Is charged lepton flavour violation a high energy phenomenon?

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Searches for rare processes such as $\mu \to e\gamma$ put stringent limits on lepton flavour violation expected in many Beyond the Standard Model physics scenarios. This usually precludes the observation of flavour violation at high energy colliders such as the LHC. We here discuss a scenario where right-handed neutrinos are produced via a Z' portal but which can only decay via small flavour violating couplings. Consequently, the process rate is unsuppressed by the small couplings and can be visible despite unobservably small $\mu \to e\gamma$ rates.

INTRODUCTION

Despite a long history of searches for lepton flavour violation (LFV) in charged leptons no such signal beyond the Standard Model (SM) has ever been observed, with the most impressive limit $Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$ reported recently by the MEG Collaboration [1]. The existence of neutrino oscillations suggests that, at some level, LFV should also take place in such processes. With only the light neutrinos of the SM present, LFV is strongly suppressed by $\Delta m_\nu^2/m_W^2 \approx 10^{-50}$, due to the Glashow-Iliopoulos-Maiani (GIM) mechanism. This results in LFV process rates far below any experimental sensitivity which can be safely ignored. On the other hand, many Beyond the Standard Model scenarios predict new sources for charged lepton flavour violation associated, for example, with the exchange of neutral heavy leptons or supersymmetric states. Since these LFV processes can proceed even in the limit of strictly massless neutrinos, their rates are unconstrained by the smallness of neutrino masses [2]. However in many such scenarios the non-observation of $\mu \to e\gamma$ in the MEG experiment places stringent limits on expected LFV rates at high energies. As a consequence, the observation of LFV at high energy colliders such as the LHC is precluded due to either the mediating particles being too heavy or their couplings to the charged leptons too small.

There are a few phenomenological solutions to this problem. For example, the suppression with respect to the mass difference of the LFV mediating particles differs depending on whether they are virtual or produced as real resonances. In the latter case, the suppression is only $\Delta M^2/(M\Gamma)$ instead of a GIM-like $\Delta M^2/M^2$. This was demonstrated in the case of mediating heavy neutrinos and a right-handed W boson in Left-Right symmetrical models in [3, 4]. We here discuss an alternative scenario where right-handed neutrinos are pair-produced via a Z' portal and can only decay via the flavour-dependent Yukawa coupling to the light neutrinos [5]. Consequently, the process rate is unsuppressed by the small flavour couplings and hence can be observable despite unobservably small $\mu \to e\gamma$ rates. Such a scenario can be realized in models with an extra U(1) or extended gauge sector such as left-right symmetric models [6].

NEUTRINO SEESAW MECHANISM

Within the standard type-I seesaw scenario with the mass matrix

$$\begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix}, \quad (1)$$

for the left- and right-handed neutrino, the mixing between the heavy N and light ν states is completely fixed once the masses are specified, $\theta \equiv m_D/m_N \approx \sqrt{m_\nu/m_N}$ [7]. Eq. (1) is expressed in terms of one generation; for detailed multi-generation seesaw expansion formulas for the mixing coefficients see Ref. [8]. For the observed light neutrino mass scale $m_\nu \approx 0.1$ eV and a TeV scale heavy neutrino, the mixing is negligibly small, $\theta \approx 10^{-7}$ and, despite the breakdown of the GIM mechanism [9], the heavy neutrinos do not enhance low energy LFV process rates sufficiently for detectability. This can dramatically change in extended seesaw scenarios with TeV scale heavy neutrinos. For example the inverse seesaw mechanism [10] is described by the mass matrix

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & m_N \\ 0 & m_N & \mu \end{pmatrix}, \quad (2)$$

including a sequential singlet state S as third entry. With the additional freedom introduced by the small lepton number violating μ parameter, light neutrinos can be accommodated for any value of $\theta \equiv m_D/m_N$ [11]. In essence, the magnitude of neutrino mass becomes decoupled from the strength of lepton flavour violation [2]. Alternatively, the light-heavy mixing can also be enhanced within the standard minimal seesaw sector by choosing specific flavour textures in the mass matrix of the type-I seesaw, see for example [12–14].

