Charged lepton flavor violation from beyond standard model particles

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Abstract: We summarize the potential charged lepton flavor violation (LFV) from some representative beyond standard model (BSM) particles, i.e. the BSM neutral scalar $H$, doubly-charged scalar $H_{\pm\pm}$, heavy neutrino $N$, heavy $W_R$ boson, and the $Z'$ boson. For the neutral scalar, doubly-charged scalar and $Z'$ boson, the LFV signals originate from the (effective) LFV couplings of these particles to the charged leptons, while for the heavy neutrino $N$ and $W_R$ boson, the LFV effects are from flavor mixing in the neutrino sector. We consider current limits on these BSM particles and estimate their prospects in future experiments.

Keywords: lepton flavor violation; BSM neutral scalar; doubly-charged scalar; heavy neutrino; heavy $W_R$ boson, $Z'$ boson

1. Introduction

In the Standard Model (SM) of particle physics, lepton flavor violation (LFV) processes are always highly suppressed, such as the decays $\ell_\alpha \rightarrow \ell_\beta \gamma$, $\ell_\alpha \rightarrow \ell_\beta \ell_\gamma \ell_\delta$ (with $\alpha, \beta, \gamma, \delta = e, \mu, \tau$ the lepton flavor indices), muonium-antimuonium oscillation [1]. Other process such as the anomalous magnetic dipole moment of electron and muon might also receive sizable contributions from the beyond SM (BSM) particles and their interactions [2]. Therefore, these precision measurements at the high-intensity frontier are one of the primary probes of the BSM physics. Depending on model details and specific UV completions, the BSM particles can be of spin zero, half or one, i.e. CP-even scalars or pseudoscalars, fermions, and vector bosons. In principle, these particles can be either heavy at the TeV scale or relatively light at the GeV scale or even lighter, if allowed by experimental data. Furthermore, some of the LFV signals induced by these particles can also be lepton number violating (LNV) and/or lepton flavor universality violating (LFUV), which are closely related to neutrino mass generation and the $B$-anomalies [3], respectively. For simplicity, we will not consider LNV or LFUV, but focus only on LFV.

In this paper, we summarize the LFV effects from a couple of representative particles, i.e. the BSM neutral scalar $H$, doubly-charged scalar $H_{\pm\pm}$, heavy neutrino $N$, heavy $W_R$ boson, and the $Z'$ boson. We will work as much in a model-independent way as possible, and do not consider too much dependence on the model details. With given LFV couplings, we will check the relevant LFV limits from current data, and then estimate the prospects of these particles at future high-energy and/or high-intensity experiments. More details can be found in the original papers.

2. BSM neutral scalar $H$

If a BSM neutral scalar couples direct to the SM quarks or mixes with the SM Higgs, it may induce flavor-changing neutral currents (FCNCs) in the quark sector, which are...
stringently constrained by the $K$ and $B$ meson data. Therefore, for simplicity, we assume the neutral scalar $H$ does not couple directly to the SM quarks and its mixing with the SM Higgs $h$ is sufficiently small. In a large variety of BSM scenarios, the scalar $H$ can couple to the SM charged leptons in a flavor-violating way \cite{4}, e.g. in the left-right symmetric model (LRSM) \cite{5–8}, two Higgs doublet model \cite{9,10}, $R$-parity violating supersymmetric theories \cite{11–14}, and mirror models \cite{15–18}. The LFV couplings of $H$ can arise at the tree-level or 1-loop level, depending on model details. In the perspective of effective theory, the couplings of $H$ to the SM charged leptons can be written in the following way, without loss of generality:

$$\mathcal{L}_Y = h_{\alpha \beta} \ell_\alpha H \ell_\beta + \text{H.c.}, \quad (1)$$

where $\ell$ is the charged lepton, and $h_{\alpha \beta}$ is the Yukawa coupling. For simplicity, we have assumed $H$ to be a real field and CP-even. As a result, the matrix $h_{\alpha \beta}$ is symmetric.

The couplings $h_{\alpha \beta}$ of the scalar $H$ can induce very rich LFV signals at the high-energy colliders. In light of the clean backgrounds, the future $e^+e^-$ colliders are the primary facilities to search for such smoking-gun signals, such as at the International Linear Collider (ILC) \cite{19}, Circular Electron-Positron Collider (CEPC) \cite{20}, Future Circular Collider (FCC-ee) \cite{21}, and Compact Linear Collider (CLIC) \cite{22}. Given a single LFV coupling $h_{a\beta}$ with $a \neq \beta$, if kinematically allowed the scalar $H$ can be on-shell produced at high-energy $e^+e^-$ colliders via the process

$$e^+e^- \rightarrow \ell_\alpha^+ \ell_\beta^- H.$$ \quad (2)

For simplicity, we assuming all other Yukawa couplings in the matrix $h_{\alpha \beta}$ are vanishing. As a result, a single coupling $h_{a\beta}$ can not induce the LFV decays, such as $\ell_\beta \rightarrow \ell_\alpha \gamma$ and $\ell_\beta \rightarrow 3\ell_\alpha$, which depend on the combinations of $h_{a\beta}$ with other Yukawa couplings, e.g. $h_{aa} h_{a\beta}$. It turns out that only a few precise LFV measurements can be used to set limits on the single coupling $h_{a\beta}$.

