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

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based on

P. S. B. Dev, R. N. Mohapatra & YCZ, **PRL120**(2018)221804 [1711.08430]

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

contributing to **CEPC CDR** & **CLIC CERN Yellow Book**

# Outline

- 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]

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

- 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 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, 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.*

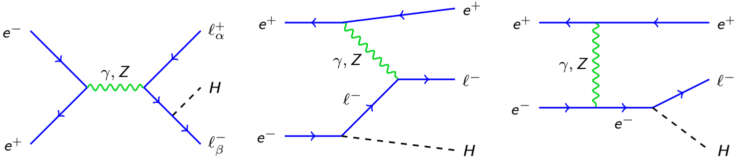
- Effective Dim-4 couplings $\neq$ Effective 4-fermion couplings like $\frac{1}{\Lambda^2}(\bar{e}e)(\bar{e}\mu)$

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

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

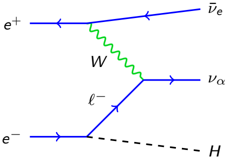
- the $e^+e^-$ process

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




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

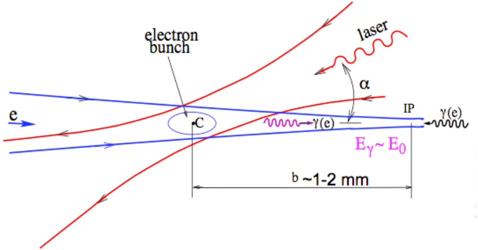
$$e^+e^- \to \nu_\alpha \bar{\nu}_e + H$$



# Laser photon in future lepton colliders

- 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 $\left(x = \omega/E_e \lesssim 0.83\right.$ the fraction of electron energy carried away by the scattered photon, $\left.\xi = 4\omega_0 E_e/m_e^2\right)$

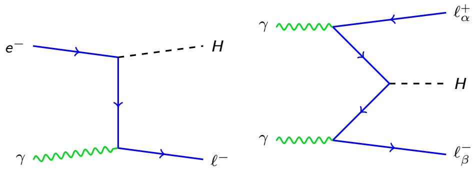
$$
\begin{aligned}
f_{\gamma/e}(x) &= \frac{1}{D(\xi)}\left[(1-x) + \frac{1}{(1-x)} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\right], \\
\text{with} \quad D(\xi) &= \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right)\log(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2},
\end{aligned}
$$



# On-shell production of $H$ at lepton colliders

- involving the laser photon(s)

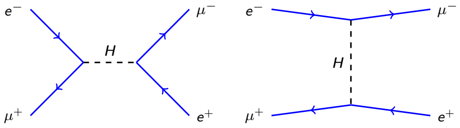
$$e^{\pm}\gamma \to \ell^{\pm} + H\,, \quad \gamma\gamma \to \ell_{\alpha}^{\pm}\ell_{\beta}^{\mp} + H$$



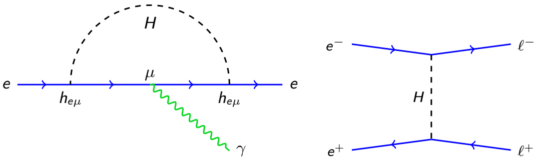
# Constraints on the LFV couplings: on-shell

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

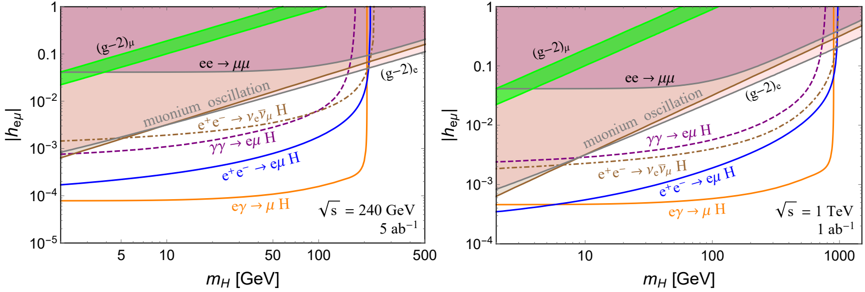
- muonium anti-muonium oscillation: $(\bar{\mu}e) \leftrightarrow (\mu\bar{e})$ $(h_{e\mu})$
  [Clark, Love '03]




