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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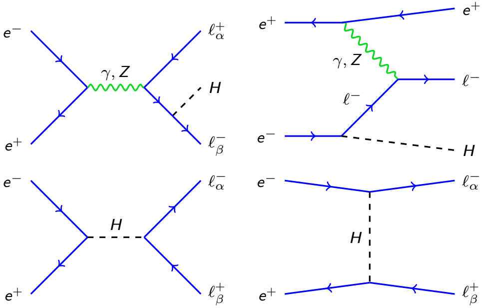
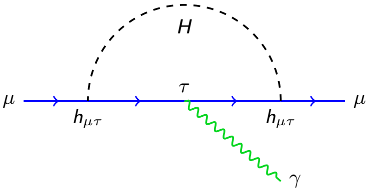
- Prospects and discussions



Motivation examples: LFV beyond SM

- muon $g-2$

  [Carena, Giudice, Wagner '96; Raidal+ '08; Wolfgang Altmannshofer, Carena, Crivellin '16]



H: beyond SM scalar

- 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]

Calling for New Physics...

- 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]

$$\mathcal{L}_{\rm RPV} = \frac{1}{2}\lambda_{\alpha\beta\gamma}\widehat{L}_\alpha\widehat{L}_\beta\widehat{E}^c_\gamma$$

- 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 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

Beyond SM neutral Higgs & effective LFV couplings

- Model-independent effective LFV couplings of H

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

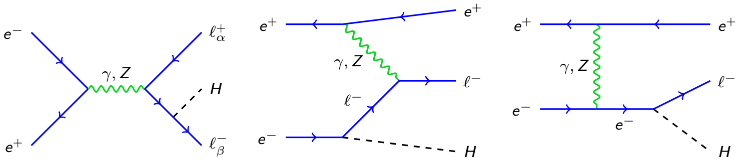
For simplicity, we assume $h_{\alpha\beta}$ are real, symmetric, H is CP-even.
H might originate from a isospin singlet, doublet or triplet, depending on specific underlying models.

- 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

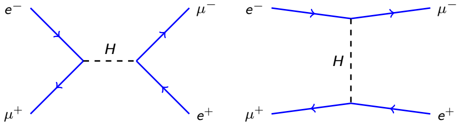
$$e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp + H$$



Constraints on the LFV couplings: on-shell

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

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



Oscillation probablity [Clark, Love '03]

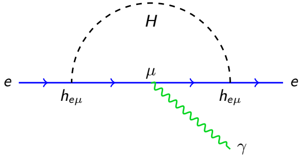
$$\mathcal{P} = \frac{2(\Delta M)^2}{\Gamma_\mu^2 + 4(\Delta M)^2}$$

with the H-induced mass splitting

$$\Delta M = \frac{2\alpha_{\rm EM}^3 h_{e\mu}^2 \mu^3}{\pi m_H^2}, \quad \mu = \frac{m_e m_\mu}{m_e + m_\mu}$$

Constraints on the LFV couplings: on-shell

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



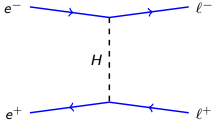
$$\Delta a_e \ \simeq \ \frac{h_{e\mu}^2 m_e m_\mu}{16\pi^2 m_H^2}\left[2\log\left(\frac{m_H^2}{m_\mu^2}\right)-3\right].$$

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

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

Constraints on the LFV couplings: on-shell

- Bhabha scattering, LEP $ee \to \ell\ell$ 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 Λ do not apply, and we have to consider the kinetic dependence

$$\frac{1}{m_H^2} \to \frac{1}{q^2 - m_H^2} \simeq \frac{1}{-s\cos\theta/2 - m_H^2}$$

SM backgrounds: on-shell

Main SM backgronds are particle misidentification for

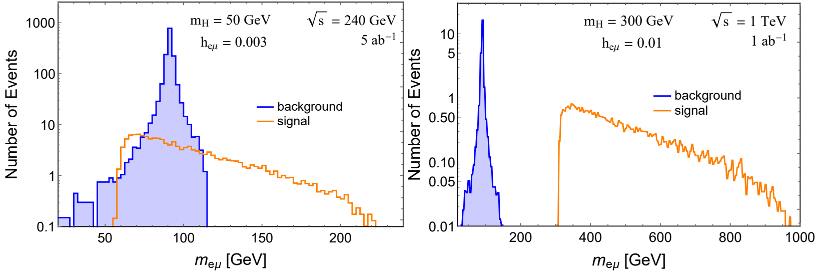
$$e^+e^- \to \ell_\alpha^+\ell_\beta^- + X\,, \quad (\alpha \neq \beta)$$

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]

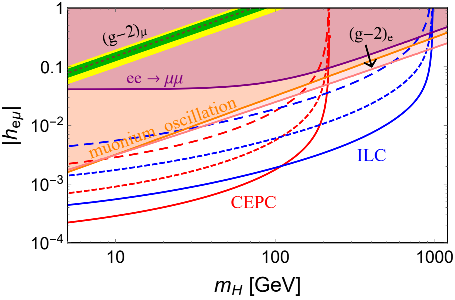
Examle:

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



$S/\sqrt{S+B} = 55$ $\qquad$ $S/\sqrt{S+B} = 61$

CEPC & ILC prospects: on-shell

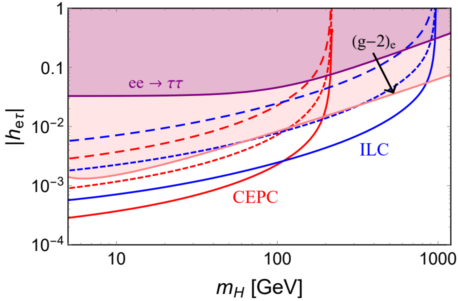


Long-dashed, short-dashed, solid lines:
1%, 10%, and 100% of the decay products of H is reconstructible (visible).