The coupling $h_{\mu\mu}$ can induce muonium-antimuonium oscillation at the tree-level, contributes to the anomalous magnetic moment $a_\mu$ of electron via the $H - \mu$ loop, and affects also the measurements of $e^+e^- \rightarrow \mu^+\mu^-$ at the LEP. The precise measurements of muonium oscillation by MACS \cite{23}, the current value of $a_\mu$ \cite{24} and the LEP data \cite{25} exclude large region in the parameter space of the scalar mass $m_H$ and the coupling $h_{\mu\mu}$, as depicted by the shaded regions in Fig. 1. More calculation details can be found in Refs. \cite{4,26}. The coupling $h_{\mu\mu}$ contributes also to the magnetic moment $a_\mu$ of muon via the $H - e$ loop. However, this contribution is highly suppressed by the electron mass, and can not explain the current discrepancy of muon $g - 2$ anomaly $\Delta a_\mu$ \cite{27,28} (cf. the left panel of Fig. 1).
The coupling $h_{e\mu}$ can induce the signal $e^+e^- \rightarrow e^\pm \mu^\mp H$ at future high-energy $e^+e^-$ colliders. After being produced, the scalar $H$ can decay back into a pair of opposite-sign different-flavor charged leptons, i.e. $H \rightarrow e^\pm \mu^\mp$. In the SM, such process are absent, and the most important backgrounds at $e^+e^-$ colliders are mainly from electrons mis-identified as muons or vice versa. Therefore, the LFV signal of $e\mu$ resonance can be easily distinguished from the SM backgrounds. Taking CEPC 240 GeV with an integrated luminosity of $5 \text{ ab}^{-1}$ and ILC 1 TeV with $1 \text{ ab}^{-1}$ as benchmark facilities, the resultant prospects of $m_H$ and $h_{e\mu}$ are shown as the red and blue lines in the left panel of Fig. 1, assuming at least 10 signal events. The long-dashed, short dashed and solid lines correspond respectively to the branching ratio (BR) of $H \rightarrow e^\pm \mu^\mp$ to be 1%, 10% and 100%. Benefiting from the larger luminosity, the CEPC can probe a smaller $h_{e\mu}$ than ILC, down to $O(10^{-4})$ in the limit of massless $H$. On the other end, when $H$ is heavy, ILC can probe a heavier $H$ than CEPC due to the kinematics reason.

If the LFV coupling $h_{\tau\tau}$ is present, it will contribute to the electron $g \rightarrow 2$ via the $H \rightarrow \tau \tau$ loop and the $e^+e^- \rightarrow \tau^+\tau^-$ process at LEP. The corresponding constraints are shown as shaded regions in the middle panel of Fig. 1. With the coupling $h_{\mu\tau}$, the neutral scalar $H$ provide a simple explanation for the muon $g \rightarrow 2$ anomaly via the $H \rightarrow \tau \tau$ loop. The corresponding 1$\sigma$ and 2$\sigma$ ranges of $\Delta a_{\mu}$ in the parameter space of $m_H$ and $h_{\mu\tau}$ are presented in the right panel of Fig. 1 respectively as the green and yellow bands, while the gray shaded region is excluded by the muon $g \rightarrow 2$ discrepancy at the 5$\sigma$ C.L. As for the case of $h_{e\mu}$, the prospects of $h_{\tau\tau}$ and $h_{\mu\tau}$ are shown respectively in the middle and right panels of Fig. 1, with again at least 10 signal events. The reconstruction efficiency of $\tau$ lepton has taken conservatively to be 60% at both CEPC and ILC [19]. For all the three LFV couplings $h_{e\mu,\tau\tau,\mu\tau}$, even if all the current stringent lepton flavor constraints are taken into account, there are yet large regions of parameter space of $m_H$ and $h_{a\beta}$ (with $\alpha \neq \beta$) that can be probed at future high-energy $e^+e^-$ colliders, as seen in Fig. 1.