For definiteness here we focus on LFV in the electron-muon sector induced by the mixing between isodoublet and isosinglet neutrinos, via the corresponding Yukawa couplings. As a result, the heavy neutrinos couple to charged leptons via their small isodoublet components $\theta^{e,\mu}$, which we treat as free parameters. It is convenient to write these couplings in terms of an overall mixing strength, $\theta \equiv \sqrt{\theta^e \theta^\mu}$ and the ratio of mixing strengths, $r_{e\mu} \equiv \theta^e/\theta^\mu$. These parameters are unrestricted by the smallness of neutrino masses; however they are constrained by weak universality precision measurements to be $\theta^{e,\mu} \lesssim 10^{-2}$ [15]. We do not take into account possible constraints on θ from neutrinoless double beta decay searches. Although highly stringent for a heavy Majorana neutrino, they are avoided in the presence of cancellations, such as in the quasi-Dirac neutrino case.

Z' MODELS

Various physics scenarios beyond the Standard Model predict different types of TeV-scale Z' gauge bosons associated with an extra U(1) that could arise, say, from unified SO(10) or E(6) extensions. An introduction and extensive list of references can be found in Ref. [16]. Electroweak precision measurements restrict the mass and couplings of a Z' boson. For example, lepton universality at the Z peak places lower limits on the Z' boson mass of the order $\mathcal{O}(1)$ TeV [17] depending on hypercharge assignments. From the same data, the mixing angle between Z' and the SM Z is constrained to be $\zeta_Z < \mathcal{O}(10^{-4})$. For a discussion of direct limits on Z' masses see [15]. Recent limits from searches at the LHC will be discussed in more detail below.

In the following we work in a simplified U(1)$'$ scenario with only a Z' and N present beyond the SM. For the mechanism described here to work, it is crucial that there are no other particles present through which the heavy neutrino can decay unsuppressed. For definiteness we assume two reference model cases: the SO(10) derived U(1)$'$ coupling strength with the charge assignments of the model described in [6], and a leptophobic variant where the U(1)$'$ charges of SM leptons are set to zero.

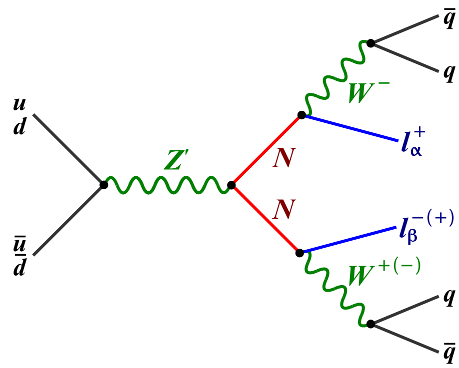

FIG. 1: Feynman diagram for heavy Majorana neutrino production through the Z' portal at the LHC.

LOW ENERGY LEPTON FLAVOUR VIOLATION

In the scenario considered here, the LFV branching ratio for the process $\mu \to e\gamma$ can be expressed as [18]

$$Br(\mu \to e\gamma) = 3.6 \times 10^{-3} G_\gamma^2 \left(\frac{m_N^2}{m_W^2}\right) \times \theta^4, \quad (3)$$

$$\text{with } G_\gamma = -\frac{2x^3 + 5x^2 - x}{4(1-x)^3} - \frac{3x^3}{2(1-x)^4}\log(x),$$

where the loop function $G_\gamma(x)$ is of order one with the limits $G_\gamma \to 1/8$ for $m_N \to m_W$ and $G_\gamma \to 1/2$ for $m_N \gg m_W$. This prediction should be compared with the current experimental limit [1],

$$Br_{\text{MEG}}(\mu \to e\gamma) < 5.7 \times 10^{-13} \text{ (90\% C.L.)}, \quad (4)$$

from the MEG experiment which aims at a final sensitivity of $Br(\mu \to e\gamma) \approx 10^{-13}$. The expression (3) therefore results in a current upper limit on the mixing parameter $\theta \lesssim 0.5 \times 10^{-2}$ for $m_N = 1$ TeV. In contrast, the mixing strength $\theta \approx 10^{-7}$ expected in the standard high-scale type-I seesaw mechanism Eq. (1) would lead to an unobservable LFV rate with $Br(\mu \to e\gamma) \approx 10^{-31}$.

If the photonic dipole operator responsible for $\mu \to e\gamma$ and also contributing to $\mu \to eee$ and $\mu - e$ conversion in nuclei is dominant, searches for the latter two processes do not provide competitive bounds on the LFV scenario at the moment. Depending on the breaking of the additional U(1)$'$ symmetry, non-decoupling effects may appear which can boost the effective $Z'e\mu$ vertex contributing to $\mu \to eee$ and $\mu - e$ conversion in nuclei [19].

