Lepton flavor violation induced by a neutral scalar at future lepton colliders

P. S. Bhupal Dev

Department of Physics and McDonnell Center for the Space Sciences, Washington University,
St. Louis, MO 63130, USA
E-mail: bdev@wustl.edu

Rabindra N. Mohapatra

Maryland Center for Fundamental Physics, Department of Physics, University of Maryland,
College Park, MD 20742, USA
E-mail: rmohapat@umd.edu

Yongchao Zhang[*]

Department of Physics and McDonnell Center for the Space Sciences, Washington University,
St. Louis, MO 63130, USA
E-mail: yongchao.zhang@physics.wustl.edu

Many new physics scenarios beyond the Standard Model often necessitate the existence of a neutral scalar H, which might couple to the charged leptons in a flavor violating way, while evading all existing constraints. Such scalars could be effectively produced at future lepton colliders like CEPC, ILC and FCC-ee, either on-shell or off-shell, and induce lepton flavor violating (LFV) signals. We find that a large parameter space of the scalar mass and the LFV couplings can be probed, well beyond the current low-energy constraints in the lepton sector. In particular, a scalar-loop induced explanation of the longstanding muon $g-2$ anomaly can be directly tested in the on-shell mode.

---

[*]Speaker.

1. Introduction

There are various theoretical models of new physics which lead to charged lepton flavor violation (cLFV) effects at an observable level. They generally involve extending the Higgs sector, which allows flavor-violating Yukawa couplings of new neutral scalars beyond the standard model (SM). Some well-motivated examples include supersymmetric models with leptonic *R*-parity violation, left-right symmetric models, mirror models, and two-Higgs doublet models, where the cLFV couplings might arise at tree or loop level.

In this paper, we show that such scenarios of neutral scalar-induced cLFV can be effectively probed in a model-independent way at future lepton colliders, such as the CEPC, ILC, FCC-ee and CLIC. Here we include both on and off-shell production of the new neutral scalar H at lepton colliders, which enables us to derive the lepton flavor violation (LFV) sensitivity as a function of the mass m_H for a direct comparison with the current bounds from low-energy experiments. Moreover, for m_H small compared to the center-of-mass energy, the effective four-fermion approximation does not work. Without loss of generality, we can write the effective Yukawa couplings of H to the charged leptons as

$$\mathscr{L}_Y = h_{\alpha\beta}\bar{\ell}_{\alpha,L}H\ell_{\beta,R} + \text{H.c.}. \tag{1.1}$$

Here for simplicity we assume the couplings $h_{\alpha\beta}$ are all real and chirality-independent and thus symmetric. We assume futher that H is CP even and its mixing with and/or coupling to the SM Higgs is small. With an ab^{-1} level of integrated luminosity, a large parameter space of m_H and $h_{\alpha\beta}$ could be probed, well beyond the current cLFV constraints. More details can be found in Ref. [1], and the application to the left-right symmetric models is given in Ref. [2].

2. On-shell LFV

If kinematically allowed, the neutral scalar H can be directly produced at lepton colliders, in association with a pair of flavor-changing leptons through the couplings in Eq. (1.1), i.e. $e^+e^- \to \ell_\alpha^\pm\ell_\beta^\mp H$ (with $\alpha \neq \beta$). Let us first switch on the coupling $h_{e\mu}$ and off all other (LFV) couplings. It should be emphasized that the production amplitudes depend only on the LFV couplings $h_{\alpha\beta}$ (here $\alpha\beta = e\mu$), and thus could be easily made to satisfy the rare lepton decay constraints, such as $\mu \to eee$ and $\mu \to e\gamma$, which depend on the product $|h_{ee}^\dagger h_{e\mu}|$. We have only the following constraints: (*i*) Muonium-antimuonium oscillation: This could occur in both *s* and *t*-channels, with the oscillation probability $\mathscr{P} \propto |h_{e\mu}|^4/m_H^4$. (*ii*) The anomalous magnetic moment of electron a_e receives a contribution from the $H - \mu$ loop. (*iii*) the LEP $e^+e^- \to \mu^+\mu^-$ data [3]: A *t*-channel H could mediate the scattering $e^+e^- \to \mu^+\mu^-$, which interferes with the SM diagrams in the *s*-channel. All these constraints on m_H and $h_{e\mu}$ are shown in the left panel of Fig. 1 as the shaded regions. To explain the longstanding theoretical and experimental discrepancy of the muon $g-2$, i.e. $\Delta a_\mu = (2.87\pm0.80)\times10^{-9}$ [4], the LFV coupling $h_{e\mu}$ is required to be larger, which is already excluded by the $(g-2)_e$ data.