- Electron and muon $g-2$ $(h_{e\ell},\ h_{\mu\ell})$
  [Lindner, Platscher, Queiroz '16]
- Bhabha scattering, LEP $ee \to \ell\ell$ data $(h_{e\ell})$
  [OPAL '03; L3 '03; DELPHI '05]



# Prospects of $H$: on-shell production

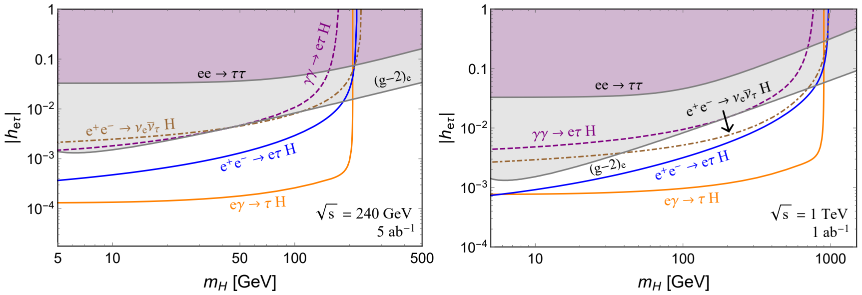



$\gamma\gamma$ ($e\gamma$) channel: laser photon collision.

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

Assuming the dominant decay mode $H \to e^{\pm}\mu^{\mp}$.

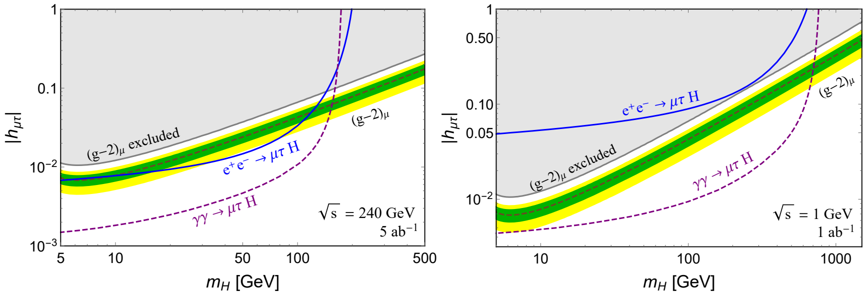
# Prospects of $H$: on-shell production




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

Assuming the dominant decay mode $H \to e^{\pm}\tau^{\mp}$.

# Prospects of $H$: on-shell production

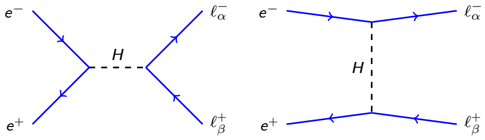



- $\gamma\gamma$ $(e\gamma)$ channel: laser photon collision.
- Assuming the dominant decay mode $H \to \mu^\pm\tau^\mp$.
- The muon $g-2$ discrepancy can be directly tested at CEPC & ILC via the searches $e^+e^-, \gamma\gamma \to \mu\tau + H$.

# Off-shell production of $H$ at lepton colliders

- 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]

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



# Constraints on the LFV couplings: off-shell

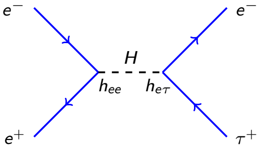
Off-shell production amplitudes depend *quadratically* on the LFV couplings

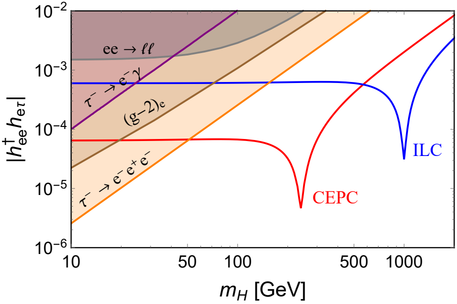
| process | current data | constraints $[\mathrm{GeV}^{-2}]$ |
|---|---|---|
| $\mu^- \to e^- e^+ e^-$ | $< 10^{-12}$ | $\lvert h^\dagger_{ee} h_{e\mu}\rvert / m_H^2 < 6.6 \times 10^{-11}$ |
| $\tau^- \to e^- e^+ e^-$ | $< 2.7 \times 10^{-8}$ | $\lvert h^\dagger_{ee} h_{e\tau}\rvert / m_H^2 < 2.6 \times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

