Lepton flavor violation induced by neutral and doubly-charged scalars at future lepton colliders

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October 25, 2018
International Workshop on Future Linear Colliders (LCWS2018)
University of Texas, Arlington

based on
P. S. B. Dev, R. N. Mohapatra & YCZ, 1803.11167, accepted by PRD

contributing to CEPC CDR & CLIC CERN Yellow Book
Motivations of the LFV processes

Beyond SM neutral scalar $H$ at future lepton colliders
  - On-shell production
  - Off-shell production
  - Prospects at ILC and CEPC (CLIC in backup slides)

Doubly-charged scalar $H^{\pm\pm}$ at future lepton colliders
  - On-shell production through the (LFV) Yukawa couplings
  - Off-shell production
  - Prospects at ILC and CEPC (CLIC in backup slides)

Conclusion
Why lepton-flavor violation (LFV) at future lepton colliders?

- “Smoking-gun” signal beyond the SM;
- Clean SM background at lepton colliders

...Connection to neutrino mass generation (and other pheno)

- Beyond SM neutral scalar $H$ from e.g. left-right model, sneutrino in RPV SUSY models;
- Doubly-charged scalar $H^{\pm\pm}$ in type-II seesaw and its extensions like left-right model;
- Might also be connected to the heavy neutrino searches, effective 4-fermion interactions, or even DM pheno at future lepton colliders.
Beyond SM neutral scalar $H$
@ future lepton colliders
Well-motivated underlying models

- **RPV SUSY**: sneutrinos ($\tilde{\nu}$)
  
  [Aulakh, Mohapatra '82; Hall, Suzuki '84; Ross, Valle '85, Barbier+ '04; Duggan, Evans, Hirschauer '13]

  \[ \mathcal{L}_{\text{RPV}} = \frac{1}{2} \lambda_{\alpha\beta\gamma} \hat{L}_\alpha \hat{L}_\beta \hat{E}_\gamma^c \]

- **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 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, hadrophobic and the mixing with the SM Higgs $h$ is small.

$H$ 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 production of $H$ at lepton colliders

- the $e^+ e^-$ process

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

involving the charged-currents [$H$ decaying into visible particles]

$$e^+ e^- \rightarrow \nu_\alpha \bar{\nu}_e + H$$
In future lepton colliders, high luminosity photon beams can be obtained by Compton backscattering of low energy, high intensity laser beam off the high energy electron beam [Ginzburg+ '83, '84].

The effective photon luminosity distribution

\( x = \frac{\omega}{E_e} \lesssim 0.83 \) the fraction of electron energy carried away by the scattered photon, \( \xi = \frac{4\omega_0 E_e}{m_e^2} \)

\[
\begin{align*}
f_{\gamma/e}(x) &= \frac{1}{D(\xi)} \left[ (1 - x) + \frac{1}{(1-x)} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right], \\
D(\xi) &= \left( 1 - \frac{4}{\xi} - \frac{8}{\xi^2} \right) \log(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2},
\end{align*}
\]
On-shell production of $H$ at lepton colliders

- involving the laser photon(s)

$$e^\pm \gamma \rightarrow \ell^\pm + H, \quad \gamma \gamma \rightarrow \ell^\pm_{\alpha} \ell^\mp_{\beta} + H$$
Constraints on the LFV couplings: on-shell

On-shell production amplitudes depend *linearly* on the LFV couplings

- muonium anti-muonium oscillation: \((\bar{\mu}e) \leftrightarrow (\mu\bar{e}) (h_{e\mu})\)
  [Clark, Love '03]

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

- Bhabha scattering, LEP \(ee \rightarrow \ell\ell\) data \((h_{e\ell})\)
  [OPAL '03; L3 '03; DELPHI '05]
\gamma \gamma (e\gamma) channel: laser photon collision.

Green bands: muon $g - 2$ anomaly (excluded).

Assuming the dominant decay mode $H \to e^\pm \mu^\mp$. 
Prospects of $H$: on-shell production

$\gamma\gamma$ ($e\gamma$) channel: laser photon collision.

