Theory of LFV in exotic decays

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Outline

- Motivations of the LFV processes
- BSM neutral scalar H
- Doubly-charged scalar $H^{\pm\pm}$
- Heavy neutrino N and W_R boson
- Z' boson
- More scenarios

(Charged) LFV in and beyond the SM

- Neutrino oscillations $\Rightarrow$ LFV! why not cLFV?
- Neutrino mass generation and heavy neutrinos:
  seesaw models, left-right symmetric model (LRSM), GUTs...
- Charged lepton phenomenology: muon/electron $g-2$
- DM phenomenology
- Hierarchy problem: supersymmetric models...

- "Smoking-gun" signal beyond the SM;
- Comparatively clean backgrounds at hadron/lepton colliders.

See the talk by W. Altmannshofer for LFV from heavy SM particle decays and also the talks by C. Caillol, S. Xella and M. Swagata for experimental searches.

Well-motivated underlying models for BSM heavy H

- 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

LFV couplings of a BSM heavy scalar H

- The mixing of H with SM Higgs h:
  - induce loop-level FCNC couplings of H to quarks, thus highly constrained by K and B meson mixings;
  - LFV couplings of h is highly suppressed by tiny neutrino masses.

  Let us "turn off" the mixing of H with the SM Higgs.
- For simplicity assume H does not couple directly to quarks (leptonic scalar).

- Model-independent effective LFV couplings of H

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

  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.

- 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]

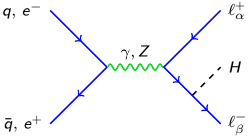
$$m_H < \sqrt{s} \Rightarrow \text{on-shell production}$$

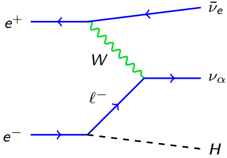
On-shell production of H at hadron/lepton colliders

Dev, Mohapatra & YCZ '18 PRL; PRD

- the $q\bar{q}/e^+e^-$ process

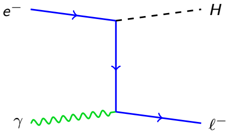
$$q\bar{q},\, e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp + H\,, \quad e^+e^- \to \nu_\alpha \bar{\nu}_e + H$$

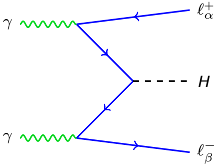




- involving the laser photon(s)

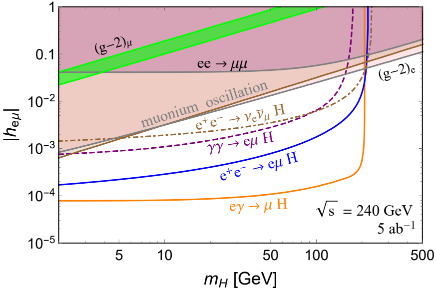
$$e^\pm\gamma \to \ell^\pm + H\,, \quad \gamma\gamma \to \ell_\alpha^\pm \ell_\beta^\mp + H$$

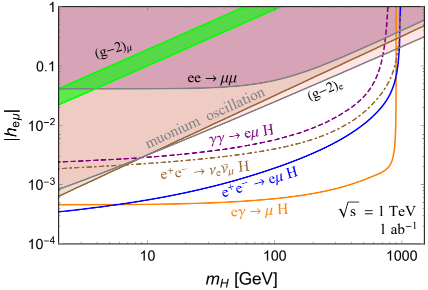




Prospects of H: on-shell production

Dev, Mohapatra & YCZ '18 PRL; PRD





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

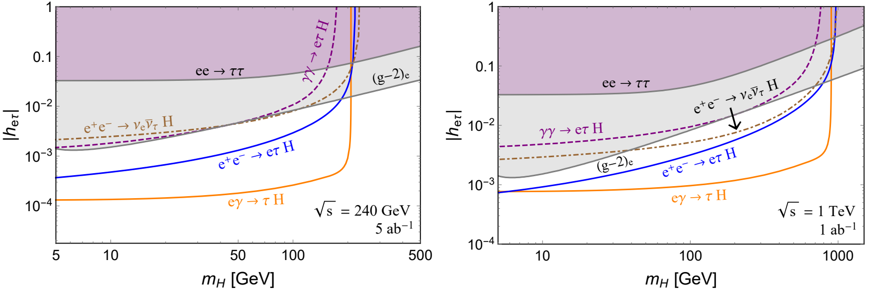
$\gamma\gamma$ ($e\gamma$) channel: laser photon collision.