# Prospects of $H$: off-shell production

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




- 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

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

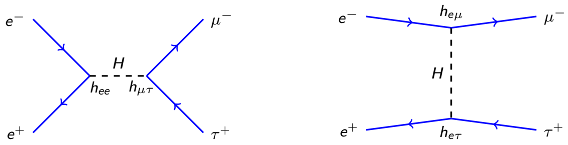
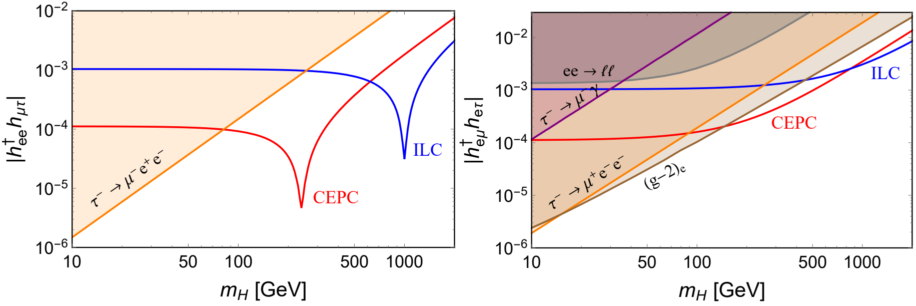



Figure: The $s$ and $t$ channels depend on different $h^\dagger h$ couplings.



Doubly-charged scalar $H^{\pm\pm}$

@ future lepton colliders

# $H^{\pm\pm}$ at lepton (and hadron) colliders

- The (left- and right-handed) $H^{\pm\pm}$ can be pair produced from the gauge interactions to the $\gamma/Z$ bosons.
- The Drell-Yan production channels can not be used to measure *directly* the (LFV) Yukawa couplings $f_{\alpha\beta}$ of $H^{\pm\pm}$ to charged leptons, unless $H^{\pm\pm}$ is long-lived.
- The current LHC same-sign dilepton limits depend largely on the branching fractions $\mathrm{BR}(H^{\pm\pm} \to \ell_\alpha^\pm \ell_\beta^\pm)$.

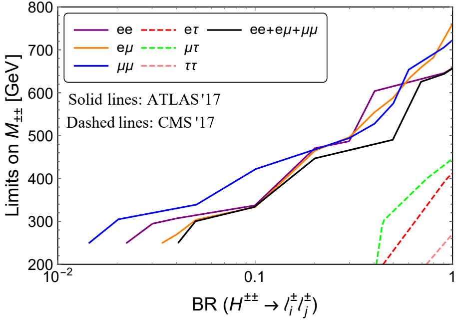


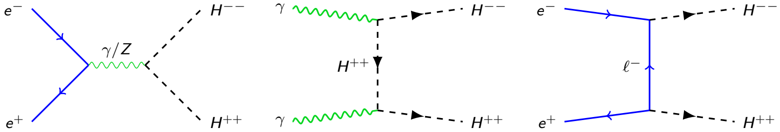

Figure: LHC dilepton limits on the right-handed $H^{\pm\pm}$.

# 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) $H^{\pm\pm}$

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

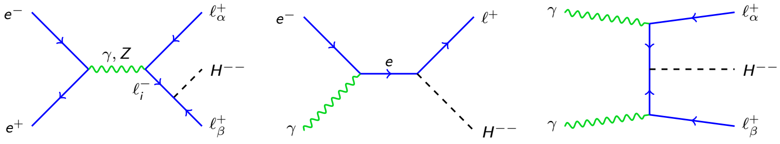
- Pair production through the gauge and Yukawa couplings
  [Chakrabarti+, hep-ph/9804297]



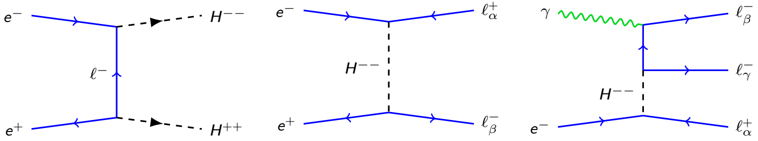

The Drell-Yan processes dominate the pair production if the Yukawa couplings $f_{e\ell}$ are very small.