HEAVY NEUTRINOS FROM THE Z' PORTAL

The process under consideration is depicted in Figure 1. As shown, we will focus on the channel where the heavy neutrinos decay into SM W bosons which in turn

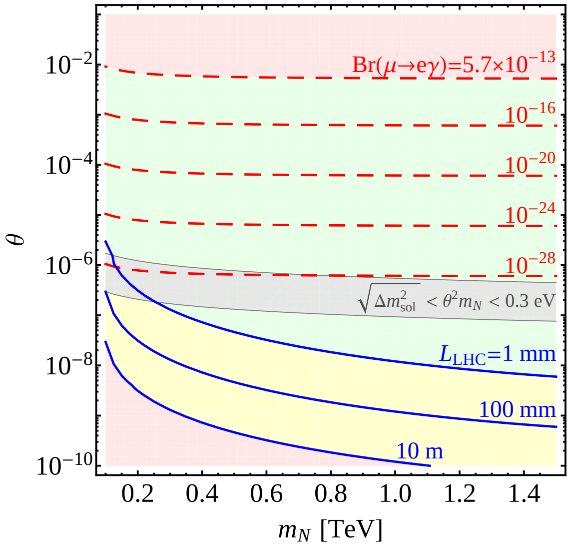

FIG. 2: Average decay length of a heavy neutrino N produced in $Z' \to NN$ with $m_{Z'} = 3$ TeV as a function of its mass m_N and the light-heavy mixing θ (solid blue contours). The dashed red contours denote constant values for $Br(\mu \to e\gamma)$ whereas the grey shaded band corresponds to parameter values which produce light neutrino mass scales $m_\nu = \theta^2 m_N$ between $\sqrt{\Delta m^2_{\rm sol}}$ and 0.3 eV within the canonical type-I seesaw mechanism.

decay hadronically. The cross section of the production part $pp \to Z'$ can be approximated by [20]

$$\sigma(pp \to Z') \approx K \times C \times \frac{4\pi^2}{3s}\frac{\Gamma_{Z'}}{m_{Z'}} \times \exp\left(-A\frac{m_{Z'}}{\sqrt{s}}\right) \times \left[Br(Z' \to u\bar{u}) + \frac{1}{2}Br(Z' \to d\bar{d})\right], \quad (5)$$

with $C = 600$, $A = 32$ and the factor $K \approx 1.3$ describing higher order QCD corrections. The target LHC beam energy is $\sqrt{s} = 14$ TeV. Here we focus on LFV at the LHC but not on lepton number violation. The latter is usually considered as a smoking gun signal of heavy Majorana neutrinos but realistic models with TeV scale neutrinos such as inverse [10] and linear seesaw [6] scenarios usually lead to a quasi-Dirac nature for the heavy neutrinos [21]. It is strictly required in case of large light-heavy mixing θ in order to ensure adequately small neutrino masses $m_\nu \approx 0.1$ eV [12]. We therefore perform our calculations assuming a Dirac heavy neutrino producing only opposite sign leptons. If it were a genuine Majorana neutrino, inclusion of the same sign lepton signature would improve the discovery potential by taking advantage of the low background expected for same sign lepton signatures. From this point of view the results obtained here are conservative.

The total cross section of the LFV signal process $pp \to Z' \to NN \to e^\pm\mu^\mp + 4$j is then given by

$$\sigma_{e\mu} = \sigma(pp \to Z') \times Br(Z' \to NN) \times Br(N \to e^\pm W^\mp) \times Br(N \to \mu^\mp W^\pm) \times Br^2(W^\pm \to 2\text{j}). \quad (6)$$

The neutrino N can decay via the channels $\ell^\pm W^\mp$, $\nu_\ell Z$ and $\nu_\ell h$, all of which are suppressed by the small mixing parameters θ^ℓ, $\ell = e, \mu$. In the presence of multiple heavy neutrinos with small mass differences we neglect the decays involving either real or virtual Z', $N_i \to N_j Z'$. The branching ratio of the above channels into a given lepton flavour is independent of the overall mixing strength θ.