If the couplings $h_{e\mu}$ and $h_{e\tau}$ are both nonzero, the scalar $H$ will induce the process
\[
e^+e^- \rightarrow e^\pm \mu^\mp
\] (3)
at high-energy colliders, which is also apparently LFV. However, the coupling $h_{e\mu}h_{e\mu}$ is severely constrained by the limit from $\mu \rightarrow eee$ [29], which precludes all the prospects of $e^\pm \mu^\mp$ at future high-energy lepton colliders. In the $\tau$ sector, the limits are much weaker. Let us consider the process $e^+e^- \rightarrow e^+\tau^-$, which can be induced by the combination $h_{e\mu}^2 h_{\mu\tau}^2$ of Yukawa couplings. Such couplings are subject to the limits from the decays $\tau \rightarrow eee$, $\tau \rightarrow e\gamma$, electron $g \rightarrow 2$ and the LEP data $e^+e^- \rightarrow e^+e^-$, $\tau^+\tau^-$, which are shown as the shaded regions in the left panel of Fig. 2. Requiring at least 10 signal events, the prospects of $m_H$ and $|h_{e\mu}^2 h_{\mu\tau}|$ at CEPC 240 GeV and ILC 1 TeV are presented in the left panel of Fig. 2 respectively as the solid and blue lines. The dips are due to the resonant production of $H$ at CEPC and ILC with $m_H \simeq \sqrt{s}$. As $H$ is only in the mediator for the LFV processes, its mass can go well above the center-of-mass energy $\sqrt{s}$ at the lepton colliders, as seen in the three panels of Fig. 2. In the limit of $m_H \gg \sqrt{s}$, the high-energy lepton colliders probe the effective four-fermion interaction $(\bar{e}e)(\bar{\tau}\tau)/\Lambda^2$ with the cut-off scale $\Lambda \simeq m_H/\sqrt{|h_{e\mu}^2 h_{\mu\tau}|}$ [30–34].

To obtain the signatures of $e^+e^- \rightarrow \mu^+\tau^-$, there are two different combinations of Yukawa couplings, i.e. $h_{e\mu}^2 h_{\mu\tau}$ and $h_{e\tau} h_{\mu\tau}$. For the case of $h_{e\mu}^2 h_{\mu\tau}$, there is only constraint from the decay $\tau^- \rightarrow \mu^- e^+e^-$ [35], while for $h_{e\tau} h_{\mu\tau}$ the limits are mainly from the rare decays $\tau^- \rightarrow \mu^+ e^- e^-$, $\tau^- \rightarrow \mu^- \gamma$, electron $g \rightarrow 2$ and the LEP data $e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$. These constraints are shown respectively in the middle and right panels of Fig. 2 as the shaded regions. The prospects of $h_{e\mu}^2 h_{\mu\tau}$ and $h_{e\tau} h_{\mu\tau}$ at the CEPC and ILC are also shown in these two figures as the red and blue lines. As the coupling combination $h_{e\mu}^2 h_{\mu\tau}$ can not
induce any $s$-channel process at colliders, the prospects in the right panel of Fig. 2 do not have any resonance structure. For all these $H$-induced LFV processes $e^+e^-\rightarrow e^\mp\tau^\mp$, $\mu^\pm\tau^\mp$, the future high-energy $e^+e^-$ colliders can probe large unconstrained parameter space of $m_H$ and $h^{\dagger}_\mu h_{\nu\tau}$, as seen in Fig. 2.

Before switching to the doubly-charged scalar in the next section, here are a few more comments on $H$:

- In analogous to the neutral current process in Eq. (2), we can also have charged current process $e^+e^-\rightarrow \mu^-\tau^\mp$, which is mediated by a $W$-boson. See Ref. [26] for more details.

- At future high-energy $e^+e^-$ colliders, high-energy photon beams can be obtained from the back scattering of high-intensity low-energy laser beam off high-energy electron beams [36–38], which provides more production channels for the neutral scalar $H$, e.g. via the process $\gamma\gamma\rightarrow e^\pm\mu^\mp H$. These channels are largely complementary to the $e^+e^-$ channels above [26].

- Future high-energy muon colliders can probe larger regions of parameter space for the muon flavor couplings, in particular for the explanation of muon $g-2$ anomaly (see e.g. Ref. [39]).

3. Doubly-charged scalar $H^{\pm\pm}$

The doubly-charged scalar $H^{\pm\pm}$ exists in a large variety of BSM scenarios, such as the type-II seesaw [40–44], LRSM [45–47] and the Zee-Babu model [48]. The doubly-charged scalars can couple either to left-handed or right-handed charged fermions in the SM, and the most general Yukawa couplings can be written in the form of