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

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

Prospects of H: on-shell production

Dev, Mohapatra & YCZ '18 PRL; PRD

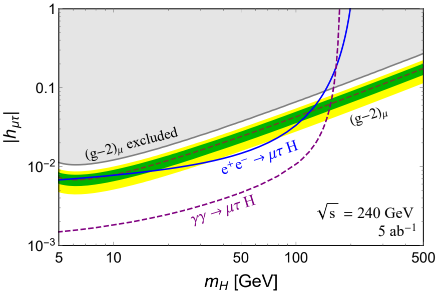


$\gamma\gamma$ ($e\gamma$) channel: laser photon collision.

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

Prospects of H: on-shell production

Dev, Mohapatra & YCZ '18 PRL; PRD

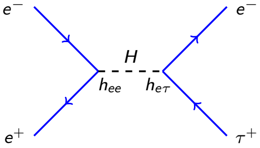


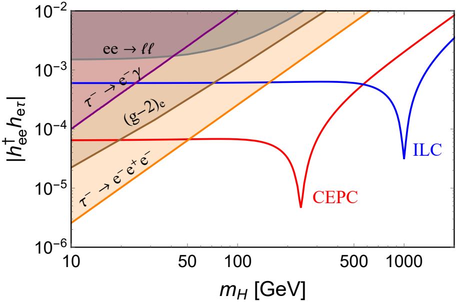
- $\gamma\gamma$ ($e\gamma$) channel: laser photon collision.
- Assuming the dominant decay mode $H \to \mu^\pm\tau^\mp$.
- The muon $g-2$ discrepancy can be directly tested at CEPC & ILC via the searches e^+e^-, $\gamma\gamma \to \mu\tau + H$.

Off-shell production of H: prospects

Dev, Mohapatra & YCZ '18 PRL; PRD

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





- The $\mu \to 3e$ limit is so strong that the it leaves no hope to see any signal in the $ee \to e\mu$ channels.
- The limits such as $\mu \to eee$ depend *quadratically* on the LFV couplings.
- 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.

Off-shell production of H: prospects

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

Dev, Mohapatra & YCZ '18 PRL; PRD

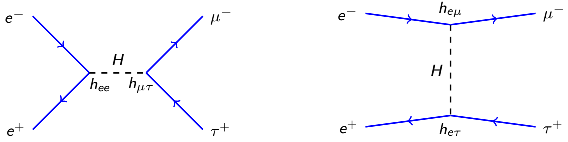
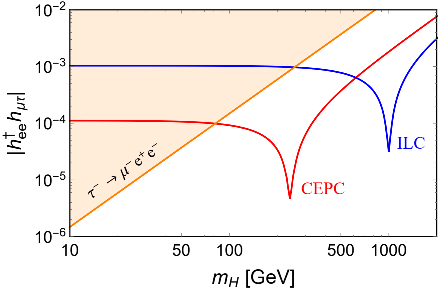
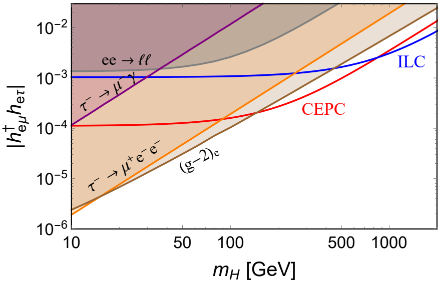


Figure: The s and t channels depend on different $h^\dagger h$ couplings.



