Charged lepton flavour violation at colliders

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based on the following papers
Yi Cai, MS 1510.02486,
Yi Cai, MS and German Valencia 1802.09822,
Tong Li, MS 1809.07924

Motivation

- neutrino oscillations $\rightarrow$ lepton flavour violation (LFV)
- also charged LFV, processes $\ell \rightarrow \ell' X$, $\nu \notin X$
- in SM+m_ν suppressed by unitarity, $\mathcal{A} \sim G_F m_\nu^2 / 16\pi^2 \sim 10^{-27}$
- many neutrino mass models have large charged LFV, e.g. inverse seesaw, radiative mass models
- could be completely unrelated to neutrino mass
- mostly searched for at low-energy precision experiments $\rightarrow$ new possibilities at lepton colliders

$\rightarrow$ compare sensitivity to charged LFV at colliders to low-energy precision experiments using simplified models and EFT

Charged LFV at a lepton collider

Six simplified models: $\Delta L = 0$

complex scalar

$$\mathcal{L} = y_2^{ij} H_2 \bar{\ell}_i P_R \ell_j + h.c.$$

e.g. from electroweak doublet scalar

see Dev, Mohapatra, Zhang 1711.08430 for a similar study

left-handed vector

$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{\ell}_i \gamma^\mu P_L \ell_j$$

possibly from new gauge interaction

right-handed vector

$$\mathcal{L} = y_1'^{ij} H'_{1\mu} \bar{\ell}_i \gamma^\mu P_R \ell_j$$

possibly from new gauge interaction

Six simplified models: $\Delta L = 2$

doubly-charged (right-handed) scalar

$$\mathcal{L} = \lambda_1^{ij} \Delta_1^{++} \bar{\ell}_i^c P_R \ell_j + h.c.$$

e.g. Zee-Babu model

doubly-charged (left-handed) scalar

$$\mathcal{L} = -\lambda_3^{ij} \Delta_3^{++} \bar{\ell}_i^c P_L \ell_j + h.c.$$

e.g. type-II seesaw model

doubly-charged vector

$$\mathcal{L} = \lambda_2^{ij} \Delta_{2\mu}^{++} \bar{\ell}_i^c \gamma^\mu P_R \ell_j + h.c.$$

e.g. embedded in a 331-model

general assumption: real and symmetric Yukawa coupling matrices

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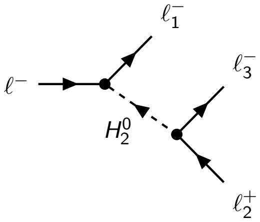
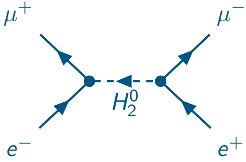
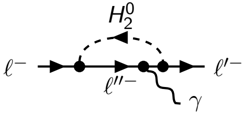
general assumption: real and symmetric Yukawa coupling matrices

- LFV trilepton decays, $\ell \to \ell_1\overline{\ell}_2\overline{\ell}_3$
- Muonium antimuonium conversion, $\mu^+ e^- \to \mu^- e^+$
- LFV radiative lepton decays, $\ell \to \ell'\gamma$
- anomalous magnetic (and electric) dipole moments, a_ℓ







Improved sensitivity at future/current experiments:
Belle-II, COMET, Mu3E, . . .

Low-energy precision constraints

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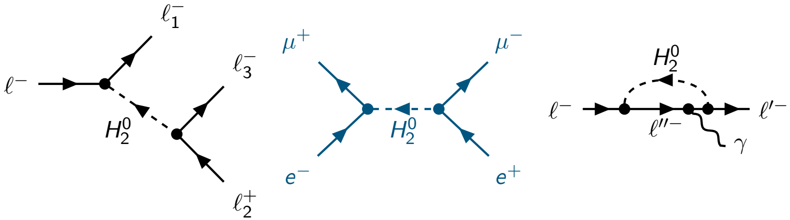


Improved sensitivity at future/current experiments:
Belle-II, COMET, Mu3E, ...