As long as the total decay width Γ_N is large enough so that the heavy neutrino decays within the detector, the LHC LFV process rate is unsuppressed by the overall mixing strength θ. The decay length of the heavy neutrino (in the rest frame of a 3 TeV Z') is shown in Figure 2 as a function of m_N and the light-heavy mixing θ, in comparison with $Br(\mu \to e\gamma)$. For $\theta \gtrsim 10^{-7}$ and $m_N \gtrsim 0.3$ TeV, the neutrino decays promptly with a decay length $L < 1$ mm, and the LHC LFV process considered here is independent of and completely unsuppressed by θ. The inclusion of the Z' boost in the detector frame does not significantly alter this conclusion, but in general leads to a slight broadening of the yellow region. For lengths between 1 mm - 10 m, the N decay may still be observable with potentially spectacular signatures such as displaced vertices or in-detector decays. Figure 2 also indicates the parameter area corresponding to the observed neutrino mass scale $m_\nu = \theta^2 m_N$ in the standard type-I seesaw mechanism, clearly showing that this regime cannot be probed by low energy searches but potentially by the LHC process considered here.

The total cross section (6) only depends on the ratio $r_{e\mu}$ of the flavour couplings, $\sigma_{e\mu} \propto r^2_{e\mu}/(r^2_{e\mu}+1)^2$, and is maximal for $r_{e\mu} = 1$. This is very much in contrast to $Br(\mu \to e\gamma)$ in Eq. (3) which is heavily suppressed by a small value of θ, though is independent of the ratio $r_{e\mu}$.

In order to examine the viability of observing the signal at the 14 TeV run of the LHC we perform a simulation of $pp \to Z' \to NN \to \ell_1^+ W^- \ell_2^- W^+$ using Pythia 8 [22] with both W bosons decaying into quarks producing a 2ℓ+4j final state. Possible SM backgrounds arise from the channels $(t\bar{t},\ Z,\ tW,\ WW,\ WZ,\ ZZ)+n$j which we simulate using Madgraph 5 [23]. We include parton showering and hadronization for both signal and background using Pythia 8. We apply the following selection criteria: (i) An event must have four jets with a transverse momentum of at least 40 GeV each and (ii) two opposite-sign leptons with transverse momenta $p_T > 120$ GeV; (iii) since there is no source of missing transverse energy (MET) in the signal, we require MET < 30 GeV and (iv) a large dilepton invariant mass $M_{\ell\ell} > 400$ GeV further reduces the $t\bar{t}$ background and reduces the $Z + n$j and $VV + n$j to negligible amounts. In addition, the heavy neutrino mass could be determined through a peak in

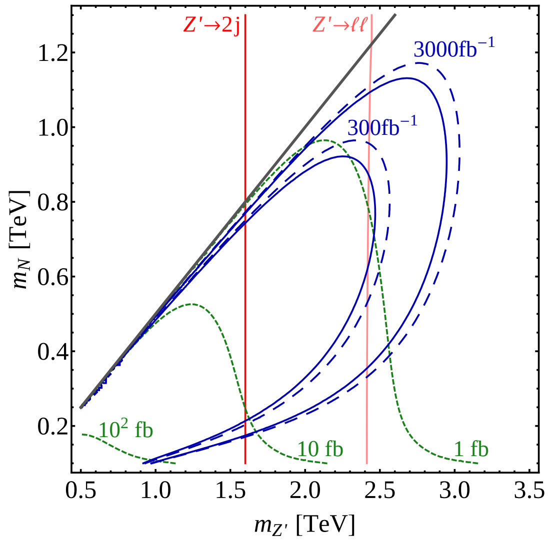

FIG. 3: Cross section $\sigma(pp \to Z' \to NN \to e^{\pm}\mu^{\mp} + 4\mathrm{j})$ at the LHC with 14 TeV as a function of $m_{Z'}$ and m_N for maximal LFV (dotted contours). The solid and long dashed contours give the required luminosity at the LHC for a 5σ discovery, in the case of SO(10) and leptophobic charges, respectively. The vertical lines denote the upper limit on $m_{Z'}$ from existing LHC searches in dijet and dilepton channels.