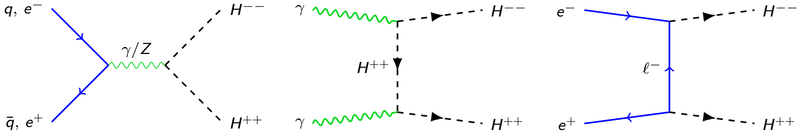


Doubly-charged scalar $H^{\pm\pm}$

- $H^{\pm\pm}$ exists in many BSM scenarios, such as type-II seesaww, LRSM, Zee-Babu model, G331 model...
- LNV (& LFV) effective couplings of (left- or right-handed) $H^{\pm\pm}$

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

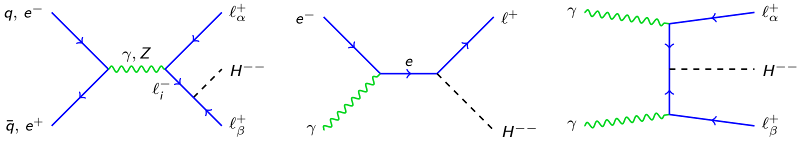
- Pair production through the gauge and Yukawa couplings
  [Chakrabarti, Choudhuryb, Godbolec, Mukhopadhyaya '98 PLB]



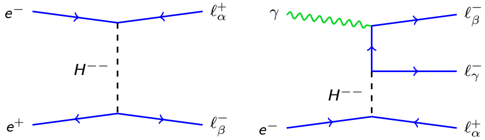
- The Drell-Yan channels can not be used to measure *directly* the (LFV) Yukawa couplings $f_{\alpha\beta}$, unless $H^{\pm\pm}$ is long-lived.

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]

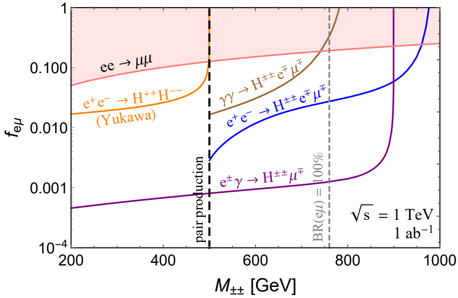


- Off-shell production
  [Godfrey, Kalyniak, Romanenko, hep-ph/0108258; hep-ph/0207240; Rizzo, PRD**25**, 1355



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

Dev, Mohapatra & YCZ '18 PRD



- 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.

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

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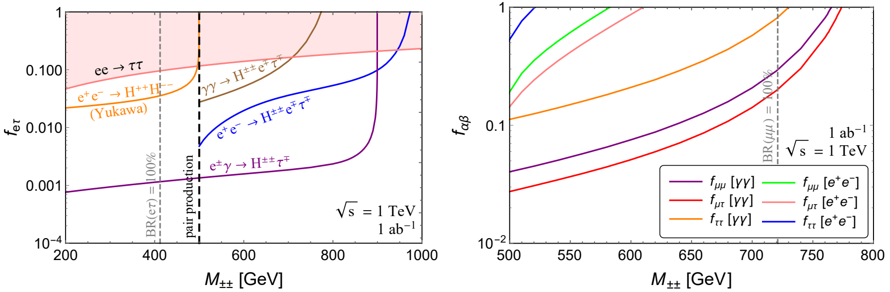
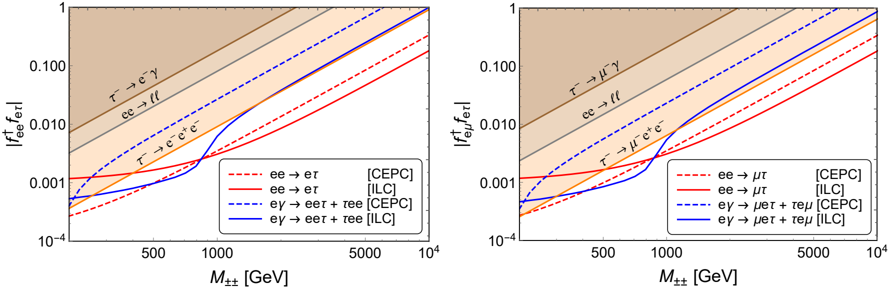