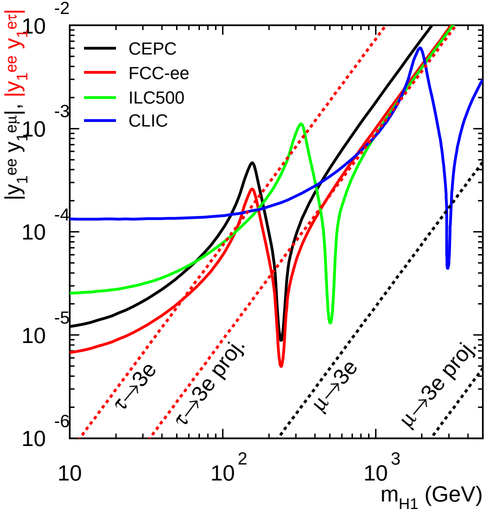
Opposite-sign lepton collider

Lepton colliders

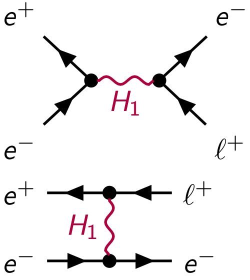
- Circular Electron Positron Collider (CEPC): 5 ab^{-1} at 240 GeV
- Future Circular Collider (FCC-ee): 16 ab^{-1} at 240 GeV
- International Linear Collider (ILC500): 4 ab^{-1} at 500 GeV
- Compact Linear Collider (CLIC): 5 ab^{-1} at 3 TeV

Basic cuts: $p_T > 10$ GeV and $|\eta| < 2.5$

$H_{1\mu}$: $e^+e^- \to e^\pm\mu^\mp(e^\pm\tau^\mp)$



$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{\ell}_i \gamma^\mu P_L \ell_j$$

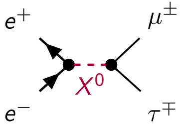


same result for right-handed $H'_{1\mu}$

τ efficiency not included in figure

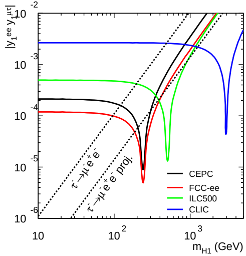
60% τ eff. $\Rightarrow$ 77% (60%) sensitivity reduction for 1 (2) τ leptons

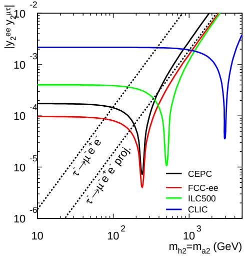
$H_{1\mu}, H_2$: $e^+e^- \to \mu^\pm\tau^\mp$