$$L_Y = f_{\alpha\beta} H^{\pm\pm} \ell_\alpha \ell_\beta + \text{H.c.},$$

which is not only LNV but also potentially LFV. As a result of the gauge couplings of $H^{\pm\pm}$ to photon and the $Z$-boson and the Yukawa couplings $f_{\alpha\beta}$, $H^{\pm\pm}$ can be pair produced at the high-energy lepton and hadron colliders, i.e. $e^+e^-, pp\rightarrow H^{\pm\pm}H^{\pm\pm}$. The usual gauge interaction induced Drell-Yan process can not be used to directly probe the Yukawa couplings $f_{\alpha\beta}$, unless the Yukawa couplings are sufficiently small such that $H^{\pm\pm}$ is long-lived at the high-energy colliders. After being produced, the doubly-charged scalars decay into pairs of same-sign dileptons, i.e. $H^{\pm\pm}\rightarrow \ell_\alpha^+ \ell_\beta^-$, which is apparently “smoking-gun” LNV signature beyond the SM. In some models, the doubly-charged scalar may decay also into other particles, e.g. $H^{\pm\pm}\rightarrow W^\pm W^\pm$ in the type-II seesaw. The most stringent limit on the doubly-charged scalar mass $M_{\pm\pm}$ is from the direct searches of same-sign dilepton pairs from $H^{\pm\pm}$ decay at the LHC [49,50]. At the low-energy high-precision frontier, the
Figure 3. Prospects of the doubly-charged scalar mass $M_{\pm\pm}$ and the LFV coupling $f_{e\mu}$ at ILC 1 TeV with 1 ab$^{-1}$, in the Yukawa pair (orange) and single production modes of the $e^+e^-$ (blue), $\gamma\gamma$ (purple) and $\gamma\gamma$ (brown) processes. The pink shaded region is excluded by the LEP $ee\to\mu^+\mu^-$ data. The vertical dashed gray lines indicate the current same-sign dilepton limits on the doubly-charged scalar mass from LHC, assuming BR($H^{\pm\pm}\to\ell_\alpha^+\ell_\beta^-$) = 100%. See text for more details. Figure from Ref. [26].

coupling $f_{e\beta}$ is also constrained by the LFV decays $\ell_\alpha \to \ell_\beta\gamma$, $\ell_\alpha \to \ell_\beta\ell_\gamma\ell_\delta$, the electron and muon $g - 2$, muonium oscillation and the LEP $e^+e^-\to\ell^+\ell^-$ data (see e.g. Ref. [26]).

As for the neutral scalar $H$ case above, the doubly-charged scalar $H^{\pm\pm}$ can also be singly produced at the high-energy lepton colliders via the Yukawa couplings $f_{e\beta}$ [51–56], e.g. $e^+e^-\to H^{\pm\pm}\ell_\alpha^+\ell_\beta^-$. The corresponding production cross section of this channel is proportional to the Yukawa coupling $|f_{e\beta}|^2$, therefore the Yukawa coupling $f_{e\beta}$ can be directly measured in such processes. Take $f_{e\mu}$ as an explicit example, with the $e^\pm$ beams and the the high-energy photon beams, we can have the following single production processes

$$e^+e^-, \gamma\gamma \to H^{\pm\pm}e^\mp\mu^\mp, \quad e^\pm\gamma \to H^{\pm\pm}\mu^\mp.$$

(5)

For simplicity, we assume the doubly-charged scalar decays predominately into $e^\pm\mu^\mp$, which can be ensured if the coupling $f_{e\mu}$ is much larger than other Yukawa couplings and other decay channels of the doubly-charged scalar such as $H^{\pm\pm}\to W^\pm W^\mp$ are subdominant. With BR($H^{\pm\pm}\to e^\pm\mu^\mp$) = 100%, the corresponding LHC limit on $M_{\pm\pm}$ is shown as the vertical dashed line in Fig. 3 [50,57]. The coupling $f_{e\mu}$ will also induce extra contribution to $e^+e^-\to\mu^+\mu^-$ at the LEP, and the corresponding limit is presented as the pink shaded region in Fig. 3. The contribution of doubly-charged scalars to the muon $g - 2$ is always negative, and therefore can not explain the muon $g - 2$ anomaly. Furthermore, the doubly-charged scalar contribution to muon $g - 2$ is highly suppressed by the charged lepton mass [2], thus not shown in Fig. 3.

The prospects of $H^{\pm\pm}$ at the ILC 1 TeV with luminosity of 1 ab$^{-1}$ are shown in Fig. 3. For the photon beam, we take the effective photon luminosity distribution from Refs. [36–38]. In the $e^+e^-$ and $\gamma\gamma$ channels, for doubly-charged scalar mass $M_{\pm\pm} \lesssim \sqrt{s} = 500$ GeV, the production of $H^{\pm\pm}$ will be dominated by pair production via both gauge and Yukawa interactions, while for $M_{\pm\pm} \gtrsim 500$ GeV only the single production of $H^{\pm\pm}$ is kinematically allowed. The $e^+\gamma$ process has only two particles in the final state, thus it can probe a smaller Yukawa coupling $f_{e\mu}$. For the LFV coupling $f_{e\tau}$, the prospects at the ILC 1 TeV is to some extent similar to the $f_{e\mu}$ case, with a smaller reconstruction efficiency for $\tau$ than muons. For the LFV coupling $f_{\mu\tau}$, the production cross section for $e^+e^-, \gamma\gamma \to H^{\pm\pm}e^\mp\tau^\mp$ is much smaller than that for $H^{\pm\pm}e^\mp\mu^\mp$ and $H^{\pm\pm}e^\mp\tau^\mp$. As a result, the prospects of $f_{\mu\tau}$ are only at the order of 0.1 [26].
Figure 4. Prospects of the Yukawa couplings $|f_{ee}^{d}\ell\tau|$ (left) and $|f_{e\gamma}^{d}\ell\tau|$ (right) for the doubly-charged scalar $H^{\pm\pm}$ production via the $ee\to \ell_\alpha \ell_\beta$ (red) and $e\gamma \to \ell_\alpha \ell_\beta \gamma$ (blue) processes, at CEPC with 240 GeV with 5 ab$^{-1}$ (dashed) and ILC 1 TeV with 1 ab$^{-1}$ (solid). The shaded regions are excluded by the corresponding limits. See text for more details. Figure from Ref. [26].

