effective couplings (inferred for a choice $\Lambda = 1 \text{ TeV}$).
Table 1: Bounds on the effective couplings and lower bounds on the scale $\Lambda$ (TeV), following the hypotheses described on the text; the last column refers to the observable leading to the most stringent bounds.

| Effective coupling (example) | Bounds on $\Lambda$ (TeV) for $|C^{6}_{ij}| = 1$ | Bounds on $|C^{6}_{ij}|$ (for $\Lambda = 1$ TeV) | Observable |
|-----------------------------|---------------------------------|---------------------------------|------------|
| $C^{\mu e}_{ee}$           | $6.3 \times 10^{4}$            | $2.5 \times 10^{-10}$          | $\mu \rightarrow e\gamma$ |
| $C^{\tau e}_{ee}$          | $6.5 \times 10^{2}$            | $2.4 \times 10^{-6}$           | $\tau \rightarrow e\gamma$ |
| $C^{\tau\mu}_{ee}$         | $6.1 \times 10^{2}$            | $2.7 \times 10^{-6}$           | $\tau \rightarrow \mu\gamma$ |
| $C^{\mu e}_{e\ell,ee}$     | $207$                          | $2.3 \times 10^{-5}$           | $\mu \rightarrow 3e$       |
| $C^{\tau e}_{e\ell,ee}$    | $10.4$                         | $9.2 \times 10^{-5}$           | $\tau \rightarrow 3e$      |
| $C^{\tau\mu}_{e\ell,ee}$   | $11.3$                         | $7.8 \times 10^{-5}$           | $\tau \rightarrow 3\mu$   |
| $C^{(1,3)H\mu, C^{\mu e}_{H_e}}$ | $160$                          | $4 \times 10^{-5}$             | $\mu \rightarrow 3e$       |
| $C^{(1,3)H\mu, C^{\tau e}_{H_e}}$ | $\approx 8$                   | $1.5 \times 10^{-2}$           | $\tau \rightarrow 3e$      |
| $C^{(1,3)H\mu, C^{\tau\mu}_{H_e}}$ | $\approx 9$                   | $\approx 10^{-2}$              | $\tau \rightarrow 3\mu$   |

Despite its appeal for leading to a generic evaluation of the new physics contributions to a given cLFV observable, and thus to model-independent constraints, there are several limitations to the effective approach. These include taking “natural” values for the couplings, assuming the dominance of a single operator when constraining a given process and the uniqueness of the new physics scale; the latter should be kept in mind when weighing the impact of the thus derived constraints on new physics.

A second approach consists in considering specific new physics models or theories, and evaluating the corresponding impact for a given class of cLFV processes. As extensively explored in the literature, cLFV might be a powerful test of new physics realisations, probing scales beyond collider reach, offering valuable hints on properties and parameters of a given model, and allowing to disentangle (and ultimately disfavour) between candidate models. Interesting examples include generic cLFV extensions of the SM, as is the case of general supersymmetric (SUSY) models, geometric mechanisms of cLFV, as in the case of extra-dimensional Randall-Sundrum models, compositness frameworks (e.g. little(st) Higgs, holographic composite Higgs, ...), multi-Higgs doublet models, SM extensions via leptoquarks and/or $Z'$, and finally additional symmetries (be them flavour or gauge) - of which Left-Right symmetric models and Grand Unified theories are interesting examples.

A particular appealing class of new physics models regarding cLFV is that in which all sources lepton flavour violation (neutral and charged) are related, arising from the mechanism of neutrino mass generation. In what follows, we will address some examples of the latter, focusing in realisations of low-scale seesaws and in the supersymmetrisation of a type I seesaw, further emphasising the rôle of cLFV in potentially providing important information on the mechanism of neutrino mass generation.

4 cLFV from $\nu$ mass generation

Although cLFV need not arise from the mechanism of $\nu$ mass generation, models in which this is indeed the case - such as the different seesaw realisations - are particularly appealing and well-motivated frameworks. Whether or not a given mechanism of neutrino mass generation does have an impact regarding cLFV stems from having non-negligible flavour violating couplings (e.g., the Yukawa couplings) provided that the rates are not suppressed by excessively heavy propagator masses. While “standard” high-scale seesaws do accommodate neutrino data with natural values of the neutrino Yukawa couplings, the typical scale of the mediators (close to the GUT scale) leads to a very strong suppression of the different cLFV rates. On the other hand,
low-scale seesaws, or the embedding of a high-scale seesaw in larger frameworks (as is the case of the SUSY seesaw), are associated with a rich phenomenology, with a strong impact regarding cLFV.