Shaded regions are excluded.

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

CEPC & ILC prospects: on-shell



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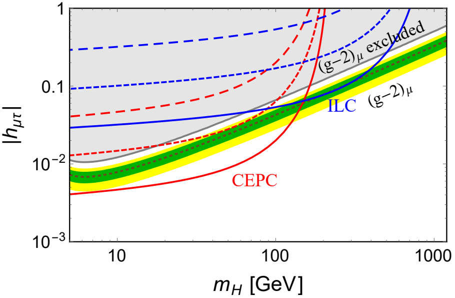

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1%, 10%, and 100% of the decay products of H is reconstructible (visible).

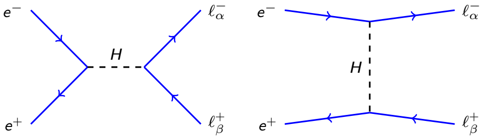
Shaded regions are excluded.

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

The muon $g-2$ discrepancy can be directly tested at CEPC
via the searches of $ee \to \mu\tau + H$

off-shell production

$e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp$



...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 *quadratically* on the LFV couplings

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

$$\Gamma(\tau^- \to e^+ e^- e^-) \simeq \frac{1}{\delta} \frac{|h_{ee}^\dagger h_{e\tau}|^2 m_\tau^5}{3072\pi^3 m_H^4}, \quad (\delta = 2)$$

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

$$\Gamma(\tau \to e\gamma) = \frac{\alpha_{\rm EM} m_\tau^5}{64\pi^4} \left(|c_L|^2 + |c_R|^2\right), \quad c_L = c_R \simeq \frac{h_{ee}^\dagger h_{e\tau}}{24 m_H^2}.$$

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

$$|h_{ee}^\dagger h_{e\tau}| \quad \Rightarrow \quad ee \to e\tau$$

$$|h_{e\mu}^\dagger h_{e\tau}| \quad \Rightarrow \quad ee \to \mu\tau \; (t\text{-channel})$$

Constraints on the LFV couplings: off-shell

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

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:

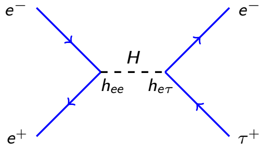
$$e^+e^- \to W^+W^- \to \ell_\alpha^+\ell_\beta^-\nu\bar{\nu}$$

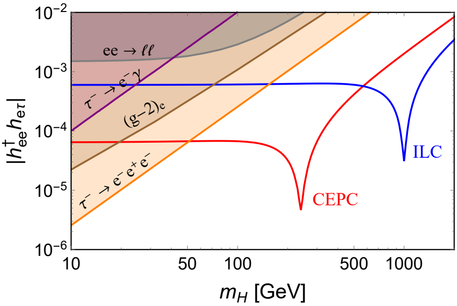
The backgrounds can be well controlled by
[Kabachenko, Pirogov '97; Cho, Shimo '16; Bian, Shu, YCZ '15]

requiring that the constructed energy $E_\ell \simeq \sqrt{s}/2$,
kinetic distribution analysis of the backgrounds and signals

CEPC & ILC prospects: off-shell

$$e^+e^- \to e^\pm\tau^\mp$$





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

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

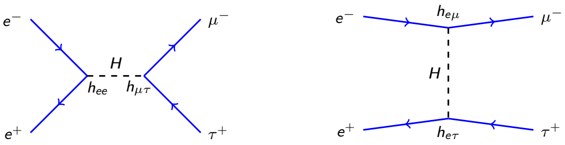
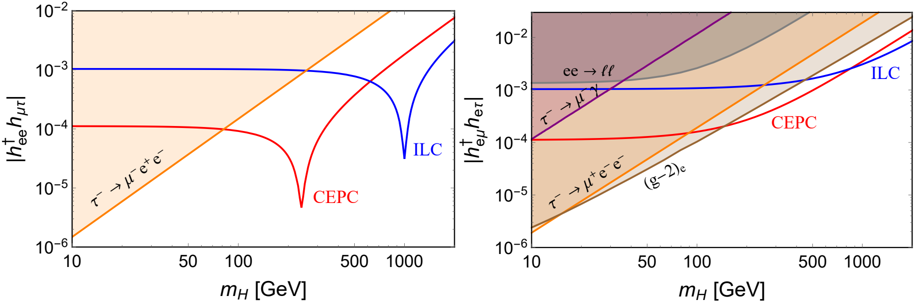


Figure: The s and t channels depend on different $h^\dagger h$ couplings.



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 $e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp + H$ or off-shell via $e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp$.
- 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 $e^+e^- \to \mu^\pm \tau^\mp + H$.

Thank you for your attention!