In analogous to the neutral scalar $H$ above, the doubly-charged scalar $H^{\pm\pm}$ can also induce LFV processes $e^+e^-\to \ell^+\ell^-$ at the high-energy lepton colliders by playing the role of mediator. The limit from $\mu\to eee$ is very stringent, and it precludes the prospects of $H^{\pm\pm}$ in the channel of $e^\pm\mu^\mp$. In the $\tau$ flavor sector, with the coupling $f_{e\gamma}^{d}\ell\tau$, the doubly-charged scalar can induce the processes

$$e^+e^-\to e^\pm\tau^\mp,$$  
$$e^\pm\gamma\to e^\pm e^\pm\tau^\mp,$$  
$$\tau^\pm\to e^\pm e^\pm e^\mp.$$

(6)

Similar to the neutral scalar case, the relevant limits for the doubly-charged scalar are from the LFV decays $\tau\to e\gamma$, $\tau\to eee$ and the LEP data $\ell^+\ell^-$ data, which are presented as the shaded regions in the left panel of Fig. 4. The prospects of $M_{\pm\pm}$ and $|f_{ee}^{d}\ell\tau|$ at the CEPC 240 GeV with the luminosity of 5 ab$^{-1}$ and ILC 1 TeV with 1 ab$^{-1}$ are shown in the left panel of Fig. 4, with red lines for the channel $e^+e^-\to e^\pm\tau^\mp$ and the blue lines for $e\gamma\to eee$ (combing the two possible final state in Eq (6)). The dashed lines denote the CEPC sensitivities, and the solid lines are for ILC. As in the neutral scalar case in Section 2, both CEPC and ILC can probe $H^{\pm\pm}$ with mass larger than the center-of-mass energy in the $e^+e^-$ channel, which corresponds to detecting the effective four-fermion interaction $(\bar{e}c)(\bar{e}\tau)$ with the cut-off scale $\Lambda\simeq M_{\pm\pm}/\sqrt{|f_{ee}^{d}\ell\tau|}$. With three particles in the final state, the cross section for $e\gamma$ processes are not as competitive as the $e^+e^-$ channel, as seen in the left panel of Fig. 4.

Given the coupling $f_{e\mu}^{d}\ell\tau$, the doubly-charged scalar $H^{\pm\pm}$ can induce the processes $e^+e^-\to \mu^+\tau^-$ and $e^\pm\gamma\to \mu^\pm e^\mp\tau^\mp$, $\tau^\pm e^\mp\mu^\mp$, and the corresponding limits from $\tau^-\to \mu^-\gamma$, $\tau^-\to \mu^- e^+e^-$, the LEP $\ell^+\ell^-$ data and prospects at the CEPC 240 GeV and ILC 1 TeV are presented in the right panel of Fig. 4. As for the case of $f_{e\gamma}^{d}\ell\tau$, the $e^+e^-$ processes have better sensitivities than the $e\gamma$ collisions. These processes can also be induced by the coupling $f_{e\ell}^{d}\mu\tau$. However, the corresponding production cross sections are smaller, which weakens the detectability of $f_{e\ell}^{d}\mu\tau$ at future high-energy lepton colliders. More $H^{\pm\pm}$ induced LFV processes such as $e\gamma\to \mu\mu\mu$, $\mu\mu\tau$ are also possible, but the corresponding prospects are suppressed by the small cross sections. More details can be found in Ref. [26].

Here are more comments on the doubly-charged scalar $H^{\pm\pm}$:

- The CLIC energy can go up to 3 TeV, and this will improve significantly the prospects of $M_{\pm\pm}$ in both the on-shell and off-shell searches at future lepton colliders.
- The future muon collider will provide more channels for searches of LFV due to the doubly-charged scalar, in particular for the muon relevant couplings.
4. Heavy neutrino $N$

In the type-I seesaw [59–63], heavy neutrinos are introduced to generate the tiny neutrino masses. With the mass term $M_{\nu_{i,j}}N_i^\dagger N_j$ ($i, j$ are the mass indices), the heavy neutrinos $N_i$ are Majorana particles. In some other seesaw models such as the inverse seesaw [64–66], by adding three more neutral singlet fermions, the heavy neutrinos form pseudo-Dirac states. No matter being either Majorana or Dirac fermions, the heavy neutrinos could mix with the active neutrinos $\nu_\alpha$ ($\alpha = e, \mu, \tau$), and thus couple to the SM $W$ and $Z$ bosons through the heavy-light neutrino mixing $V_{\alpha N}$. If the heavy neutrinos are at or below the TeV-scale, they can be produced at the high-energy lepton and hadron colliders. For simplicity, let us focus here only on the LFV signals from the heavy neutrinos. To this end, let us neglect the specific UV completions of seesaw models and consider only one heavy neutrino $N = N_1$, with the other two states $N_{2,3}$ much heavier and not contributing significantly to the LFV signals.

