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

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based on
Bhupal Dev, Mohapatra & YCZ, 1711.08430
Lepton Flavor Violation Induced by a Neutral Scalar at Future Lepton Colliders
Bhupal Dev, Mohapatra & YCZ, 18xy.abcde
Probing TeV scale origin of Neutrino Masses at lepton colliders
Outline

- Motivations
- Effective LFV couplings of a (light) BSM neutral scalar $H$
- On-shell production of $H$ at CEPC & ILC
- Off-shell production of $H$ at CEPC & ILC
- Prospects and discussions
Motivation: LFV beyond SM

- **muon $g - 2** [Carena, Giudice, Wagner '96; Raidal+ '08; Wolfgang Altmannshofer, Carena, Crivellin '16]

- **neutrino mass generation** [Dreiner, Nickel, Staub+ '12; de Gouvea, P. Vogel '13; Vicente '15; Lindner, Platscher, Queiroz '16]

  charged LFV is always connected to neutrino mass generation by beyond SM scalars.

$H$: beyond SM scalar

see also Altmannshofer, Gori Kagan+ '15; Altmannshofer, Eby, Gori '16
charged LFV beyond SM & lepton colliders

- The LFV couplings of the SM Higgs $h$, e.g. $y_{\mu\tau}$;
  [Blankenburg, Ellis, Isidori ’12; Harnik, Kopp, Zupan ’12]

- Beyond SM doubly-charged scalars $H^{\pm\pm}$, e.g. from type-II seesaw;
  [Fileviez Perez, Han, Huang+ ’08; Rentala, Shepherd, Su ’11; King, Merle, Panizzi ’14]

- **Beyond SM (light) neutral scalar $H$ with LFV couplings $h_{\alpha\beta}$**

- Beyond SM neutral scalar:
  - its mass & the LFV couplings: model-dependent...

- The most efficient way to probe the LFV couplings:
  - future lepton colliders, like CEPC, ILC, FCC-ee, CLIC
  - if the beyond scalar $H$ is hadrophobic and does not mixing sizably with the SM Higgs.
Well-motivated underlying models

- **RPV SUSY**: LFV couplings of sneutrino to the charged leptons
  [Aulakh, Mohapatra '82; Hall, Suzuki '84; Ross, Valle '85, Barbier+ '04; Duggan, Evans, Hirschauer '13]
  \[
  \mathcal{L}_{\text{RPV}} = \frac{1}{2} \lambda_{\alpha\beta\gamma} \hat{L}_\alpha \hat{L}_\beta \hat{E}^c_\gamma
  \]

- **Left-right symmetric models**: the $SU(2)_R$-breaking scalar $H_3$
  [Dev, Mohapatra, YCZ '16; '16; '17; Maiezza, Senjanović, Vasquez '16]
  LFV couplings are generated through mixing of $H_3$ with other heavy scalars

- **2HDM**: CP-even or odd (heavy) scalars from the 2nd doublet
  [Branco+ '11; Crivellin, Heeck, Stoffer '15]
  LFV couplings are induced from small deviation from the lepton-specific structure.

- **Mirror models**: singlet scalar connecting the SM leptons to heavy mirror leptons
  [Hung '06, '07; Bu, Liao, Liu '08; Chang, Chang, Nugroho+ '16; Hung, Le, Tran+ '17]
  LFV couplings arise from the SM-heavy lepton mixing
Model-independent effective LFV couplings of $H$

\[ \mathcal{L}_Y = h_{\alpha \beta} \bar{\ell}_\alpha, L H \ell_\beta, R + \text{H.c.} \]

- For simplicity, we assume $h_{\alpha \beta}$ are real and chirality-independent. Symmetric matrix: $h_{\alpha \beta} = h_{\beta \alpha}$

- For concreteness we assume $H$ is CP-even. A CP-odd scalar leads to some differences, e.g. to muonium oscillation [Hou, Wong '95], but would not change qualitatively the main results.

- $H$ might originate from a isospin singlet, doublet or triplet, depending on specific underlying models.

Effective Dim-4 couplings \( \neq \) Effective 4-fermion couplings like \( \frac{1}{\Lambda^2} (\bar{e}e)(\bar{e}\mu) \)

[Kabachenko, Pirogov '97; Ferreira, Guedes, Santos '06; Aranda, Flores-Tlalpa, Ramirez-Zavaleta+ '09; Murakami, Tait '14; Cho, Shimo '14]

\[ m_H < \sqrt{s} \Rightarrow \text{on-shell production} \]
On-shell & off-shell production

