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

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based on
(see also P. S. B. Dev, R. N. Mohapatra & YCZ, 1803.11167)

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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 plenary talk by S. Petcov]
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: sneutrinos ($\tilde{\nu}$)
  [Aulakh, Mohapatra '82; Hall, Suzuki '84; Ross, Valle '85, Barbier+ '04; Duggan, Evans, Hirschauer '13]
  \[ \mathcal{L}_{\text{RPV}} = \frac{1}{2} \lambda_{\alpha\beta\gamma} \hat{L}_\alpha \hat{L}_\beta \hat{E}_\gamma \]

- 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 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]

$$m_H < \sqrt{s} \Rightarrow \text{on-shell production}$$
on-shell production

\[ e^+ e^- \rightarrow \ell^+_{\alpha} \ell^-_{\beta} + H \]
Constraints on the LFV couplings: on-shell

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

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

Oscillation probability [Clark, Love '03]

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

with the \(H\)-induced mass splitting

\[
\Delta M = \frac{2\alpha_{EM}^3 h_{e\mu}^2 \mu^3}{\pi m_H^2}, \quad \mu = \frac{m_e m_\mu}{m_e + m_\mu}
\]
Electron and muon $g - 2 \left( h_{e\ell}, h_{\mu\ell} \right)$

[Lindner, Platscher, Queiroz '16]

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

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

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

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

Effective 4-fermion interaction

$$\frac{h_{e\ell}^2}{m_H^2} (\bar{e}\ell)(\bar{e}\ell) \xrightarrow{\text{Fierz transf.}} \frac{1}{\Lambda^2} (\bar{e}\gamma_\mu e)(\bar{\ell}\gamma^\mu \ell)$$

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

$$\frac{1}{m_H^2} \rightarrow \frac{1}{q^2 - m_H^2} \simeq -\frac{1}{-s \cos \theta/2 - m_H^2}$$
SM backgrounds: on-shell

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:

\[ e^+ e^- \rightarrow Zh \rightarrow (e^+ e^-/\mu^+ \mu^-)h \rightarrow e^{\pm} \mu^{\mp} + h \]
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 1σ and 2σ regions.
Long-dashed, short-dashed, solid lines: 1%, 10%, and 100% of the decay products of $H$ is reconstructible (visible).

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

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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 $ee \rightarrow \mu\tau + H$.
off-shell production

\[ e^+ e^- \rightarrow \ell^\pm_\alpha \ell^{\mp}_\beta \]

...at resonance when \( m_H \simeq \sqrt{s} \)

might also be mediated by a (light) gauge boson \( Z' \) with LFV couplings [Heeck '16]
Constraints on the LFV couplings: off-shell

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

\begin{itemize}
  \item 3-body LFV decays of muon and tauon, e.g. [Sher, Yuan '91]
    \[\Gamma(\tau^- \to e^+ e^- e^-) \simeq \frac{1}{\delta} \frac{|h_{ee}^\dagger h_{e\tau}|^2 m_\tau^5}{3072 \pi^3 m_H^4}, \quad (\delta = 2)\]

  \item 2-body LFV decays of muon and tauon, e.g. [Harnik, Kopp, Zupan '12]
    \[\Gamma(\tau \to e\gamma) = \frac{\alpha_{EM} m_\tau^5}{64 \pi^4} \left(|c_L|^2 + |c_R|^2\right), \quad c_L = c_R \simeq \frac{h_{ee}^\dagger h_{e\tau}}{24 m_H^2}.\]

  \item \(h_{ee}, h_{e\mu}, h_{e\tau}\) contribute to \((g - 2)_e\) & LEP \(ee \to \ell\ell\) data, [DELPHI '05; Hou, Wong '95]
    \[|h_{ee}^\dagger h_{e\tau}| \Rightarrow ee \to e\tau\]
    \[|h_{e\mu}^\dagger h_{e\tau}| \Rightarrow ee \to \mu\tau \quad (t\text{-channel})\]
\end{itemize}
The $\mu \rightarrow 3e$ limit is so strong that it leaves no hope to see any signal in the channel $ee \rightarrow e\mu$ at CEPC & ILC.
Main SM backgrounds:

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

The backgrounds can be well controlled by

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

requiring that the constructed energy \[ E_\ell \approx \sqrt{s}/2 \],

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

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

Resonance effect at \( m_H \approx \sqrt{s} \) 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.
Conclusion

- 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 $e^+e^- \rightarrow \ell^\pm \ell^\mp + H$ or off-shell via $e^+e^- \rightarrow \ell^\pm \ell^\mp$.
- 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!