- Assuming the dominant decay mode $H^{\pm\pm} \to e^\pm\tau^\pm$ (left), $\ell_\alpha^\pm\ell_\beta^\pm$ (right).
- Below $\sqrt{s}/2 \simeq 500$ GeV, the process $e^+e^- \to H^{\pm\pm}\ell_\alpha^\mp\ell_\beta^\mp$ is dominated by the Drell-Yan pair production $e^+e^- \to H^{++}H^{--}$ with the subsequent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

Prospects of $H^{\pm\pm}$ @ CEPC & ILC: off-shell production

Dev, Mohapatra & YCZ '18 PRD



- 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).

$H_L^{\pm\pm}$ might be long-lived

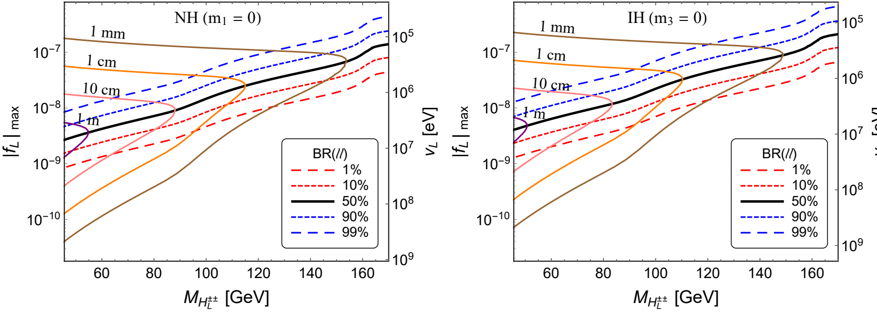
Pérez, Han, Huang, Li, Wang '08; Dev & YCZ, '18 JHEP

- In type-II seesaw

$$\Gamma_{\rm total}(H_L^{\pm\pm}) = \underbrace{\Gamma(H_L^{\pm\pm} \to \ell_\alpha \ell_\beta)}_{\propto m_\nu^2/v_L^2} + \underbrace{\Gamma(H_L^{\pm\pm} \to W^{\pm(*)} W^{\pm(*)})}_{\propto v_L^2/v_{\rm EW}^2} .$$

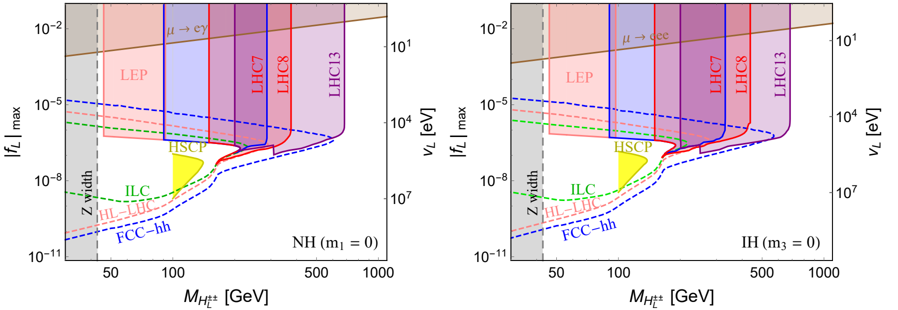
- Assuming lightest neutrino mass $m_0 = 0$.

$$v_L |f_L|_{\rm max} \simeq \begin{cases} 0.027\,{\rm eV}\,, & \text{for NH with } m_1 = 0\,, \\ 0.048\,{\rm eV}\,, & \text{for IH with } m_3 = 0\,. \end{cases}$$



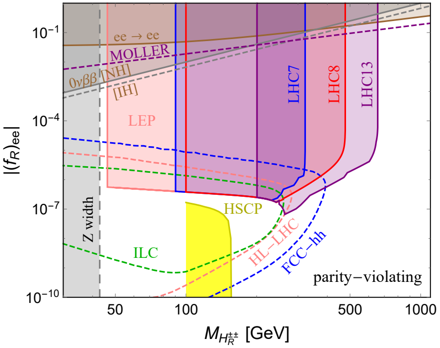
Sensitivities of displaced vertices

Dev & YCZ, '18 JHEP



- Assuming at least 100 events for the DV sensitivities of $H_L^{\pm\pm} \to e^\pm e^\pm,\ e^\pm \mu^\pm,\ \mu^\pm \mu^\pm$.