# On/off-shell production of $H^{\pm\pm}$ at lepton colliders

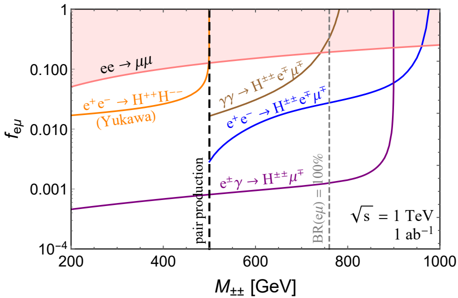
- Single production through the Yukawa couplings
  [Kuze & Sirois, hep-ex/0211048; Barenboim, Huitu, Maalampi & Raidal, hep-ph/9611362; Lusignoli & Petrarca, PLB**226**, 397; Yue & Zhao, hep-ph/0701017; Godfrey, Kalyniak, Romanenko, hep-ph/0108258; hep-ph/0207240; Rizzo, PRD**25**, 1355; Yue, Zhao & Ma, 0706.0232]




- Off-shell production
  [Godfrey, Kalyniak, Romanenko, hep-ph/0108258; hep-ph/0207240; Rizzo, PRD**25**, 1355



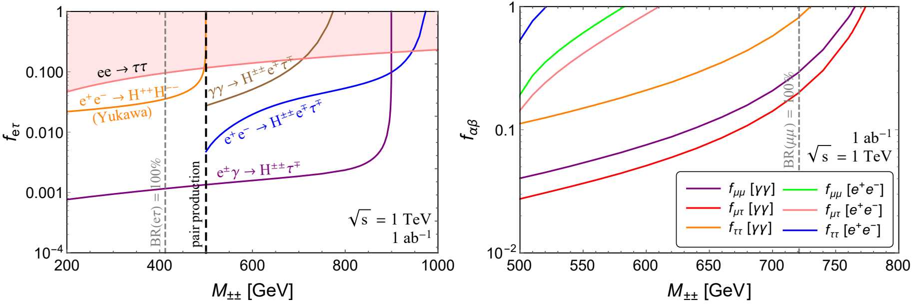
# Prospects of $H^{\pm\pm}$ @ ILC 1TeV: single production




- Assuming the dominant decay mode $H^{\pm\pm} \to e^{\pm}\mu^{\pm}$.
- Below $\sqrt{s}/2 \simeq 500$ GeV, the process $e^+e^- \to H^{\pm\pm}\ell_\alpha^\mp\ell_\beta^\mp$ is dominated by the Drell-Yan pair production $e^+e^- \to H^{++}H^{--}$ with the subsequent decay $H^{\mp\mp} \to \ell_\alpha^\mp\ell_\beta^\mp$.
- 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.

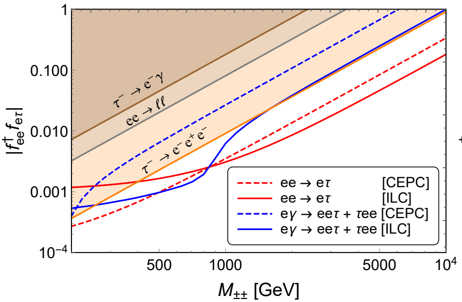
# Prospects of $H^{\pm\pm}$ @ ILC 1TeV: single production