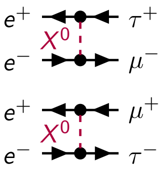


rel. couplings

$|y^{ee}y^{\mu\tau}|$

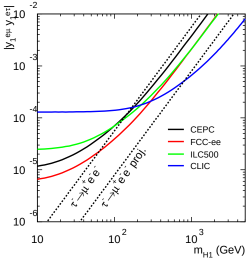


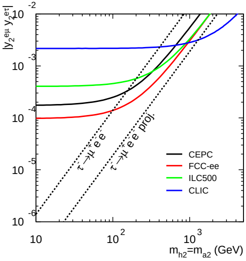




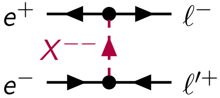
rel. couplings

$|y^{e\mu}y^{e\tau}|$

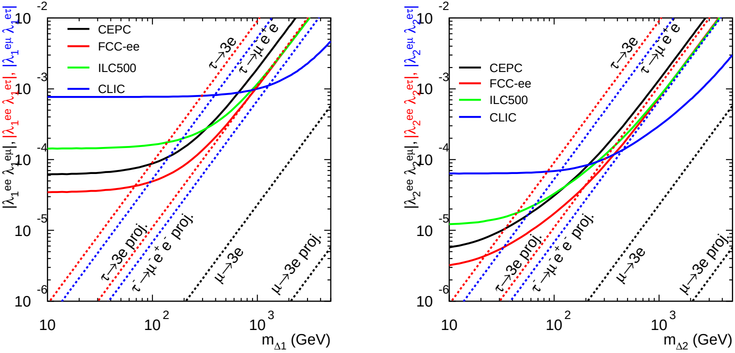




Δ_1, $\Delta_{2\mu}$: $e^+e^- \to \ell^+\ell'^-$



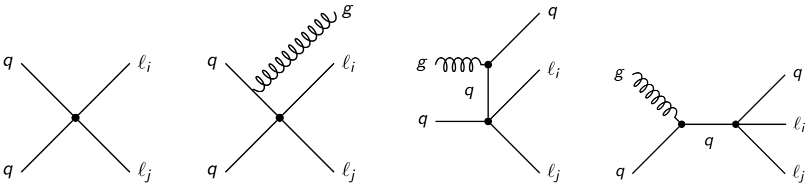
relevant couplings
$|\lambda^{ee}\lambda^{e\ell}|$ and $|\lambda^{e\mu}\lambda^{e\tau}|$



Hadron colliders – LHC

Charged LFV at hadron colliders: Quark initial state Cai,MS 1510.02486

Processes at LHC: $pp \to \ell_i \ell_j + \mathrm{jets}$



Signal: opposite-sign different flavour pair of leptons

Recast limits of most sensitive previous searches (at that time)

ATLAS 1503.04430	ATLAS 1205.0725
8 TeV	7 TeV
20.3 fb^{-1}	2.1 fb^{-1}
$e\mu$, $e\tau$, $\mu\tau$	$e\mu$
inclusive	exclusive
including arbitrary number of jets	separated by number of jets

14 TeV projection

- Assuming 300 fb^{-1}
- Following exclusive 7 TeV search

Charged LFV at the LHC: setup

Quark initial state Cai,MS 1510.02486

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8 TeV	7 TeV
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$e\mu$, $e\tau$, $\mu\tau$	$e\mu$
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14 TeV projection

- Assuming 300 fb^{-1}
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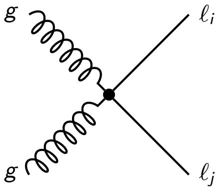
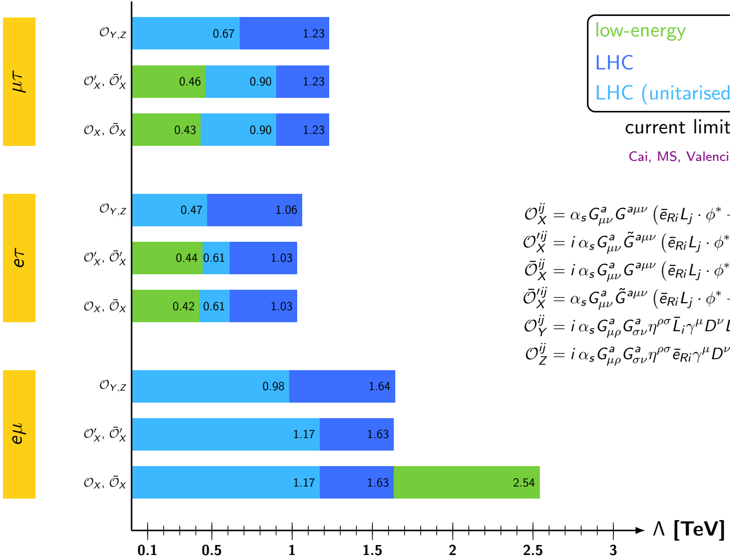
Gluon initial state Cai,MS,Valencia 1802.09822

CMS-PAS-EXO-16-058	ATLAS 1607.08079
13 TeV	13 TeV
35.9 fb^{-1}	3.2 fb^{-1}
$e\mu$	$e\tau$, $\mu\tau$