- **On-shell production** (based on the process $ee \rightarrow \ell\ell$)

$$e^+ e^- \rightarrow \ell^\pm \ell^- + H$$

- **Off-shell production** (at resonance when $m_H \simeq \sqrt{s}$)

might also be mediated by a (light) gauge boson $Z'$ with LFV couplings [Heeck '16]

$$e^+ e^- \rightarrow \ell^\pm \ell^-$$
Constraints on the LFV couplings: on-shell

On-shell production amplitudes depend \textit{linearly} on the LFV couplings

- muonium anti-muonium oscillation: \((\bar{\mu}e) \leftrightarrow (\mu\bar{e}) (h_{e\mu})\)

Oscillation probability \cite{Clark, Love '03}

\[
P = \frac{2(\Delta M)^2}{\Gamma_{\mu}^2 + 4(\Delta M)^2}
\]

with the \(H\)-induced mass splitting

\[
\Delta M = \frac{2\alpha_{EM}^3 h_{e\mu}^2 \mu^3}{\pi m_H^2}, \quad \mu = \frac{m_e m_\mu}{m_e + m_\mu}
\]
Constraints on the LFV couplings: on-shell

- Electron and muon $g - 2 \left( h_{e\ell}, h_{\mu\ell} \right)$

  [Lindner, Platscher, Queiroz ’16]

\[
\Delta a_e \simeq \frac{h_{e\mu}^2 m_e m_\mu}{16\pi^2 m_H^2} \left[ 2 \log \left( \frac{m_H^2}{m_\mu^2} \right) - 3 \right].
\]

\[(g/2)_e = 1.00115965218073 (28)
\]

used to determine $\alpha_{EM}$, 20 times more accurate than other experiments

The value of $h_{e\mu}$ to explain $(g - 2)_\mu$ discrepancy is excluded by the $(g - 2)_e$ constraint.

\[
\Delta a_\mu \equiv \Delta a_{\mu}^{\text{exp}} - \Delta a_{\mu}^{\text{th}} = (2.87 \pm 0.80) \times 10^{-9}
\]
Constraints on the LFV couplings: on-shell

- Bhabha scattering, LEP $ee \rightarrow \ell\ell$ data ($h_{\ell\ell}$)
  
  [OPAL '03; L3 '03; DELPHI '05]

\[
\begin{align*}
\text{Effective 4-fermion interaction} & \quad \sim \frac{h^2}{m_H^2} (\bar{\ell}\ell)(\bar{\ell}\ell) \\
& \xrightarrow{\text{Fierz transformation}} \frac{1}{\Lambda^2} (\bar{e}\gamma_\mu e)(\bar{\ell}\gamma^\mu \ell)
\end{align*}
\]

If $m_H \lesssim \sqrt{s}$, the LEP limits on the cut-off scale $\Lambda$ do not apply, and we have to consider the kinetic dependence:

\[
\frac{1}{m_H^2} \rightarrow \frac{1}{q^2 - m_H^2} \sim \frac{1}{-s \cos \theta / 2 - m_H^2}
\]
Main SM backgrounds are particle misidentification for
\[ e^+ e^- \rightarrow \ell_\alpha^+ \ell_\beta^- + X, \quad (\alpha \neq \beta) \]

The mis-identification rate is expected to be small, of order \( 10^{-3} \)
[Milstene, Fisk, Para '06; Hammad, Khalil, Un '16; Yu, Ruan, Boudry+ '17]

Example:
\[ e^+ e^- \rightarrow Zh \rightarrow (e^+ e^- / \mu^+ \mu^-)h \sim e^\pm \mu^\mp + h \]
CEPC & ILC prospects: on-shell

Long-dashed, short-dashed, solid lines:
1%, 10%, and 100% of the decay products of $H$ is reconstructible (visible).

Shaded regions are excluded.

Dotted brown line: central values of muon $g - 2$ anomaly,
green and yellow bands: the $1\sigma$ and $2\sigma$ regions.
CEPC & ILC prospects: on-shell

Long-dashed, short-dashed, solid lines: 1%, 10%, and 100% of the decay products of $H$ is reconstructible (visible).

Shaded regions are excluded.

$|\eta_{e\tau}|$ vs $m_H$ [GeV]

$ee \rightarrow \tau\tau$
Long-dashed, short-dashed, solid lines: 1%, 10%, and 100% of the decay products of $H$ is reconstructible (visible).

Shaded regions are excluded.

Dotted brown line: central values of muon $g-2$ anomaly, green and yellow bands: the $1\sigma$ and $2\sigma$ regions.