Assuming the dominant decay mode $H \rightarrow e^\pm \tau^\mp$. 
Prospects of $H$: on-shell production

$\sqrt{s} = 240$ GeV
5 ab$^{-1}$

$\sqrt{s} = 1$ GeV
1 ab$^{-1}$

- $\gamma\gamma$ ($e\gamma$) channel: laser photon collision.
- Assuming the dominant decay mode $H \rightarrow \mu^\pm \tau^\mp$.
- The muon $g - 2$ discrepancy can be directly tested at CEPC & ILC via the searches $e^+e^-$, $\gamma\gamma \rightarrow \mu\tau + H$. 
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: off-shell

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

<table>
<thead>
<tr>
<th>process</th>
<th>current data</th>
<th>constraints [GeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^- \rightarrow e^- e^+ e^-$</td>
<td>$&lt; 10^{-12}$</td>
<td>$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^- e^+ e^-$</td>
<td>$&lt; 2.7 \times 10^{-8}$</td>
<td>$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^- e^+ e^-$</td>
<td>$&lt; 1.8 \times 10^{-8}$</td>
<td>$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^+ e^- e^-$</td>
<td>$&lt; 1.5 \times 10^{-8}$</td>
<td>$</td>
</tr>
<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; $6.3$ TeV</td>
<td>$</td>
</tr>
<tr>
<td>ee $\rightarrow$ $\mu\mu$, $\tau\tau$</td>
<td>$\Lambda &gt; 5.7$ &amp; $7.9$ TeV</td>
<td>$</td>
</tr>
</tbody>
</table>

The $\mu \rightarrow 3e$ limit is so strong that the it leaves no hope to see any signal in the ee $\rightarrow$ e$\mu$ channel at future lepton colliders.
Prospects of $H$: off-shell production

- Resonance effect at $m_H \simeq \sqrt{s}$ with width $\Gamma_H = 10\,(30)$ GeV at CEPC (ILC).
- The off-shell scalar could be probed well beyond 10 TeV scale for couplings $h_{\alpha\beta}$ of order one.
Prospects of $H$: off-shell production

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

Figure: The $s$ and $t$ channels depend on different $h^\dagger h$ couplings.
Doubly-charged scalar $H^{\pm\pm}$

@ future lepton colliders
The (left- and right-handed) $H^{±±}$ can be pair produced from the gauge interactions to the $γ/Z$ bosons.

The Drell-Yan production channels can not be used to measure directly the (LFV) Yukawa couplings $f_{αβ}$ of $H^{±±}$ to charged leptons, unless $H^{±±}$ is long-lived.

The current LHC same-sign dilepton limits depend largely on the branching fractions $\text{BR}(H^{±±} \rightarrow ℓ_α^{±} ℓ_β^{±})$. 

Figure: LHC dilepton limits on the right-handed $H^{±±}$. 

Yongchao Zhang (Wustl)
On-shell Production of $H^{\pm\pm}$ at lepton colliders through the (LFV) Yukawa couplings $f_{\alpha\beta}$

Model-independent effective couplings of (right-handed) $H^{\pm\pm}$

$$\mathcal{L}_Y = f_{\alpha\beta} H^{++} \ell^C_\alpha \ell_\beta + \text{H.c.}$$

- Pair production through the gauge and Yukawa couplings
  [Chakrabarti+, hep-ph/9804297]

The Drell-Yan processes dominate the pair production if the Yukawa couplings $f_{e\ell}$ are very small.
On/off-shell production of $H^{\pm \pm}$ at lepton colliders

- **Single production through the Yukawa couplings**

- **Off-shell production**
Prospects of $H^{±±} \oplus$ ILC 1TeV: single production

- Assuming the dominant decay mode $H^{±±} \rightarrow e^{±} \mu^{±}$.
- Below $\sqrt{s}/2 \simeq 500$ GeV, the process $e^{+} e^{-} \rightarrow H^{±±} \ell^{±}_\alpha \ell^{±}_\beta$ is dominated by the Drell-Yan pair production $e^{+} e^{-} \rightarrow H^{++} H^{--}$ with the subsequent decay $H^{±±} \rightarrow \ell^{±}_\alpha \ell^{±}_\beta$.
- The electron and muon $g - 2$ limits are highly suppressed by the charge lepton masses and are not shown in the plot.