Charged LFV at the LHC: gluons



low-energy
LHC
LHC (unitarised)

current limits

Cai, MS, Valencia 1802.09822

$$\mathcal{O}_X^{ij} = \alpha_s G^a_{\mu\nu} G^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* + \bar{L}_j \cdot \phi e_{Ri}\right)$$
$$\mathcal{O}_X'^{ij} = i\,\alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* - \bar{L}_j \cdot \phi e_{Ri}\right)$$
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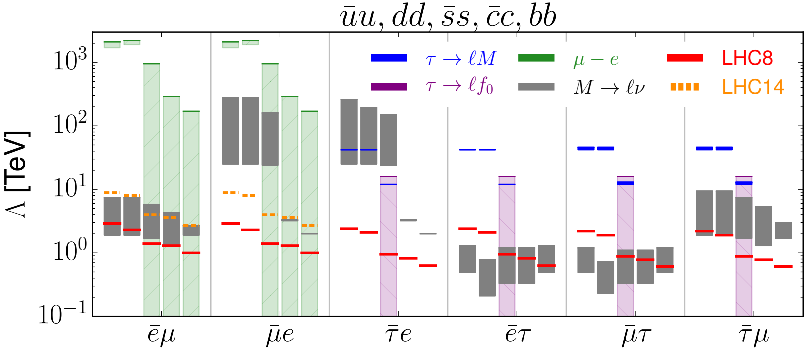
$$\mathcal{O}_Y^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j$$
$$\mathcal{O}_Z^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

Charged LFV at the LHC: quarks

Cai, MS 1510.02486



$$\mathcal{Q}_{ledq} = (\bar{L}^\alpha \ell)(\bar{d} Q^\alpha)\,, \qquad \mathcal{Q}^{(1)}_{lequ} = (\bar{L}^\alpha \ell)\epsilon_{\alpha\beta}(\bar{Q}^\beta u)$$

Summary

(lepton) colliders complementary way to search for charged LFV

$\mu \leftrightarrow e$ flavour: stringent limits from low-energy precision exp.

$\tau \leftrightarrow \ell$ flavour: future lepton colliders provide competitive limits

similar conclusions for hadron colliders

LHC provides most stringent limits for τ flavour
also for operators with derivatives and $G\tilde{G}$

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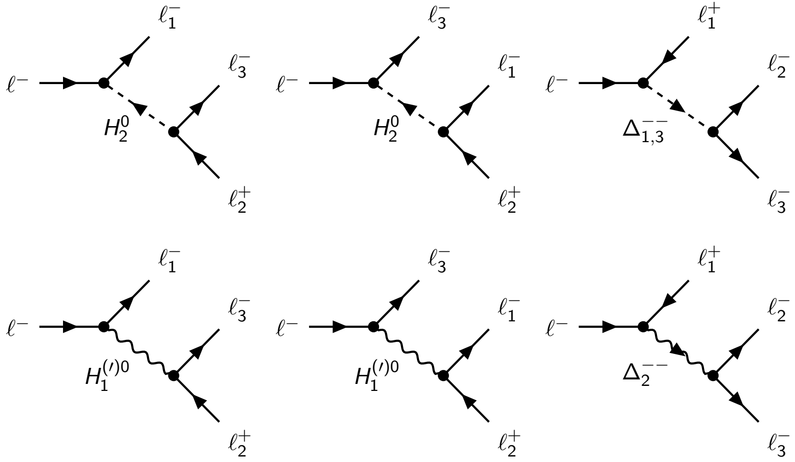
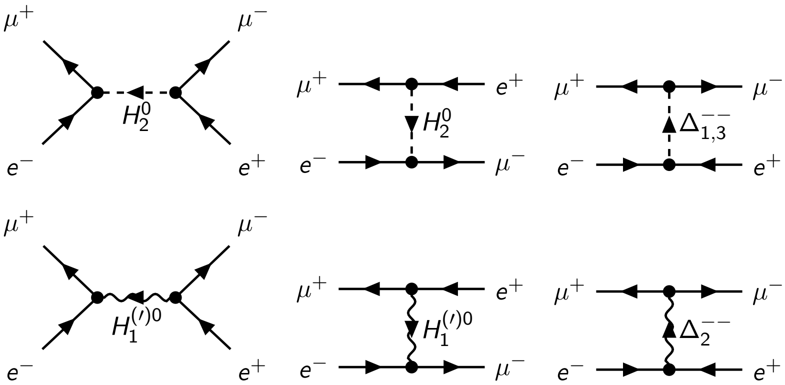
Backup Slides