4.1 Low-scale seesaws

In low-scale seesaws (as is the case of the low-scale type I seesaw, inverse and linear seesaw realisations, ...), the new “heavy” states do not fully decouple; their non-negligible mixings with the light (active) neutrinos lead to the non-unitarity of the left-handed lepton mixing matrix \( \left( U_{\text{PMNS}} \rightarrow \tilde{U}_{\text{PMNS}} \right) \), and thus to having modified neutral and charged lepton currents. The latter are at the origin of potentially abundant experimental/observational signatures, which have been intensively searched for in recent years; negative results have allowed to derive strong constraints on the parameter space of the new degrees of freedom (see \( \cite{7} \) for comprehensive discussions of cLFV in low-scale seesaws). An example of such constraints (presented in the parameter space generated by the masses of the heavy states and their couplings to the active neutrinos) \( \cite{7} \) is displayed on the left panel of Fig. 2, also including the impact of \( \mu \rightarrow e \) cLFV observables. Provided that the right-handed neutrinos are not excessively heavy, they can be produced in high-energy colliders and be searched for in several processes (frequently relying on lepton number violation signatures): current data (from both LEP and the LHC) already puts strong constraints on the parameter space; future colliders can further improve these bounds \( \cite{9} \), as shown in the right panel of Fig. 2.

A very appealing example of such low-scale models are Inverse Seesaw (ISS) realisations: other than right-handed neutrinos, further sterile states are added; in the case of a (3,3) ISS realisation, three copies of each are present. The masses of the light active neutrinos are given by a modified seesaw relation, \( m_{\nu_i} \approx (Y_{\nu v})^2 M_{R}^{-2} \mu_X \), where \( \mu_X \) is the only source of lepton number violation in the model. By taking small values of \( \mu_X \), one can naturally accommodate the smallness of active neutrino masses for large Yukawa couplings and a comparatively low seesaw scale \( (M_R \text{ lying close to the TeV scale}) \). The spectrum contains, in addition to the light states, three heavier (mostly sterile) pseudo-Dirac pairs, whose masses are given by \( m_N \approx M_R \pm \mu_X \).

The (3,3) ISS opens the door to a very rich phenomenology, which includes abundant cLFV signatures, both at low- and at high-energies (see, for example, \( \cite{10,11,12} \)). To illustrate the potential impact regarding high-intensity facilities, the left panel of Fig. 3 displays the prospects for \( \mu \rightarrow e \) conversion, as well as the Coulomb enhanced decay of a muonic atom (both for the
Although CR(\(\mu - e\), Al) is in general associated to larger rates, for sterile states above the TeV, both observables are expected to be well within reach of the COMET experience (horizontal lines respectively denoting the sensitivity of Phase I and II), or of the Mu2e experiment.

At higher energies (for example, in the case of a future circular collider, as FCC-ee), one can also explore cLFV in the decay of heavier states, as for instance in \(Z \to \ell \ell\). In the ISS (3,3) realisation, especially in the “large” sterile mass regime, the cLFV decays exhibit a strong correlation with cLFV 3-body decays (since the latter are dominated by the \(Z\)-penguin contribution). The prospects for a (3,3) ISS realisation, for the case of \(\mu - \tau\) flavour violation, are shown in the right panel of Fig. 3. Not only can one expect to have \(\text{BR}(Z \to \tau \mu)\) within FCC-ee reach, but this observable does allow to probe \(\mu - \tau\) flavour violation well beyond the sensitivity of a future SuperB factory (large values of \(\text{BR}(\tau \to 3\mu)\) are precluded in this realisation due to the violation of other cLFV bounds).

At the LHC, searches for heavy ISS mediators relying on cLFV signatures can be carried; as recently proposed, a significant number of events (after cuts) could be expected from the channel \(qq' \to \tau \mu + 2\text{jets (no missing }E_T)\).  

### 4.2 SUSY type I seesaw

Another rich and well-motivated framework leading to observable cLFV is that of the SUSY seesaw (a high-scale seesaw embedded in the context of otherwise flavour conserving SUSY models). In the case of a type I SUSY seesaw, sizeable neutrino Yukawa couplings (as characteristic of a high-scale seesaw) and the possibility of new, not excessively heavy mediators (the SUSY partners), open the door to large contributions to cLFV observables. Having a unique source of flavour violation implies that the observables exhibit a high degree of correlation; such a synergy can be explored, allowing to put the seesaw hypothesis to the test and possibly hinting on certain parameters. For example, the complementarity of two low-energy observables as is the case of \(\mu \to e\gamma\) and \(\tau \to \mu\gamma\) has been explored for different seesaw scales\(^{15}\); the determination of these two observables, in association with the discovery of SUSY, would allow to infer information on the seesaw scale \(M_R\), or then readily disfavour the SUSY seesaw as the only source of cLFV.