To be specific, we consider two benchmark configurations for future lepton colliders: i.e. the CEPC 240 GeV with an integrated luminosity of 5 ab^{-1} and ILC 1 TeV witha a luminosity of 1 ab^{-1}. The SM background is dominated by particle mis-identification, e.g. *e* mis-identified as μ
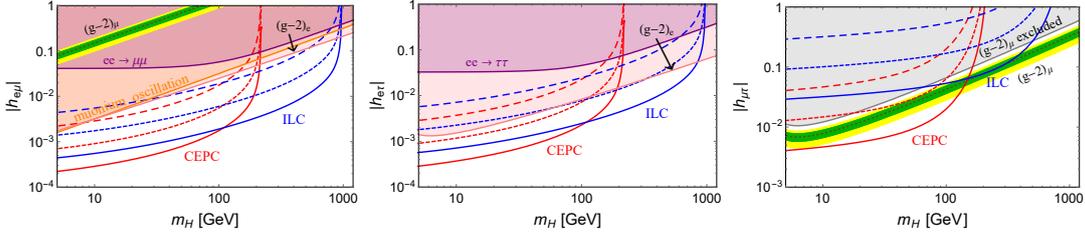
Figure 1: Prospects of probing LFV couplings $h_{\alpha\beta}$ ($\alpha \neq \beta$) from searches of $e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp H$ at CEPC 240 GeV (red) and ILC 1 TeV (blue). Here we have assumed 10 LFV signal events and a BR of 1% (long-dashed) 10% (short-dashed) or 100% (solid) from H decay to be visible. In the plots all the shaded regions are excluded by the constraints as labelled. In the left and right panels, the brown line could fit the central value of Δa_μ, and the green and yellow bands cover the 1σ and 2σ ranges of Δa_μ.
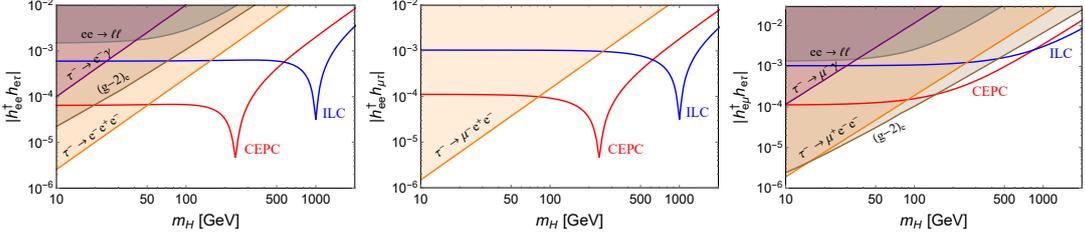

Figure 2: Prospects of $|h_{ee}^\dagger h_{e\tau}|$ (left), $|h_{ee}^\dagger h_{\mu\tau}|$ (middle) and $|h_{e\mu}^\dagger h_{e\tau}|$ (right) from searches of $e^+e^- \to e^\pm\tau^\mp, \mu^\pm\tau^\mp$ at CEPC 240 GeV (red) and ILC 1 TeV (blue). Here we have assumed 10 signal events. Also shown are the constraints from the rare lepton decays, $(g-2)_e$, and the LEP $e^+e^- \to \ell^+\ell^-$ data [3].

or vice versa, and is very small. After being produced, H could decay back into the charged lepton pairs or other SM particles. To work in a model-independent way, we consider three benchmark values, where 1%, 10% or 100% of the decay products of H are visible and can be reconstructed. The corresponding LFV prospects are shown in the left panel of Fig. 1, where we have assumed a minimum of 10 signal events at both CEPC and ILC. It is clear from Fig. 1 that with a branching ratio (BR) of $\gtrsim 10\%$, a large region of m_H and $|h_{e\mu}|$ can be probed in future lepton colliders, which extends the limits well beyond what is currently available.

Turning now to the coupling $h_{e\tau}$, the most stringent limit comes from the electron $g-2$, and the LEP $e^+e^- \to \tau^+\tau^-$ data [3]. The reconstruction of τ lepton is more challenging than μ, but there is still ample parameter space to probe at both CEPC and ILC, as long as the effective BR is $\gtrsim 10\%$. Regarding the coupling $h_{\mu\tau}$, there are currently no experimental limits, except for the muon $g-2$ discrepancy. This could be explained in presence of H when it couples to muon and tau, as shown by the brown line and the green and yellow bands in the right panel of Fig. 1, while the shaded region is excluded by the current muon $g-2$ data at the 5σ level.