The muon $g-2$ discrepancy can be directly tested at CEPC via the searches of $ee \rightarrow \mu \tau + H$
Constraints on the LFV couplings: off-shell

Off-shell production amplitudes depend \textit{quadratically} on the LFV couplings

- 3-body LFV decays of muon and tauon, e.g. [Sher, Yuan '91]

\[
\Gamma(\tau^- \to e^+ e^- e^-) \simeq \frac{1}{\delta} \frac{|h^\dagger_{ee} h_{e\tau}|^2 m^5_\tau}{3072 \pi^3 m^4_H}, \quad (\delta = 2)
\]

- 2-body LFV decays of muon and tauon, e.g. [Harnik, Kopp, Zupan '12]

\[
\Gamma(\tau \to e\gamma) = \frac{\alpha_{EM} m^5_\tau}{64 \pi^4} \left( |c_L|^2 + |c_R|^2 \right), \quad c_L = c_R \simeq \frac{h^\dagger_{ee} h_{e\tau}}{24 m^2_H}.
\]

- $h_{ee}, e\mu, e\tau$ contribute to $(g - 2)_e$ & LEP $ee \to \ell\ell$ data, [DELPHI '05; Hou, Wong '95]

\[
|h^\dagger_{ee} h_{e\tau}| \Rightarrow ee \to e\tau \\
|h^\dagger_{e\mu} h_{e\tau}| \Rightarrow ee \to \mu\tau \; (t\text{-channel})
\]
<table>
<thead>
<tr>
<th>process</th>
<th>current data</th>
<th>constraints [GeV$^{-2}$]</th>
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<tbody>
<tr>
<td>$\mu^- \rightarrow e^- e^+ e^-$</td>
<td>$&lt; 10^{-12}$</td>
<td>$</td>
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<tr>
<td>$\tau^- \rightarrow e^- e^+ e^-$</td>
<td>$&lt; 2.7 \times 10^{-8}$</td>
<td>$</td>
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<tr>
<td>$\tau^- \rightarrow \mu^- e^+ e^-$</td>
<td>$&lt; 1.8 \times 10^{-8}$</td>
<td>$</td>
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<tr>
<td>$\tau^- \rightarrow \mu^+ e^- e^-$</td>
<td>$&lt; 1.5 \times 10^{-8}$</td>
<td>$</td>
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<tr>
<td>$\tau^- \rightarrow e^- \gamma$</td>
<td>$&lt; 3.3 \times 10^{-8}$</td>
<td>$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- \gamma$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
<td>$</td>
</tr>
<tr>
<td>$(g-2)_e$</td>
<td>$&lt; 5.0 \times 10^{-13}$</td>
<td>$</td>
</tr>
<tr>
<td>$ee \rightarrow ee, \tau\tau$</td>
<td>$\Lambda &gt; 5.7 &amp; 6.3 \text{ TeV}$</td>
<td>$</td>
</tr>
<tr>
<td>$ee \rightarrow \mu\mu, \tau\tau$</td>
<td>$\Lambda &gt; 5.7 &amp; 7.9 \text{ TeV}$</td>
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The $\mu \rightarrow 3e$ limit is so strong that the it leaves no hope to see any signal in the channel $ee \rightarrow e\mu$ at CEPC & ILC.
Main SM backgrounds:

\[ e^+ e^- \rightarrow W^+ W^- \rightarrow \ell_i^+ \ell_j^- \nu \bar{\nu} \]

The backgrounds can be well controlled by

[Kabachenko, Pirogov '97; Cho, Shimo '16; Bian, Shu, YCZ '15]

requiring that the constructed energy \( E_\ell \sim \sqrt{s}/2 \),
kinetic distribution analysis of the backgrounds and signals
Resonance effect at $m_H \simeq \sqrt{s}$ for both CEPC & ILC
Width $\Gamma_H = 10\,(30)$ GeV at CEPC (ILC)

The off-shell scalar could be probed up to few TeV scale.
CEPC & ILC prospects: off-shell

\[ e^+ e^- \rightarrow \mu^\pm \tau^\mp \]

Figure: The \( s \) and \( t \) channels depend on different \( h^\dagger h \) couplings.
A large variety of well-motivated models accommodate a BSM scalar with LFV couplings to the SM leptons, arising at tree or loop level.

These LFV couplings can be studied in a *model-independent* way at future lepton colliders like CEPC, ILC, FCC-ee & CLIC, which strengthens the physics case for future lepton colliders.

The BSM neutral scalar $H$ can be produced on-shell via $e^+ e^- \rightarrow \ell_\alpha^\pm \ell_\beta^\mp + H$ or off-shell via $e^+ e^- \rightarrow \ell_\alpha^\pm \ell_\beta^\mp$.

It is promising future lepton colliders could probe a broad region of $m_H$ and $h_{\alpha\beta}$ that goes well beyond the existing LFV constraints.

The scalar mass and couplings for the explanation of the muon $g - 2$ anomaly can be directly tested at future lepton colliders in $e^+ e^- \rightarrow \mu^\pm \tau^\mp + H$.

Thank you for your attention!