The heavy neutrino $N$ can be produced at $pp$ colliders via the charged current Drell-Yan and vector-boson fusion (VBF) process [67–70]

$$qq' \rightarrow W^\pm \rightarrow \ell_\alpha^\pm N \rightarrow \ell_\alpha^\pm \ell_\beta^\mp W^\mp,$$
$$W^\pm \gamma \rightarrow \ell_\alpha^\pm N \rightarrow \ell_\alpha^\pm \ell_\beta^\mp W^\mp,$$  

(7)

where we have assumed the heavy neutrino mass $m_N > m_W$ (with $m_W$ the $W$ boson mass). If the heavy neutrino $N$ is a Dirac fermion, there will only be opposite-sign charged leptons $\ell_\alpha^\pm \ell_\beta^\mp$ in the final state. For the case of Majorana $N$, there will also be the same-sign charged leptons $\ell_\alpha^\pm \ell_\beta^\pm$, which is undoubtedly LNV signals beyond the SM. For some mass ranges of $m_N$, the gluon-fusion process $gg \rightarrow Z^*, h^* \rightarrow \nu N$ is also very important [71–73]. More details about the production channels of $N$ can be found e.g. in Ref. [74]. If the heavy neutrino $N$ mixes with two neutrino flavors $\nu_{\alpha, \beta}$ (with $\alpha \neq \beta$) in the SM, the production and decay of $N$ at the high-energy colliders will produce LFV signals, i.e. $\ell_\alpha \neq \ell_\beta$ in the final state of the process in Eq. (7) via the charged currents.

Considering both the charged current Drell-Yan and VBF processes in Eq. (7), if the $W$ boson from $N$ decays leptonically, we will have three charged leptons plus significant missing transverse energy (MET) in the final state, with potentially extra (VBF) jets. With $|V_{eN}| = |V_{\mu N}|$, we can have the processes $pp \rightarrow e\ell_X + e\mu \tau_h$, with $\tau_h$ referring to the hadronic decaying taus, $\ell_X = e, \mu, \tau_h$, and all the possible lepton charges are included. Adopting dynamic jet vetoes, the sensitivities of $m_N$ and the heavy-light neutrino mixing $|V_{eN}| = |V_{\mu N}|$ at future hadron colliders are presented in Fig. 5 [74]. It is found that the prospects here are not sensitive to the Majorana or Dirac nature of $N$. In the near future, the LHC 14 TeV data with a luminosity of 300 fb$^{-1}$ can probe a mixing $|V_{eN}|^2 = |V_{\mu N}|^2 \sim \mathcal{O}(10^{-3})$ for a heavy neutrino at the scale of 100 GeV. At future 100 TeV collider, the sensitivity of heavy-light neutrino mixing can even go down to $\mathcal{O}(10^{-4})$. More simulation details can be found in Ref. [74]. In Fig. 5, the regions above the short dashed line are excluded by the direct trilepton searches of $N$ at CMS [75], and horizontal dot-dashed line represents the current electroweak precision data (EWPD) constraints on $|V_{eN}|$ [76]. More limits on the heavy-light neutrino mixing can be found e.g. in Ref. [77].

At the GeV-scale, the limits on the neutrino mass $m_N$ and $|V_{eN}|^2$ will be mostly from the high-precision LFV measurements below [78,79]:

- For sufficiently small couplings, the doubly-charged scalar can be long-lived at the high-energy colliders, which is largely complementary to the searches of prompt signals from $H^{\pm\pm}$ decay [58].
Figure 5. Sensitivities of heavy neutrino mass $m_N$ and the heavy-light neutrino mixing $|V_{eN}|^2 = |V_{\mu N}|^2$, at future LHC 14 TeV with luminosities of 300 fb$^{-1}$ and 3 ab$^{-1}$, LHC 27 TeV with 3 ab$^{-1}$ and 15 ab$^{-1}$, and 100 TeV collider with 15 ab$^{-1}$ and 30 ab$^{-1}$. Regions above the short dashed line are excluded by the CMS data, and the dot-dashed horizontal line indicates the indirect limit from current EWPD data. See text for more details. Figure from Ref. [74].