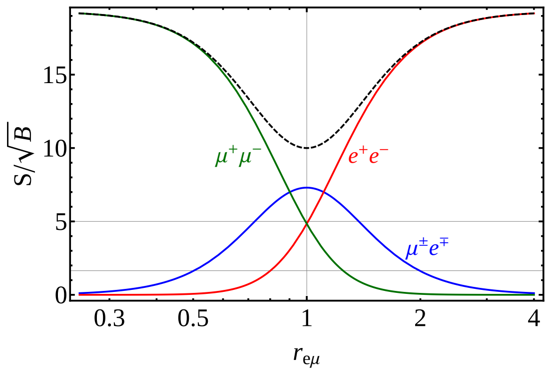

FIG. 4: Signal over background significance of $\sigma(pp \to Z' \to NN \to \ell\ell + 4\mathrm{j})$ ($\ell\ell = \mu^{\pm}e^{\mp}, e^+e^-, \mu^+\mu^-$) at the LHC with 14 TeV and $\mathcal{L} = 300$ fb^{-1} as a function of $r_{e\mu}$. The masses are $(m_{Z'}, m_N) = (2.4, 0.75)$ TeV. The dashed black curve gives the significances added in quadrature and the horizontal lines denote 5σ and 90% significance thresholds.

the invariant mass $m_{\ell jj}$, although the sharpness of such a peak is likely to be reduced due to the combinatorics of identifying the correct final particles.

Figure 3 shows the cross section of the process $pp \to Z' \to NN \to e^{\pm}\mu^{\mp} + 4\mathrm{j}$ at the LHC with 14 TeV as a function of $m_{Z'}$ and m_N for maximal LFV, $r_{e\mu} = 1$. In addition, it provides an estimate of the required luminosity at the LHC to observe a 5σ LFV signal over background significance, as derived using the simulation procedure described above. In addition to the case with SO(10) derived U(1)$'$ charges, it also shows the expected significance for a leptophobic Z' with the lepton doublet and charged lepton singlet charges put to zero. This increases the signal cross section by about 25% due to the increased Z' decay branching ratio into heavy neutrinos. We find that LFV can potentially be discovered for heavy neutrinos and Z' with masses $m_N \lesssim 0.9$ TeV and $m_{Z'} \lesssim 2.5$ TeV, respectively. In the case of three degenerate neutrinos with identical $r_{e\mu} = 1$, this reach would increase to $m_N \lesssim 1.1$ TeV and $m_{Z'} \lesssim 3.0$ TeV.

In determining the LHC potential to discover LFV through the process considered here, we must take into account existing Z' LHC searches. The vertical lines in Figure 3 indicate the upper limits on $m_{Z'}$ from the LHC 8 TeV run in the dijet channel $pp \to Z' \to 2\mathrm{j}$ [24] (assuming SM charges and couplings) and the dilepton channel $pp \to Z' \to \ell^+\ell^-$, $\ell = e, \mu$ [25] (assuming SO(10) derived couplings and charges). The corresponding limit from dilepton searches reported by CMS [26] is slightly stronger with $m_{Z'} \gtrsim 2.6$ TeV but difficult to consistently apply in our case as it is quoted only in terms of the cross section ratio to the SM Z production. The parameter space of the scenario with SO(10) derived charges is strongly constrained by dilepton searches. On the other hand, the leptophobic scenario, only limited by the dijet searches, still allows a large parameter space where a strong LFV signature could be observed.

The effect of the coupling ratio $r_{e\mu}$ on all three flavour channels $\mu^{\pm}e^{\mp}$, e^+e^- and $\mu^+\mu^-$ is shown in Figure 4 where the signal significances as well as their sum in quadrature are plotted. Strongly non-universal couplings, i.e. with the neutrino coupling dominantly to either e or μ, result in the largest overall significance as the flavour content of the background is $N(\mu^{\pm}e^{\mp}) : N(e^+e^-) : N(\mu^+\mu^-) \approx 2 : 1 : 1$. In contrast, the unambiguous discovery of LFV requires approximately universal couplings, $r_{e\mu} \approx 1$.

CONCLUSIONS

The seesaw mechanism and its low-scale variants provide a well motivated scenario for neutrino mass generation in many new physics models. The experimental non-observation of low energy lepton flavour violating processes puts stringent constraints on the scale and the flavour structure of such models. This usually means that the discovery of related LFV processes or heavy resonances at the LHC is already ruled out. Here we discussed a scenario with negligible lepton flavour violating rates in low energy rare process, while testable at the high energies accessible at the LHC. The scenario described here illustrates a general mechanism, namely, (i) a LFV messenger particle is produced through a portal via an unsuppressed coupling but (ii) can only decay via small lepton flavour violating couplings. Such a scenario would provide an alternative solution to the general flavour problem in Beyond-the-Standard Model physics which is testable at high energy colliders, despite tiny LFV couplings and consequently unobservably small low energy LFV rates.

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