Dev, Ramsey-Musolf & YCZ, '18; Dev & YCZ, '18 JHEP



- Considering the simple scenario $H_R^{\pm\pm} \to e^\pm e^\pm,\ W_R^{\pm *} W_R^{\pm *}$.
- Assuming $(f_R)_{ee}$ is a free parameter, we do not have the LFV constraints e.g. $\mu \to e\gamma$.
- MOLLER: the prospects of $H_R^{\pm\pm}$ @ MOLLER experiemnt.

LFV in heavy neutrino and W_R decays

- Smoking-gun signal of N in the type-I seesaw & LRSM:

$$pp \to W^{(*)} \to \ell_\alpha^\pm N \to \ell_\alpha^\pm \ell_\beta^\pm W$$

LFV ($\alpha \neq \beta$) $\Longrightarrow$ mixings of heavy neutrino(s) with active neutrinos.

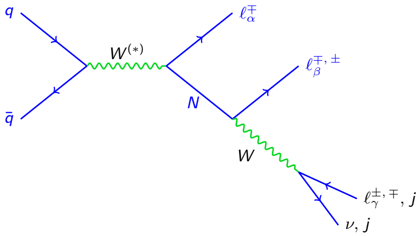
- Smoking-gun signal of W_R in the LRSM:

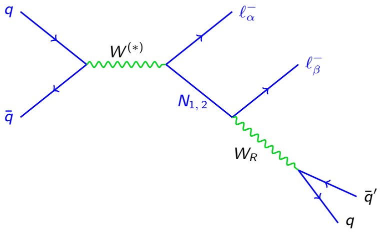
$$pp \to W_R \to \ell_\alpha^\pm \ell_\beta^\pm jj$$

LFV ($\alpha \neq \beta$) $\Longrightarrow$ mixings of heavy neutrinos.

- $\mathcal{N}(\ell_\alpha^+ \ell_\beta^+) \neq \mathcal{N}(\ell_\alpha^- \ell_\beta^-)$ $\Longrightarrow$ (PDF effects) + (CPV in heavy neutrino sector)

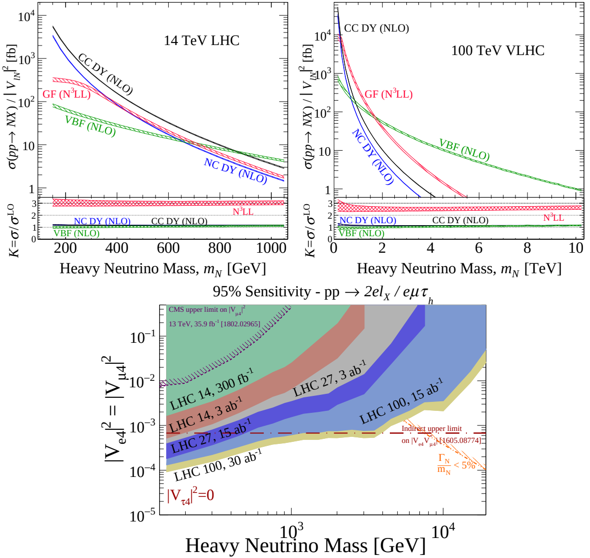
[Dev & Mohapatra, '15; Gluza, Jelinski & Szafron, '16; Anamiati, Hirsch & Nardi, '16; Antusch, Cazzato & Fischer, '17; Das, Dev & Mohapatra, '17; Dev, Mohapatra & YCZ, '19]