CLIC could probe higher mass ranges.
Prospects of $H^{±±}$ @ ILC 1TeV: single production

- Assuming the dominant decay mode $H^{±±} \rightarrow e^{±}τ^{±}$ (left), $ℓ_{α}^{±}ℓ_{β}^{±}$ (right).
- Below $\sqrt{s}/2 \simeq 500$ GeV, the process $e^{±}e^{-} \rightarrow H^{±±}ℓ_{α}^{±}ℓ_{β}^{±}$ is dominated by the Drell-Yan pair production $e^{±}e^{-} \rightarrow H^{++}H^{--}$ with the subsequent decay $H^{±±} \rightarrow ℓ_{α}^{±}ℓ_{β}^{±}$.
- The electron and muon $g–2$ limits are highly suppressed by the charge lepton masses and are not shown in the plots.

CLIC could probe higher mass ranges.
Prospects of $H^{±±}$ @ CEPC & ILC: off-shell production

▶ Suppressed by the three-body phase space, the sensitivities in the $e\gamma$ processes are comparatively much weaker.

▶ As in the neutral scalar case, the limit from $\mu \rightarrow eee$ are so stringent that it has precluded the $H^{±±}$-mediated signal $ee \rightarrow e\mu$ at CEPC & ILC.

▶ The effective cutoff scale $\Lambda \simeq M_{±±}/|f|$ can be probed at CEPC & ILC 1TeV up to few 10 TeV (even higher at CLIC).

▶ The sensitivities for more flavor combinations $\alpha, \beta, \gamma$ in $e^{±}\gamma \rightarrow \ell_α^{±}\ell_β^{±}\ell_γ^{±}$ can be found in our paper 1803.11167.
Conclusion

- A large variety of well-motivated models accommodate a beyond SM neutral scalar $H$ and/or doubly-charged scalar $H^{\pm\pm}$, with LFV couplings to the SM charged leptons.
- These LFV couplings can be studied in a *model-independent* way at future lepton colliders, which strengthens the physics case for future lepton colliders.
- The neutral scalar $H$ can be produced on-shell via $e^\pm \gamma \to \ell^\pm + H$ and $e^+ e^- \gamma \gamma \to \ell^\pm \ell^\mp + H$ or off-shell via $e^+ e^- \to \ell^\pm \ell^\mp$. 
- The doubly-charged scalar $H^{\pm\pm}$ can be (doubly & singly) on-shell and off-shell produced from the (LFV) Yukawa couplings to the charged leptons.
- It is promising that future lepton colliders could probe a broad region of mass and coupling parameters for both $H$ and $H^{\pm\pm}$, which go well beyond the existing low-energy LFV constraints like $\tau \to eee$.
- The neutral scalar explanation of the muon $g - 2$ anomaly can be directly tested at future lepton colliders in the $e^+ e^- , \gamma \gamma \to \mu^\pm \tau^\mp + H$ processes.

Thank you for your attention!
backup slides
Constraints on the LFV couplings $h_{\alpha\beta}$

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

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

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

with the $H$-induced mass splitting

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

[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.

\[
\Delta a_\mu \equiv \Delta a_\mu^{\text{exp}} - \Delta a_\mu^{\text{th}} = (2.87 \pm 0.80) \times 10^{-9}
\]
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

$$\frac{1}{m_H^2} \rightarrow \frac{1}{q^2 - m_H^2} \lesssim \frac{1}{-s \cos \theta/2 - m_H^2}$$
Constraints on the LFV couplings $h_{\alpha \beta}$

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

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

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

- $h_{ee, e\mu, e\tau}$ contribute to $(g - 2)_e$ \& LEP $ee \to \ell\ell$ data,
  [DELPHI '05; Hou, Wong '95]
  \[
  |h_{ee}^\dagger h_{e\tau}| \quad \Rightarrow \quad ee \to e\tau
  
  |h_{e\mu}^\dagger h_{e\tau}| \quad \Rightarrow \quad ee \to \mu\tau \quad (t\text{-channel})
  \]
SM backgrounds for on-shell production of $H$