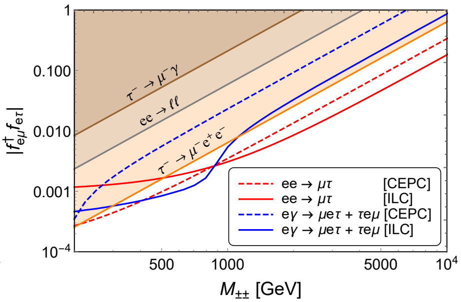



- Assuming the dominant decay mode $H^{\pm\pm} \to e^{\pm}\tau^{\pm}$ (left), $\ell^{\pm}_{\alpha}\ell^{\pm}_{\beta}$ (right).
- Below $\sqrt{s}/2 \simeq 500$ GeV, the process $e^+e^- \to H^{\pm\pm}\ell^{\mp}_{\alpha}\ell^{\mp}_{\beta}$ is dominated by the Drell-Yan pair production $e^+e^- \to H^{++}H^{--}$ with the subsequent decay $H^{\mp\mp} \to \ell^{\mp}_{\alpha}\ell^{\mp}_{\beta}$.
- 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 $H^{\pm\pm}$ @ 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 $\mu \to eee$ are so stringent that it has precluded the $H^{\pm\pm}$-mediated signal $ee \to e\mu$ at CEPC & ILC.
- The effective cutoff scale $\Lambda \simeq M_{\pm\pm}/|f|$ 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 $e^\pm\gamma \to \ell^\mp_\alpha \ell^\pm_\beta \ell^\pm_\gamma$ can be found in our paper 1803.11167.

# Conclusion

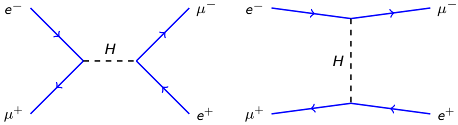
- A large variety of well-motivated models accommodate a beyond SM neutral scalar $H$ and/or doubly-charged scalar $H^{\pm\pm}$, with LFV couplings to the SM charged leptons.
- These LFV couplings can be studied in a *model-independent* way at future lepton colliders, which strengthens the physics case for future lepton colliders.
- The neutral scalar $H$ can be produced on-shell via $e^{\pm}\gamma \to \ell^{\pm} + H$ and $e^{+}e^{-}, \gamma\gamma \to \ell_{\alpha}^{\pm}\ell_{\beta}^{\mp} + H$ or off-shell via $e^{+}e^{-} \to \ell_{\alpha}^{\pm}\ell_{\beta}^{\mp}$.
- 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

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]

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

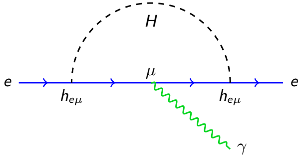
with the $H$-induced mass splitting

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

# Constraints on the LFV couplings $h_{\alpha\beta}$

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

  [Lindner, Platscher, Queiroz '16]



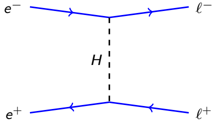

$$\Delta a_e \simeq \frac{h_{e\mu}^2 m_e m_\mu}{16\pi^2 m_H^2}\left[2\log\left(\frac{m_H^2}{m_\mu^2}\right)-3\right].$$

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 $h_{\alpha\beta}$

- 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 $\Lambda$ do not apply, and we have to consider the kinetic dependence

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

# Constraints on the LFV couplings $h_{\alpha\beta}$

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]

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

# SM backgrounds for on-shell production of $H$

Main SM backgronds are particle misidentification for

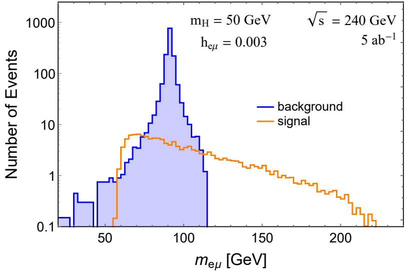
$$e^+e^- \to \ell_\alpha^+ \ell_\beta^- + X\,, \quad (\alpha \neq \beta)$$

The mis-identification rate is expected to be small, of order $10^{-3}$

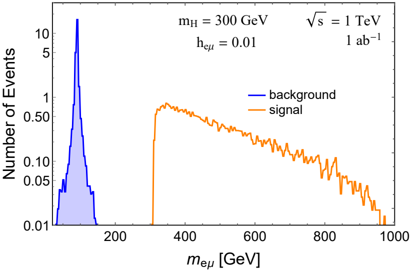
[Milstene, Fisk, Para '06; Hammad, Khalil, Un '16; Yu, Ruan, Boudry+ '17]