- At lower energies, the charged current Drell-Yan process in Eq. (7) will “hadronize” to be semileptonic weak decays of charged mesons, i.e.
  \[
P_{2}^{\pm} \rightarrow \ell_\alpha N^{(*)} \rightarrow \ell_\alpha^\pm \ell_\beta^\mp P_{1}^{\pm},
  \]
  with $P_{1,2}^{\pm}$ the charged mesons. As at the high energy, the heavy neutrino $N$ will induce LFV in meson decays if $\ell_\alpha \neq \ell_\beta$. LNV decays $P_{2}^{\pm} \rightarrow \ell_\alpha^\pm \ell_\beta^\mp P_{1}^{\pm}$ are also possible if $N$ is a Majorana fermion. It is found that for the mass range of $m_\pi < m_N < m_K$ (with $m_\pi$, $m_K$ the masses of pions and Kaons), the most stringent limit on $|V_{eN}|^2$ is from the decay $K^+ \rightarrow \pi^0 e^+ \mu^+$ leading to $|V_{eN}| \lesssim 10^{-9}$ [80]. For $m_K < m_N < m_B$ (with $m_B$ the $B$ meson mass), the strongest limit is from $B^+ \rightarrow \pi^+ e^+ \mu^+$. In the process (8), if $N$ is on-shell, it can be directly searched via the two-body meson decays, e.g. $K^+ \rightarrow \ell^+ N$. The NA62 data have excluded $|V_{eN}| < 10^{-8}$ to $10^{-9}$ for $170 \text{ MeV} < m_N < 450 \text{ MeV}$ [81]. More processes can be found e.g. in Refs. [77,79].

- For neutral mesons $P_0$, the heavy neutrino will induce LFV leptonic decays at the 1-loop level, i.e.
  \[
P_0 \rightarrow \ell_\alpha^\pm \ell_\beta^\mp,
  \]
  which can be applied to the LFV leptonic decays of $K_L$, $D_0^0$, $B_0^0$, and $B^0_s$. Such LFV meson decays are all highly suppressed in the SM, and the mass $m_N$ and heavy-light neutrino mixing $|V_{eN}V_{\mu N}|$ are tightly constrained by precision meson data. More details can be found e.g. in Ref. [80].

- In the charge lepton sector, if $N$ mixes with two SM neutrino flavors, it will induce extra contribution to the LFV radiative decays of charged leptons $\ell_\alpha \rightarrow \ell_\beta \gamma$ and $\mu \rightarrow e \gamma$ conversion in nuclei. It is found that the most stringent limit is from $\mu \rightarrow e \gamma$, which leads to $|V_{eN}V_{\mu N}| \sim 10^{-3}$ for a 10 GeV $N$ [77].
If two (or more) heavy neutrino $N_{1,2}$ are involved, there could be more phenomenological implications, such as heavy neutrino mixing and CP violation due to the TeV-scale $N$ [82] or in the decays of mesons and the SM Higgs [83–85]. All these processes might involve LFV in some way.

5. Heavy $W_R$ boson

In the LRSM, the heavy neutrinos are states from the right-handed isospin doublets, therefore $N$ couples to the heavy right-handed $W_R$ boson. As a result of the Majorana nature of $N$, the production and decay of $W_R$ at the high-energy hadron colliders will produce same-sign dileptons via the process

$$qar{q}' \to W^+_R \to \ell^+_a N \to \ell^+_a \ell^+_b W^+_R \to \ell^+_a \ell^+_b jj,$$

which constitutes the smoking-gun signal of LRSM. In such a process, the heavy neutrino mass eigenstate $N$ may be a state of pure flavor $a$, or combinations of two flavors $a$ and $\beta$, i.e. $N = c\alpha N_a + \sin N_\beta$ with $\theta$ the mixing angle of heavy neutrinos $N_{a,\beta}$ leading to LFV signatures $\ell^+_a \ell^+_b$. The most stringent limit LHC limit on $W_R$ and $N$ is from the recent searches by CMS with a luminosity of 138 fb$^{-1}$ at 13 TeV, which covers both the lepton flavor conserving cases $e\tau$, $\mu\mu$ and LFV case $e\mu$ [86]. No significant excess is found above the backgrounds, and $W_R$ mass is excluded up to 5.4 TeV. With 3000 fb$^{-1}$ data at 14 TeV, the $W_R$ mass can be improved up to roughly 6.5 TeV [87,88]. At future 100 TeV colliders, the $W_R$ mass can be probed up to roughly 38 TeV with a luminosity of 30 fb$^{-1}$, assuming the heavy neutrino decays promptly [89]. If the neutrino $N$ is light, the parameter space of three-body decay $N \to \ell jj$ will be highly compressed. This will make $N$ long-lived at the high-energy colliders, with decay length of $N$ up to the meter level for $m_N \sim 10$ GeV [87,90]. The displaced vertex signals from $N$ decay can be used to search for the heavy $W_R$ boson, and the prospect of $W_R$ mass can go up to 33 TeV at the future 100 TeV collider, with $m_N \sim 100$ GeV [87]. The prompt and displaced vertex signals from $W_R$ and $N$ can both be sources for LFV at future high-energy colliders.

