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

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based on
P. S. B. Dev, R. N. Mohapatra & YCZ, PRL120(2018)221804 [1711.08430]
(see also P. S. B. Dev, R. N. Mohapatra & YCZ, 1803.11167)

contributing to CEPC CDR & CLIC CERN Yellow Book
Outline

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

  [see the talks by Rabindra Mohapatra & Goran Senjanović]

  see also Altmannshofer, Gori Kagan+ '15; Altmannshofer, Eby, Gori '16
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: 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
  
  \[
  \mathcal{L}_{\text{RPV}} = \frac{1}{2} \lambda_{\alpha \beta \gamma} \hat{L}_\alpha \hat{L}_\beta \hat{E}^c_\gamma
  \]

  [Aulakh, Mohapatra '82; Hall, Suzuki '84; Ross, Valle '85, Barbier+ '04; Duggan, Evans, Hirschauer '13]

- **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 at tree and/or loop level

- **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, symmetric, $H$ is CP-even.

$H$ 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]

$\ m_H < \sqrt{s} \Rightarrow$ on-shell production
On-shell & off-shell production

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

  $$e^+ e^- \rightarrow \ell_\alpha^\pm \ell_\beta^\mp + H$$

- **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]

  $$e^+ e^- \rightarrow \ell_\alpha^\pm \ell_\beta^\mp$$
Constraints on the LFV couplings: on-shell

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

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

\[
\begin{align*}
\text{Oscillation probability [Clark, Love '03]} \\
\mathcal{P} &= \frac{2(\Delta M)^2}{\Gamma_{\mu}^2 + 4(\Delta M)^2} \\
\end{align*}
\]

with the $H$-induced mass splitting

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

- Electron and muon $g - 2$ ($h_{e\ell}, h_{\mu\ell}$)
  
  [Lindner, Platscher, Queiroz '16]

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

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 ($h_{e\ell}$)
  
  [OPAL '03; L3 '03; DELPHI '05]

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

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

\[
\frac{1}{m_H^2} \rightarrow \frac{1}{q^2 - m_H^2} \simeq \frac{1}{-s \cos \theta / 2 - m_H^2}
\]
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:

\[ e^+ e^- \rightarrow Zh \rightarrow (e^+ e^-/\mu^+ \mu^-)h \rightarrow e^\pm \mu^\mp + h \]

\[
\begin{align*}
\text{Number of Events} & = 240 \text{ GeV} & 5 \text{ ab}^{-1} \\
m_H = 50 \text{ GeV} & & \sqrt{s} = 240 \text{ GeV} \\
h_{e\mu} = 0.003 & & \\
\text{number of events} & & \\
\text{number of background events} & & \\
\text{number of signal events} & & \\
\end{align*}
\]

\[
\begin{align*}
\text{Number of Events} & = 1 \text{ TeV} & 1 \text{ ab}^{-1} \\
m_H = 300 \text{ GeV} & & \sqrt{s} = 1 \text{ TeV} \\
h_{e\mu} = 0.01 & & \\
\text{number of events} & & \\
\text{number of background events} & & \\
\text{number of signal events} & & \\
\end{align*}
\]

\[
\frac{S}{\sqrt{S + B}} = 55
\]

\[
\frac{S}{\sqrt{S + B}} = 61
\]
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

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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 \emph{quadratically} on the LFV couplings

- 3-body LFV decays of muon and tauon, e.g. \cite{Sher, Yuan '91}
  \[\Gamma(\tau^- \rightarrow e^+ e^- e^-) \simeq \frac{1}{\delta} \frac{|h^\dagger_{ee} h_{e\tau}|^2 m^5_\tau}{3072 \pi^3 m^4_H}, \quad (\delta = 2)\]

- 2-body LFV decays of muon and tauon, e.g. \cite{Harnik, Kopp, Zupan '12}
  \[\Gamma(\tau \rightarrow e\gamma) = \frac{\alpha_{\text{EM}} m^5_\tau}{64 \pi^4} \left( |c_L|^2 + |c_R|^2 \right), \quad c_L = c_R \simeq \frac{h^\dagger_{ee} h_{e\tau}}{24 m^2_H}.\]

- $h_{ee}, e_\mu, e_\tau$ contribute to $(g - 2)_e$ & LEP $ee \rightarrow \ell\ell$ data, \cite{DELPHI '05; Hou, Wong '95}
  \[|h^\dagger_{ee} h_{e\tau}| \Rightarrow ee \rightarrow e\tau\]
  \[|h^\dagger_{e_\mu} h_{e\tau}| \Rightarrow ee \rightarrow \mu\tau \quad (t\text{-channel})\]
### Constraints on the LFV couplings: off-shell

| process                  | current data | constraints $[\text{GeV}^{-2}]$                      |
|--------------------------|--------------|-------------------------------------------------------|
| $\mu^- \to e^- e^+ e^-$  | $< 10^{-12}$ | $|h_{ee}^\dagger h_{e\mu}|/m_H^2 < 6.6 \times 10^{-11}$ |
| $\tau^- \to e^- e^+ e^-$ | $< 2.7 \times 10^{-8}$ | $|h_{ee}^\dagger h_{e\tau}|/m_H^2 < 2.6 \times 10^{-8}$ |
| $\tau^- \to \mu^- e^+ e^-$ | $< 1.8 \times 10^{-8}$ | $|h_{ee}^\dagger h_{\mu\tau}|/m_H^2 < 1.5 \times 10^{-8}$ |
| $\tau^- \to \mu^+ e^- e^-$ | $< 1.5 \times 10^{-8}$ | $|h_{ee}^\dagger h_{e\mu}|/m_H^2 < 1.9 \times 10^{-8}$ |
| $\tau^- \to e^- \gamma$  | $< 3.3 \times 10^{-8}$ | $|h_{ee}^\dagger h_{e\tau}|/m_H^2 < 1.0 \times 10^{-6}$ |
| $\tau^- \to \mu^- \gamma$ | $< 4.4 \times 10^{-8}$ | $|h_{ee}^\dagger h_{e\tau}|/m_H^2 < 1.2 \times 10^{-6}$ |
| $(g - 2)_e$               | $< 5.0 \times 10^{-13}$ | $|h_{ee}^\dagger h_{e\mu}|/m_H^2 < 1.1 \times 10^{-7}$ |
| $ee \to ee, \tau\tau$   | $\Lambda > 5.7 & 6.3$ TeV | $|h_{ee}^\dagger h_{e\tau}|/m_H^2 < 1.4 \times 10^{-7}$ |
| $ee \to \mu\mu, \tau\tau$ | $\Lambda > 5.7 & 7.9$ TeV | $|h_{ee}^\dagger h_{e\mu}|/m_H^2 < 1.3 \times 10^{-7}$ |

The $\mu \to 3e$ limit is so strong that the it leaves no hope to see any signal in the channel $ee \to e\mu$ at CEPC & ILC.
SM backgrounds: off-shell

Main SM backgrounds:

\[ e^+ e^- \rightarrow W^+ W^- \rightarrow \ell_\alpha^+ \ell_\beta^- \bar{\nu} \bar{\nu} \]

The backgrounds can be well controlled by

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

requiring that the constructed energy \( E_\ell \simeq \sqrt{s}/2 \),

kinetic distribution analysis of the backgrounds and signals
CEPC & ILC prospects: off-shell

\[ e^+ e^- \rightarrow e^\pm \tau^{\mp} \]

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!