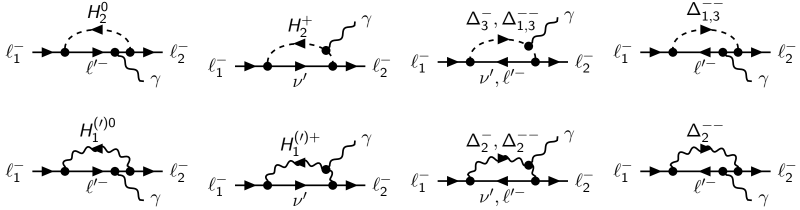
Tri-lepton decays



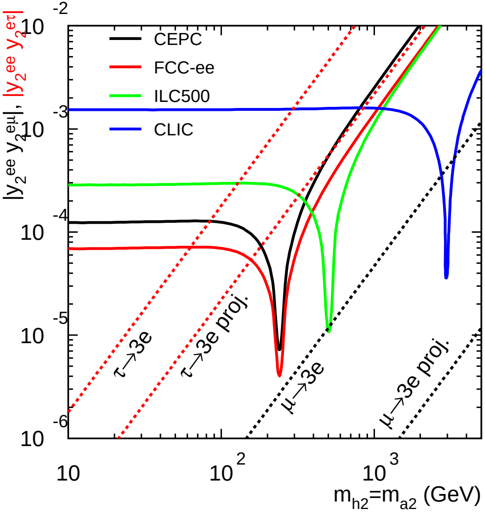
Muonium-Antimuonium Conversion



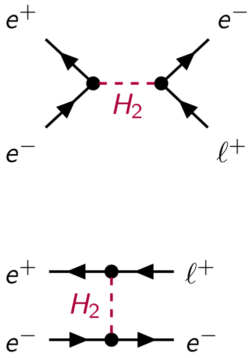
Radiative lepton decays



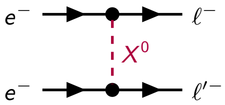
H_2: $e^+e^- \to e^\pm\mu^\mp(e^\pm\tau^\mp)$



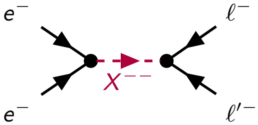
$$\mathcal{L} = y_2^{ij} H_2^0 \bar{\ell}_i P_R \ell_j + h.c.$$



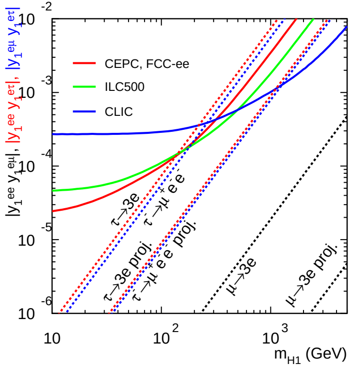
Same-sign lepton collider: $H_{1\mu}$, Δ_1: $e^- e^- \to \ell^- \ell'^-$

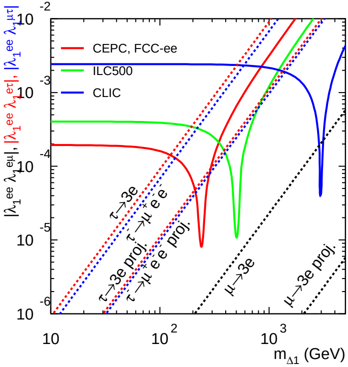


couplings $|y_1^{ee} y_1^{e\ell}|$ and $|y_1^{e\mu} y_1^{e\tau}|$



couplings $|\lambda_1^{ee} \lambda_1^{e\ell}|$ and $|\lambda_1^{ee} \lambda_1^{\mu\tau}|$





assuming luminosity of 500fb^{-1}