Theoretical aspects of charged Lepton Flavour
Violation

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Abstract. If observed, charged lepton flavour violation is a clear sign of new physics - beyond
the Standard Model minimally extended to accommodate neutrino oscillation data. We briefly
review several extensions of the Standard Model which could potentially give rise to observable
signals, also emphasising the rôle of charged lepton flavour violation in probing such new physics
models.

1. Introduction
Of the three observations which cannot be explained by the Standard Model (SM) - and which
also include the baryon asymmetry of the Universe (BAU) and dark matter (DM) - neutrino
oscillations provided the first evidence of new physics. Interestingly, among the several models
successfully accounting for and explaining ν-data, many offer the possibility to further address
the BAU via leptogenesis, succeed in putting forward viable DM candidates, or even ease certain
theoretical puzzles of the SM, as is the case of the flavour problem.

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 ν oscillation data consists in the addition of right-handed neutrinos (ν_R) while
preserving the total lepton number, thus giving rise to massive Dirac neutral leptons. In such
a framework, individual lepton numbers are violated (as encoded in the U_{PMNS} matrix), and cLFV
transitions such as μ → eγ can occur, being mediated by W± bosons and massive neutrinos;
however, and due to the tiny values of light neutrino masses, the associated rate is extremely
small, BR(μ → eγ) ~ O(10^{-55}), 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). A comprehensive review of
the experimental status of a vast array of cLFV observables was presented at this Conference
by W. Ootani [1].

Whether or not charged and neutral LFV are related, or equivalently if cLFV arises from the
mechanism of ν-mass generation, and the question of which is the New Physics model that can
be at the origin of these phenomena, have constituted the starting point to extensive studies.

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Here we very briefly review the prospects for cLFV observables of some appealing and well motivated SM extensions.

### 2. cLFV and New Physics models

Interpreting experimental data on cLFV - 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 transitions and decays.

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 $\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \sum_{n \geq 1} C_{ij}^{4+n} \Lambda^{-n} O_{ij}^{4+n}$, in which $\Lambda$ denotes the scale of new physics, and $C$, $O$ 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 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 collects some bounds on the scale of new physics (derived under the hypothesis of natural, $O(1)$, effective couplings) and on the size of the new effective couplings (inferred for a choice $\Lambda = 1$ TeV).

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 phenomenological 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.

A short, non-comprehensive list of examples has been presented at this Conference; below we highlight a small subset.

By studying the correlation of (high- and low-energy) cLFV observables as predicted in the framework of generic, flavour violating, supersymmetric (SUSY) extensions of the SM, one can derive useful information on the nature of the dominant operator at work (dipole vs. scalar); for instance, this is also the case of littlest Higgs models, which can be efficiently tested via cLFV, as they lead to very distinctive patterns for ratios of cLFV observables [3].

In the case of specific holographic composite Higgs models, it has been shown that although the predictions for most cLFV observables lie below experimental reach, current bounds on BR(μ → eγ) allow to constrain the size of boundary kinetic terms, and thus infer information on otherwise unreachable fundamental parameters of the model (cf. left panel of Fig. 1) [4].

A particularly interesting and rich example of “geometrical cLFV” is that of realisations of extra-dimensional Randall-Sundrum (RS) models, with anarchic (d = 5) Yukawa couplings [5]: current bounds from μ – e transitions and decays already constrain the scale of new physics to lie beyond LHC reach (T_{KK} ≳ 4 TeV, corresponding to having the first Kaluza-Klein excitations m_{1st}^{KK} ≳ 10 TeV); future bounds should allow to exclude generic anarchic RS models up to 8 TeV (and correspondingly first excitations m_{1st}^{KK} ≳ 20 TeV). Further examples of the constraining power of cLFV include (simple) SM extensions such as multi-Higgs doublet models, leptoquark constructions, additional Z’ bosons, etc..

Increasing the symmetry content of the model - be it in the form of a gauge or flavour symmetry - reduces its arbitrariness, thus rendering the model easier to test and possibly falsify. For instance, Left-Right symmetric models, which in addition to exhibiting a strong interplay of cLFV and lepton number violating observables, lead to very distinctive correlations of observables (see, for example, [6]), and can thus be easily falsifiable.

Extended gauge groups, and in particular grand unified theories (GUTs), in addition to possibly incorporating a mechanism of neutrino mass generation, lead to scenarios of strong predictivity for cLFV, as illustrated on the right panel of Fig. 1 [7]. The latter consists of a supersymmetrisation of an SO(10) type II seesaw model - as can be seen, data on any two observables would readily allow to exclude the model.

3. cLFV from seesaw realisations

Although cLFV need not arise from the mechanism of ν 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 the seesaw in larger frameworks (as is the case of the SUSY seesaw), are associated with a rich phenomenology, with a strong impact regarding cLFV.

In low-scale seesaws (as is the case of 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 (U_{PMNS} → ˜U_{PMNS}), 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
Figure 1. On the left, BR(\(\mu \rightarrow e\gamma\)) as a function of the size of boundary kinetic terms in the framework of Holographic Composite Higgs models (from [1]); on the right panel, correlation between different cLFV observables in for an SO(10) type II SUSY seesaw model (from [7]).

constraints on the parameter space of the new degrees of freedom (see [8,9] for comprehensive discussions of cLFV in low-scale seesaws).

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, \(m_{\nu_i} \approx (Y_{\nu}v)^2 M^{-2}_R \mu_X\), 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 (\(M_R\) 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, [10,12,11]). To illustrate the potential impact regarding high-intensity facilities, the left panel of Fig. 2 displays the prospects for \(\mu - e\) conversion, as well as the Coulomb enhanced decay of a muonic atom (both for the case of Aluminium targets), as a function of the average mass of the heavier states, \(< m_{4-9}>\). 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 line 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 \(Z \rightarrow \ell_i \ell_j\). In the ISS (3,3) realisation, especially in the “large” sterile mass regime, the cLFV \(Z\) 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. 2. Not only can one expect to have \(\text{BR}(Z \rightarrow \tau\mu)\) 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 \(\text{BR}(\tau \rightarrow 3\mu)\) 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 \(qq' \rightarrow \tau\mu + 2\text{jets}\) (no missing \(E_T\)) [14].
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 [14], 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. The complementarity of two low-energy observables is depicted on the left panel of Fig. 3: BR(μ→eγ) vs. BR(τ→μγ), for different seesaw scales (and for distinct values of the then unknown Chooz angle) [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 source of cLFV. The potential of exploring the interplay of high-intensity (for instance μ→eγ and μ→e conversion) and collider observables (for example, the splittings between the first and second generation charged slepton masses, $Δm_2$) is summarised on the right panel of Fig. 3 “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 strenghen it, furthermore hinting on the seesaw scale [16].

4. Outlook
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.

The current (and planned) experimental programme, with numerous observables being
searched for in a large array of high-intensity and high-energy experiments (see [11]) renders cLFV a privileged laboratory to search for new physics.

Acknowledgments

AMT is grateful to the Organisers of “Neutrino 2016” for the invitation and support. 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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Figure 3. On the left, correlation between $\text{BR}(\mu \rightarrow e\gamma)$ and $\text{BR}(\tau \rightarrow \mu\gamma)$ in a type I SUSY seesaw for different seesaw scales (from [15]); on the right panel, 1st and 2nd generation charged slepton mass splittings vs. $\text{BR}(\mu \rightarrow e\gamma)$, with $\text{CR}(\mu-e, Ti)$ 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 [16]).