Examle:

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




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




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

# SM backgrounds for off-shell production of $H$

Main SM backgrounds:

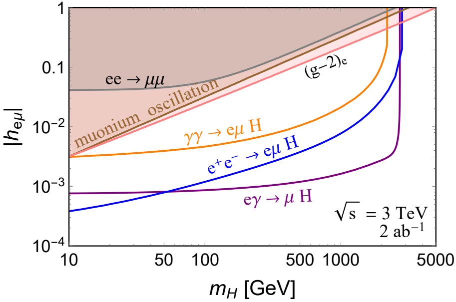
$$e^+e^- \to W^+W^- \to \ell_\alpha^+\ell_\beta^-\nu\bar{\nu}$$

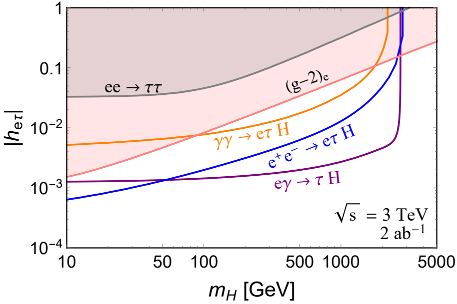
The backgrounds can be well controlled by
[Kabachenko, Pirogov '97; Cho, Shimo '16; Bian, Shu, YCZ '15]

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

# CLIC prospects of $H$ and $H^{\pm\pm}$

# CLIC prospects of $H$: on-shell production



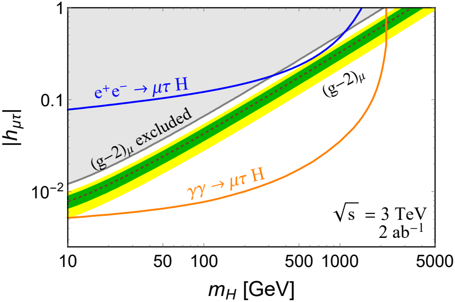




$\gamma\gamma$ ($e\gamma$) channel: laser photon collision.

Shaded regions are excluded.

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

# CLIC prospects of $H$: on-shell production




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

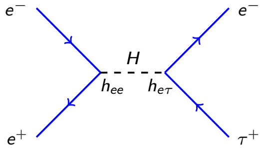
Shaded regions are excluded.

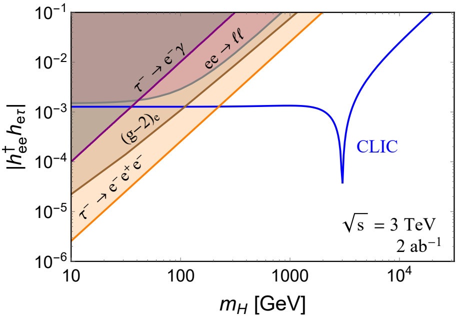
Assuming the dominant decay mode $H \to \mu^\pm\tau^\mp$.

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 $\gamma\gamma \to \mu\tau + H$.

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




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

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

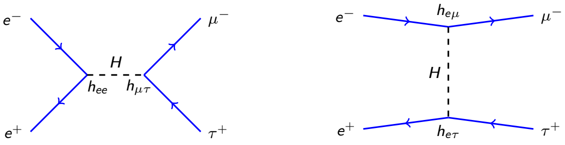
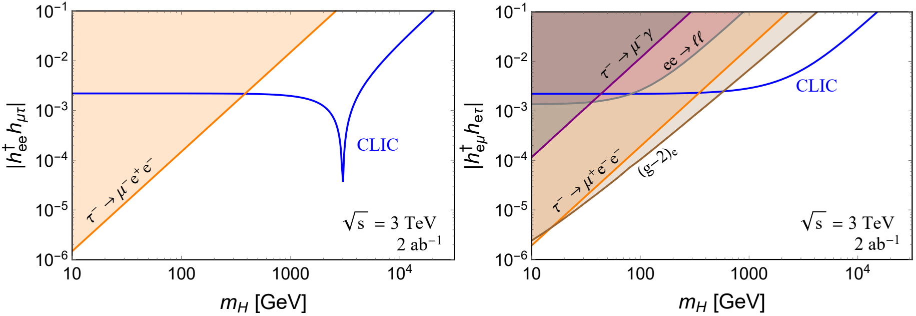
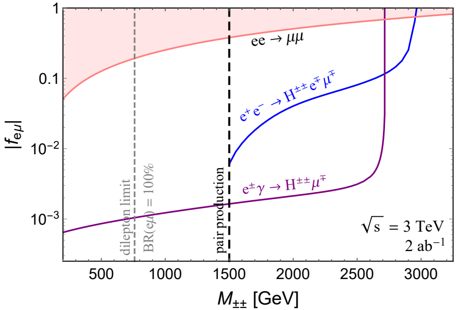