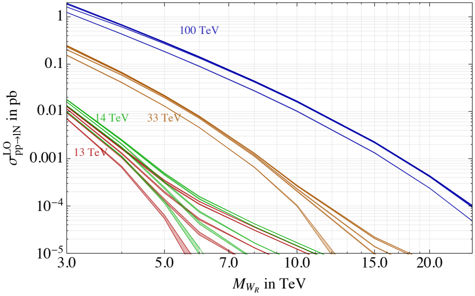
N prospects @ future colliders

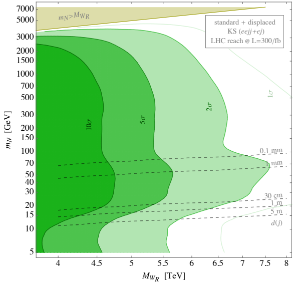
Pascoli, Ruiz, & Weiland, '18



W_R prospects @ future colliders

- Current LHC limits $m_{W_R} > 3.8 - 5$ TeV for $m_N = 0.1 - 1.8$ TeV [ATLAS, 1904.12679].
- LHC prospects of W_R boson is $\simeq 5.5$ (6.5) TeV with 300 fb^{-1} (3000 fb^{-1}) [Ferrari, Collot, Andrieux, Belhorma+, '00; Nemevšek, Nesti & Popara, '18; Chauhan, Dev, Mohapatra & YCZ, '18].
- Future 100 TeV collider prospects: up to $m_{W_R} \sim 35$ TeV, depending largely on RHN mass [Mitra, Ruiz, Scott & Spannowsky '16].



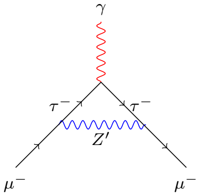


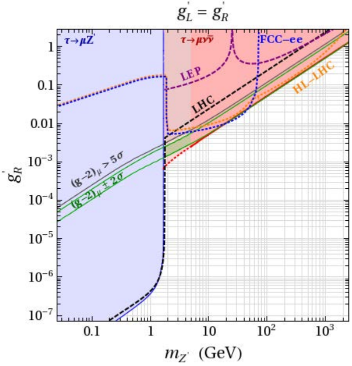
Z' boson with LFV couplings

- Direct search at LHC of $pp \to Z' \to e\mu$ [CMS,1802.01122].
- A (light) Z' boson is a good candidate for the muon $g-2$ anomaly [Heeck '16; Altmannshofer, Chen, Dev & Soni '16]

$$\mathcal{L} = g'_L Z'_\mu \left(\overline{\mu}\gamma^\mu P_L \tau + \overline{\nu}_\mu \gamma^\mu P_L \nu_\tau\right) + g'_R Z'_\mu \left(\overline{\mu}\gamma^\mu P_R \tau\right) \; + \; \text{H.c.}$$

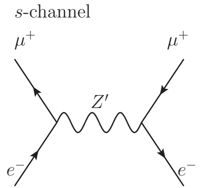
- Future colliders can probe part of the parameter space for muon $g-2$ anomaly.

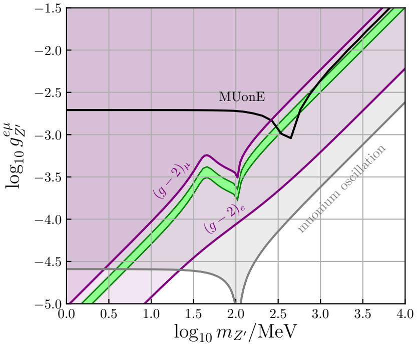




Z' @ MUonE experiment

- The MUonE experiment is a high-precision experiment to measure the hadronic vacuum polarization contribution to the muon $g-2$ via elastic muon-electron scattering [Abbiendi *et al*, '16].
- $\mu - e$ scattering can be mediated by a light (LFV) scalar or Z' boson [Dev, Rodejohann, Xu & YCZ '20; Masiero, Paradisi & Passera '20].
- Both the (LFV) scalar and Z' bosons at MUonE are precluded by current stringent limits.





More scenarios with LFV signals...