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:

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

\[\begin{array}{l}
S/\sqrt{S+B} = 55 \\
S/\sqrt{S+B} = 61
\end{array}\]
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 \( E_\ell \simeq \sqrt{s}/2 \),
kinetic distribution analysis of the backgrounds and signals
CLIC prospects of $H$ and $H^{\pm\pm}$
CLIC prospects of $H$: on-shell production

$\gamma\gamma$ ($e\gamma$) channel: laser photon collision.

Shaded regions are excluded.

Assuming the dominant decay mode $H \rightarrow e^\pm \mu^\mp$ (left), $e^\pm \tau^\mp$ (right).
CLIC prospects of $H$: on-shell production

$|h_{\mu\tau}|$

$m_H [\text{GeV}]$

$\gamma\gamma (e\gamma)$ channel: laser photon collision.

Shaded regions are excluded.

Assuming the dominant decay mode $H \rightarrow \mu^\pm \tau^\mp$.

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 CLIC via the searches of $\gamma\gamma \rightarrow \mu\tau + H$. 

$\sqrt{s} = 3 \text{ TeV}$

2 ab$^{-1}$
Resonance effect at $m_H \simeq \sqrt{s}$ with width $\Gamma_H = 30$ GeV

The off-shell scalar could be probed well beyond 10 TeV scale (or even up to 100 TeV).
CLIC prospects of $H$: off-shell production

$$e^+ e^- \rightarrow \mu^\pm \tau^\mp$$

**Figure:** The $s$ and $t$ channels depend on different $h^+ h$ couplings.
Assuming the dominant decay mode $H^{\pm\pm} \rightarrow e^\pm \mu^\pm$.

Below $\sqrt{s}/2 = 1.5$ TeV, the process $e^+ e^- \rightarrow H^{\pm\pm} \ell_\alpha^+ \ell_\beta^-$ is dominated by the Drell-Yan pair production $e^+ e^- \rightarrow H^{++} H^{--}$ with the subsequent decay $H^{++} \rightarrow \ell_\alpha^+ \ell_\beta^-$. The $\gamma \gamma \rightarrow H^{\pm\pm} \ell_\alpha^+ \ell_\beta^-$ sensitivity is weaker than the $e^+ e^-$ process.

The electron and muon $g-2$ limits are highly suppressed by the charge lepton masses and are not shown in the plot.
CLIC prospects of $H^{\pm\pm}$: single production

Assuming the dominant decay mode $H^{\pm\pm} \rightarrow e^{\pm} \tau^{\mp}$ (left), $\mu^{\pm} \tau^{\mp}$ (right).

Below $\sqrt{s}/2 = 1.5$ TeV, the process $e^{+} e^{-} \rightarrow H^{\pm\pm} \ell^{\mp}_\alpha \ell^{\mp}_\beta$ is dominated by the Drell-Yan pair production $e^{+} e^{-} \rightarrow H^{++} H^{--}$ with the subsequent decay $H^{\mp\mp} \rightarrow \ell^{\mp}_\alpha \ell^{\mp}_\beta$.

The $\gamma \gamma \rightarrow H^{\pm\pm} \ell^{\mp}_\alpha \ell^{\mp}_\beta$ sensitivity is weaker than the $e^{+} e^{-}$ process.

The electron and muon $g - 2$ limits are highly suppressed by the charge lepton masses and are not shown in the plots.
Suppressed by the three-body phase space, the sensitivities in the $e\gamma$ processes are comparatively much weaker.

As in the neutral scalar case, the limit from $\mu \rightarrow eee$ are so stringent that it has precluded the $H^{\pm \pm}$-mediated signal $ee \rightarrow e\mu$ at CLIC.

The effective cutoff scale $\Lambda \approx M_{\pm \pm} / |f|$ can be probed at CLIC up to few 10 TeV.