3. Off-shell LFV

The LFV signals could also be produced from an off-shell H, i.e. $e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp$. This could occur in both the s and t channels; in the s-channel H is on-shell if the colliding energy $\sqrt{s} \simeq m_H$ (resonance). Different from the on-shell case, the off-shell production amplitudes have a quadratic dependence on the Yukawa couplings (some of them might be flavor conserving), and thus largely complementary to the on-shell LFV searches.

The amplitude $e^+e^- \to e^\pm \mu^\mp$ is proportional to $h_{ee}^\dagger h_{e\mu}$. This is tightly constrained by the $\mu \to eee$ data, leaving no hope to see any signal in this channel. In the τ lepton sector, the LFV decay constraints are comparatively much weaker. The limits on $|h^\dagger h|/m_H^2$ from $\tau^- \to e^-\gamma$ and $\tau^- \to e^+e^-e^-$ are almost constants, as in effective field theories with superheavy mediators. As for the on-shell case above, the coupling $|h_{ee}^\dagger h_{e\tau}|$ are constrained by the electron $g-2$ and the LEP $e^+e^- \to \ell^+\ell^-$ data [3]. All the constraints are presented in the left panel of Fig. 2.

The dominant SM backgrounds are from the process $e^+e^- \to W^+W^- \to e^-\tau^+\bar{\nu}_e\nu_\tau$ which is expected to be small. Assuming 10 signal events as above, the prospects of the coupling $|h_{ee}^\dagger h_{e\tau}|$ are shown in Fig. 2. At the resonance $m_H \simeq \sqrt{s}$, the production cross section can be greatly enhanced by m_H^2/Γ_H^2. To be specific, we have set the width $\Gamma_H = 10$ (30) GeV at $\sqrt{s} = 240$ GeV (1 TeV). For $m_H > \sqrt{s}$, the production rate diminishes rapidly as H becomes heavier. An off-shell H could however be probed up to a few-TeV range, as shown in Fig. 2, and ILC is expected to be more promising than CEPC in this mass range, as a result of the higher $\sqrt{s}$.

The process $e^+e^- \to \mu^\pm\tau^\mp$ could proceed via both the s and t channels, which depend on different couplings, namely $|h_{ee}^\dagger h_{\mu\tau}|$ and $|h_{e\mu}^\dagger h_{e\tau}|$, and are constrained respectively by the rare decays $\tau^- \to \mu^-e^+e^-$ and $\tau^- \to \mu^+e^-e^-$. Analogous to the $e\tau$ case above, a broad range of m_H and $|h_{ee}^\dagger h_{\mu\tau}|$ could be probed in the s channel, in particular in vicinity of the resonance, as shown by the middle panel of Fig. 2. In the t channel, the cross sections are comparatively smaller, and the detectable regions are much narrower, as shown by the right panel of Fig. 2.

4. Conclusion

We have shown that a hadrophobic neutral scalar H, which is well-motivated in a large class of new physics scenarios, can be probed in an e^+e^- collider via its LFV couplings to the charged lepton sector. We present a model-independent analysis of how far the LFV coupling strengths and the scalar mass can be probed beyond the existing limits from the low-energy sector. In particular, we find that the full mass and coupling range of the scalar, that can explain the muon $g-2$ anomaly, can be tested in the future lepton colliders. This is largely complementary to the searches of LFV in the low-energy experiments and hadron colliders.

Acknowledgments

References

[1] P. S. B. Dev, R. N. Mohapatra and Y. Zhang, Phys. Rev. Lett. **120**, no. 22, 221804 (2018) [arXiv:1711.08430 [hep-ph]].

[2] P. S. Bhupal Dev, R. N. Mohapatra and Y. Zhang, Phys. Rev. D **98**, no. 7, 075028 (2018) [arXiv:1803.11167 [hep-ph]].

[3] J. Abdallah *et al.* [DELPHI Collaboration], Eur. Phys. J. C **45**, 589 (2006) [hep-ex/0512012].

[4] M. Tanabashi *et al.* [Particle Data Group], Phys. Rev. D **98**, no. 3, 030001 (2018).