High-energy colliders offer direct access to superpartners; the production of on-shell sleptons would allow to study cLFV in SUSY neutral current interactions. There are many cLFV...
Figure 4 – On the left, $\text{BR}(\chi_2^0 \rightarrow \mu \mu \chi_1^0)$ as a function of the dimuon invariant mass $m_{\mu \mu}$ (in GeV) for different SUSY seesaw points. (from\textsuperscript{16}); on the right panel, $1^{\text{st}}$ and $2^{\text{nd}}$ generation charged slepton mass splittings vs. $\text{BR}(\mu \rightarrow e \gamma)$, with $\text{CR}(\mu \rightarrow e, \text{Ti})$ on secondary y-axis in a type I SUSY seesaw, for different values of the heaviest right-handed neutrino mass $M_{R_3} = 10^{13,14,15}$ GeV ($M_{R_1, R_2} = 10^{10,11}$ GeV) and for a flavour conserving modified mSUGRA benchmark (from\textsuperscript{18}).

observables that can be studied - both at the LHC and at a future linear collider. These include flavoured slepton mass differences (the splittings between the first and second generation charged slepton masses, $\Delta m_{\tilde{\ell}}$), new edges in dilepton mass distributions $m_{\ell\ell}$, and direct flavour violating final states (in association with decays $\chi_2^0 \rightarrow \ell_i \ell_j \chi_1^0$)\textsuperscript{16}. A future linear collider would allow to address further observables - especially should it have the possibility to operate in $e^- e^-$ mode. In the latter case, the process $e^- e^- \rightarrow \mu^- \mu^- + 2 \chi_1^0$ could become a true "golden channel" for cLFV in the present framework\textsuperscript{17}.

A particularly interesting example is that of new edges in dimuon mass distributions, which can be studied in association with neutralino decay cascades at the LHC. In a strictly flavour conserving framework, as would be the case of the constrained Minimal Supersymmetric SM (cMSSM) one is led to double triangular distributions, with two well-defined edges, associated with the presence of an intermediate $\tilde{\mu}_L$ or $\tilde{\mu}_R$ in the decay cascade $\chi_2^0 \rightarrow \tilde{\mu}_{L,R} \mu \rightarrow \mu \mu \chi_1^0$ (corresponding to the dashed lines on the left panel of Fig. 4). In the flavour violating case of a type I SUSY seesaw, and in association with other cLFV manifestations at high and low energies, one observes the appearance of a third edge (solid lines on the left panel of Fig. 4), which reflects that a new state - a stau - has mediated the neutralino decay: $\chi_2^0 \rightarrow \tilde{\tau}_2 \mu \rightarrow \mu \mu \chi_1^0$, thus clearly signalling charged lepton flavour violation\textsuperscript{16}.

The potential of exploring the interplay of high-intensity (for instance $\mu \rightarrow e \gamma$ and $\mu - e$ conversion) and other collider observables (for example, the splittings between left-handed selectron and smuon masses, $\Delta m_{\tilde{\ell}}$) is summarised on the right panel of Fig. 4: “isolated” cLFV manifestations (i.e., outside the coloured regions) would allow to disfavour the SUSY seesaw hypothesis as the (unique) underlying source of lepton flavour violation, while “compatible” ones would strengthen it, furthermore hinting on the seesaw scale\textsuperscript{18}.

5 Conclusions

As of today, we have firm evidence that flavour is violated in the quark sector, as well as in the neutral lepton one. In the absence of a fundamental principle preventing it, there is no apparent reason for Nature to conserve charged lepton flavours. By itself, any observation of a cLFV process would constitute a clear signal of new physics - beyond the SM extended via massive (Dirac) neutrinos. As we aimed at illustrating in the present brief review, cLFV observables could provide valuable (indirect) information on the underlying new physics model,
and certainly contribute to at least disfavour several realisations. Interestingly, new physics could even manifest itself indirectly via cLFV before any direct discovery.

The current (and planned) experimental programme, with numerous observables being searched for in a large array of high-intensity and high-energy experiments clearly renders cLFV a privileged laboratory to search for new physics.

Acknowledgments

AMT is grateful to the Organisers of “XXVIII Rencontres de Blois” for the invitation to participate in the Conference. Part of the work here summarised was done within the framework of the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements No 690575 and No 674896.

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