- Slepton in SUSY [Agashe & Graesser '99; Andreev, Bityukov, Krasnikov & Toropin '06]:

$$pp \to \tilde{g}\tilde{g}, \quad \tilde{g} \to \tilde{\chi}_2^0, \quad \tilde{\chi}_2^0 \to \tilde{\ell}_i \ell_\alpha, \quad \tilde{\ell}_i \to \tilde{\chi}_1^0 \ell_\beta$$

- Heavy scalars in type-III 2HDM [Primulando & Uttayarat '16]:

$$pp \to H,\, A \to \mu^\mp \tau^\pm$$

- ...

Conclusion

- LFV can arise in may BSM scenarios.
- LFV is (comparatively) very clean signals at hadron/lepton colliders.
- We can have $\ell_\alpha \ell_\beta + X$ events from on-shell/off-shell neutral scalar, doubly-charged scalar, W' boson and heavy neutrino, Z' boson...
- Some of the singals might also be displaced vertex.
- LFV signals are always connected to the low-energy high-precision measurements.

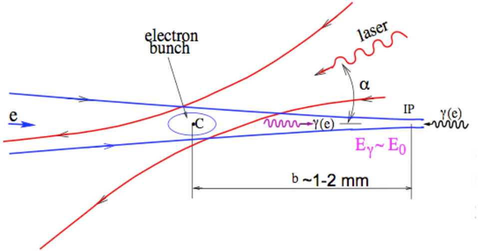
Thank you very much for your attention!

backup slides

Laser photon in future lepton colliders

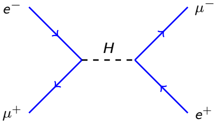
- In future lepton colliders, high luminosity photon beams can be obtained by Compton backscattering of low energy, high intensity laser beam off the high energy electron beam [Ginzburg et al '83, '84].
- The effective photon luminosity distribution ($x = \omega/E_e \lesssim 0.83$ the fraction of electron energy carried away by the scattered photon, $\xi = 4\omega_0 E_e/m_e^2$)

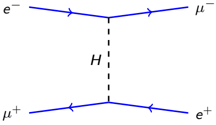
$$
\begin{aligned}
f_{\gamma/e}(x) &= \frac{1}{D(\xi)}\left[(1-x) + \frac{1}{(1-x)} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\right] , \\
\text{with} \quad D(\xi) &= \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right)\log(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2} ,
\end{aligned}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



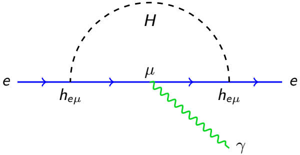
On-shell production amplitudes depend *linearly* on the LFV couplings

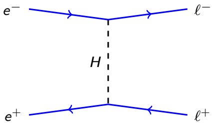
- muonium anti-muonium oscillation: $(\bar{\mu}e) \leftrightarrow (\mu\bar{e})$ $(h_{e\mu})$
  [Clark, Love '03]





- 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]





Constraints on the LFV couplings: off-shell

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

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

Current LHC constraints on $H^{\pm\pm}$

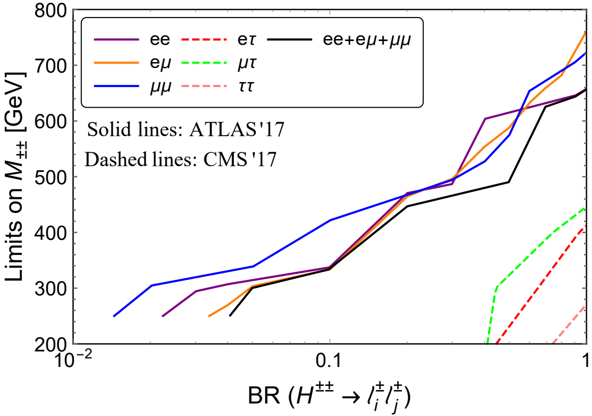


Figure: LHC dilepton limits on the right-handed $H^{\pm\pm}$.

[Dev, Mohapara & YCZ, '18 PRD]

N production @ future colliders

Pascoli, Ruiz, & Weiland, '18