Figure: The $s$ and $t$ channels depend on different $h^\dagger h$ couplings.



# CLIC prospects of $H^{\pm\pm}$: single production



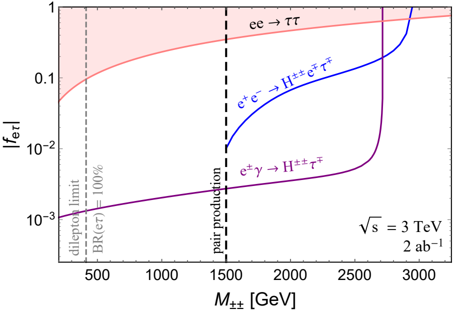

Assuming the dominant decay mode $H^{\pm\pm} \to e^\pm\mu^\pm$.

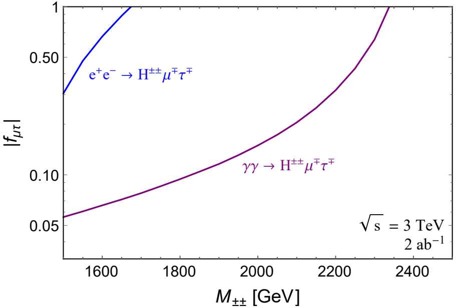
Below $\sqrt{s}/2 = 1.5$ TeV, the process $e^+e^- \to H^{\pm\pm}\ell_\alpha^\mp\ell_\beta^\mp$ is dominated by the Drell-Yan pair production $e^+e^- \to H^{++}H^{--}$ with the subsequent decay $H^{\mp\mp} \to \ell_\alpha^\mp\ell_\beta^\mp$.

The $\gamma\gamma \to H^{\pm\pm}\ell_\alpha^\mp\ell_\beta^\mp$ 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



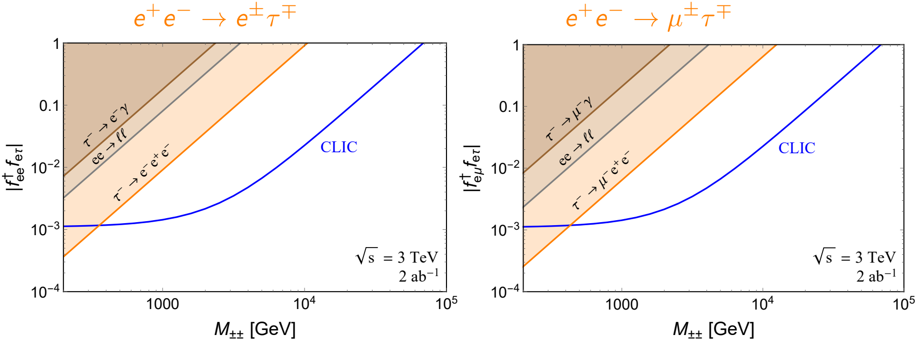

Assuming the dominant decay mode $H^{\pm\pm} \to e^{\pm}\tau^{\pm}$ (left), $\mu^{\pm}\tau^{\pm}$ (right).

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

The $\gamma\gamma \to H^{\pm\pm}\ell_\alpha^\mp\ell_\beta^\mp$ 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.

# CLIC prospects of $H^{\pm\pm}$: 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 $\mu \to eee$ are so stringent that it has precluded the $H^{\pm\pm}$-mediated signal $ee \to e\mu$ at CLIC.

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