6. $Z'$ boson

The heavy neutral $Z'$ boson can have flavor changing neutral currents, e.g. from the mixing of SM fermions with heavy exotic fermions [92]. Another important motivation of LFV couplings of $Z'$ is the muon $g-2$ anomaly, where the $Z'$ boson can be either heavy or light. For instance, the effective LFV couplings of $Z'$ to $\mu$ and $\tau$ can be written as

$$\mathcal{L} \supset Z'_\mu (g'^L_1 \bar{\mu}_L \gamma^\mu \tau_L + g'^R_1 \bar{\tau}_R \gamma^\mu \mu_R) + \text{H.c.},$$

(11)

With $\tau$ running in the loop, the $Z'$ boson with LFV couplings can explain the muon $g-2$ discrepancy, which is in some sense similar to the neutral scalar case above [2,91]. The corresponding $2\sigma$ regions for the muon $g-2$ anomaly is shown as the green band in Fig. 6, where we have assumed that the gauge couplings $g'^L_1 = g'^R_1/10$.

The direct searches of heavy $Z' \to e\mu, e\tau, \mu\tau$ have been performed at the LHC [93]. Assuming the LFV couplings of $Z'$ are the same as the couplings of $Z$ boson to charged leptons, $Z'$ mass has been excluded up to 5.0 TeV in the $e\mu$ channel, 4.3 TeV in the $e\tau$ channel, and 4.1 TeV in the $\mu\tau$ channel [93]. The LFV couplings $g'_{L,R}$ in Eq. (12) are also severely constrained by the decay $\tau \to Z' \to Z' \to \nu_\mu \bar{\nu}_e$, the lepton flavor universality violation in tauon decays, the high-precision LHC W data, the LEP Z-pole data, and the muon $g-2$ anomaly at the $5\sigma$ C.L.. As seen in Fig. 6, when all these constraints are taken into consideration, a $Z'$ with mass $m_{Z'} > 2$ GeV can provide viable interpretation of the muon $g-2$ anomaly.
Figure 6. Prospect of $m_{Z'}$ and $g'_R$ at LH-LHC (dotted orange line) and FCC-ee (dotted blue line) with $g'_L = g'_R/10$. The green band correspond the muon $g-2$ anomaly at the 2$\sigma$ C.L.. The blue, gray and red shaded regions are excluded by $\tau \rightarrow \mu Z'$, muon $g-2$ discrepancy at the 5$\sigma$ C.L., and $\tau \rightarrow \mu \nu \bar{\nu}$. The purple and black dashed lines are respectively the limits from the LEP Z-pole data and the LHC W data. See text for more details. Figure from Ref. [91].

The LFV coupling $g'_{L,R}$ of the light $Z'$ boson can be directly measured at the high-energy hadron and lepton colliders via the process

$$pp, e^+e^- \rightarrow \mu^+\tau^+Z',$$

which is quite similar to the process (2) for the neutral scalar $H$. With $Z' \rightarrow \mu^+\tau^+$, the LFV coupling $g'_{L,R}$ will generate same-sign dilepton pairs $\mu^+\mu^+\tau^+\tau^-$. The prospects at the high-luminosity LHC (HL-LHC) 14 TeV with an integrated luminosity of 3 ab$^{-1}$ and the FCC-ee 91 GeV with 2.6 ab$^{-1}$ are presented respectively as the dotted orange and blue curves in Fig. 6. It is very clear that both the two machines can probe large regions of the $Z'$ interpretation of muon $g-2$ anomaly. More details can be found in Ref. [91]. It should be noted that the prospects can be further improved at a future muon collider.

With the LFV coupling $g'_{e\mu}$, the $Z'$ boson could contribute to $\mu - e$ scattering [94,95], e.g. in the MUonE experiment, which is proposed to determine the contribution of hadronic vacuum polarization to muon $g-2$ [96]. However, the LFV coupling $g'_{e\mu}$ of $Z'$ boson is tightly constrained by muonium-antimuonium oscillation and electron $g-2$, which has precluded the sensitivity of the MUonE experiment. More details can be found in Ref. [94].

7. Conclusions

In this paper, we have summarized briefly the LFV signals from the BSM neutral scalar $H$, doubly-charged scalar $H^{\pm\pm}$, heavy neutrino $N$, heavy $W_R$ boson and the $Z'$ boson. Constrained by current data, some of these particles are required to be heavy, e.g. the doubly-charged scalar and the $W_R$ boson, while others can be either heavy at the TeV-scale or light down to the GeV-scale or even lighter. The LFV signals induced by these particles can originate from the (effective) LFV couplings in the charged lepton sector, i.e. the neutral scalar $H$, the doubly-charged scalar, and the $Z'$ boson. For the heavy $N$ and the $W_R$ boson, the LFV signals are intimately related to flavor mixing in the neutrino sector, which is
transited to the charged lepton sector via the charged currents by the $W$ and $W_R$ bosons. The detection of LFV signatures can either be at the high-energy hadron and lepton colliders, or in the high-precision measurements such as the Mu3e experiment \cite{97}. In particular, if the muon $g-2$ anomaly turns out to be true, or any other LFV signal is found in future experiments, we need to understand better these particles, as well as other well-motivated particles such as leptoquarks and supersymmetric particles.

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