Charged lepton flavour violation at colliders

Michael A. Schmidt

19 February 2019

The University of New South Wales

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

UNSW
SYDNEY

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

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

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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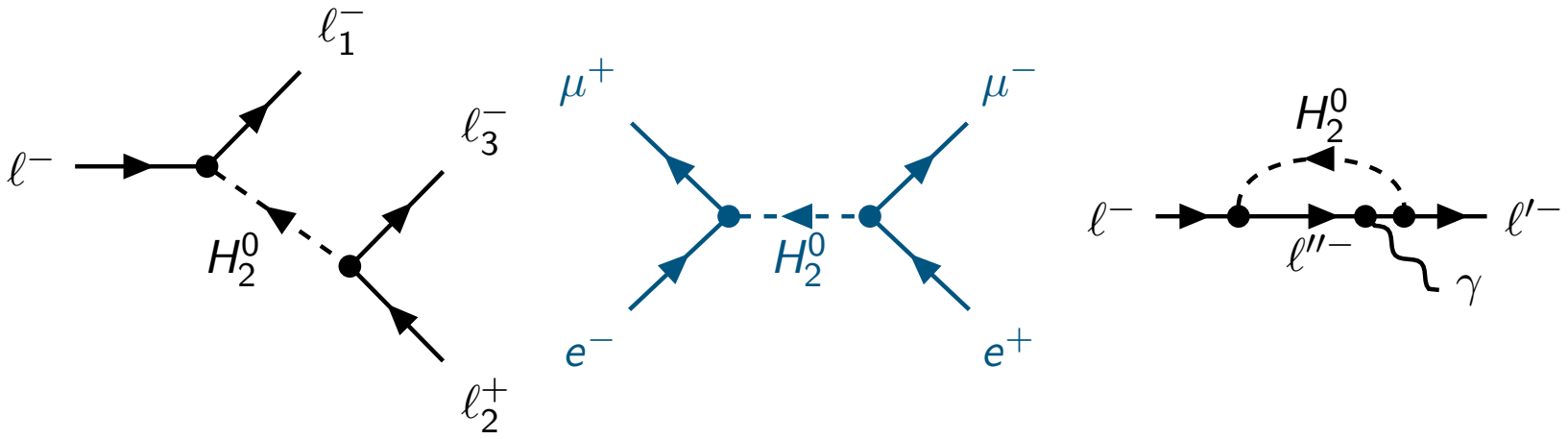
Low-energy precision constraints

- LFV trilepton decays, $\ell \to \ell_1 \bar{\ell}_2 \bar{\ell}_3$
- 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, ...

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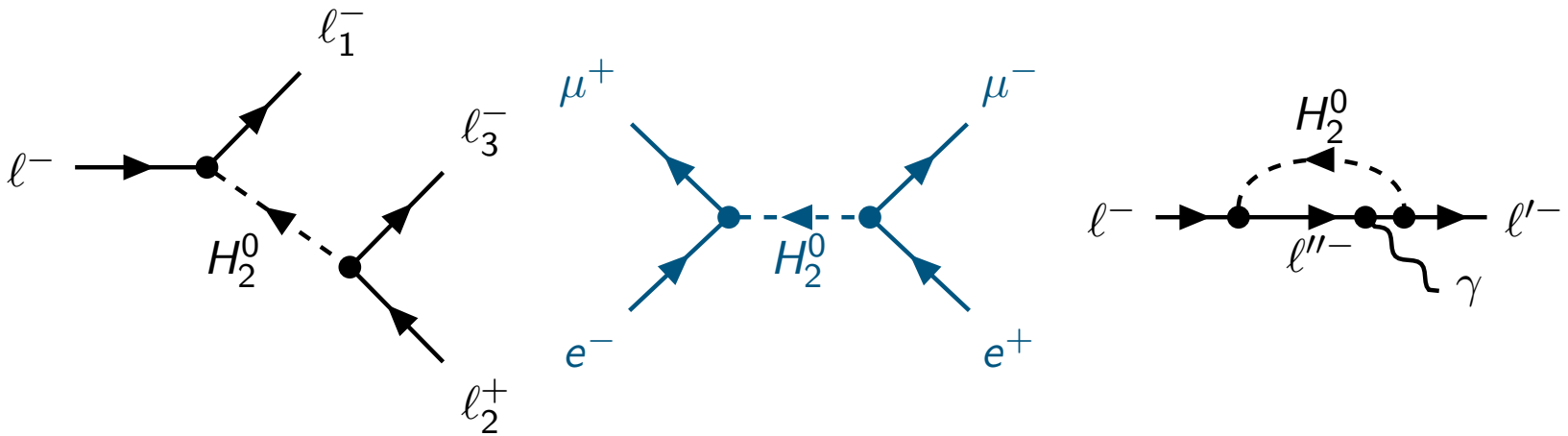

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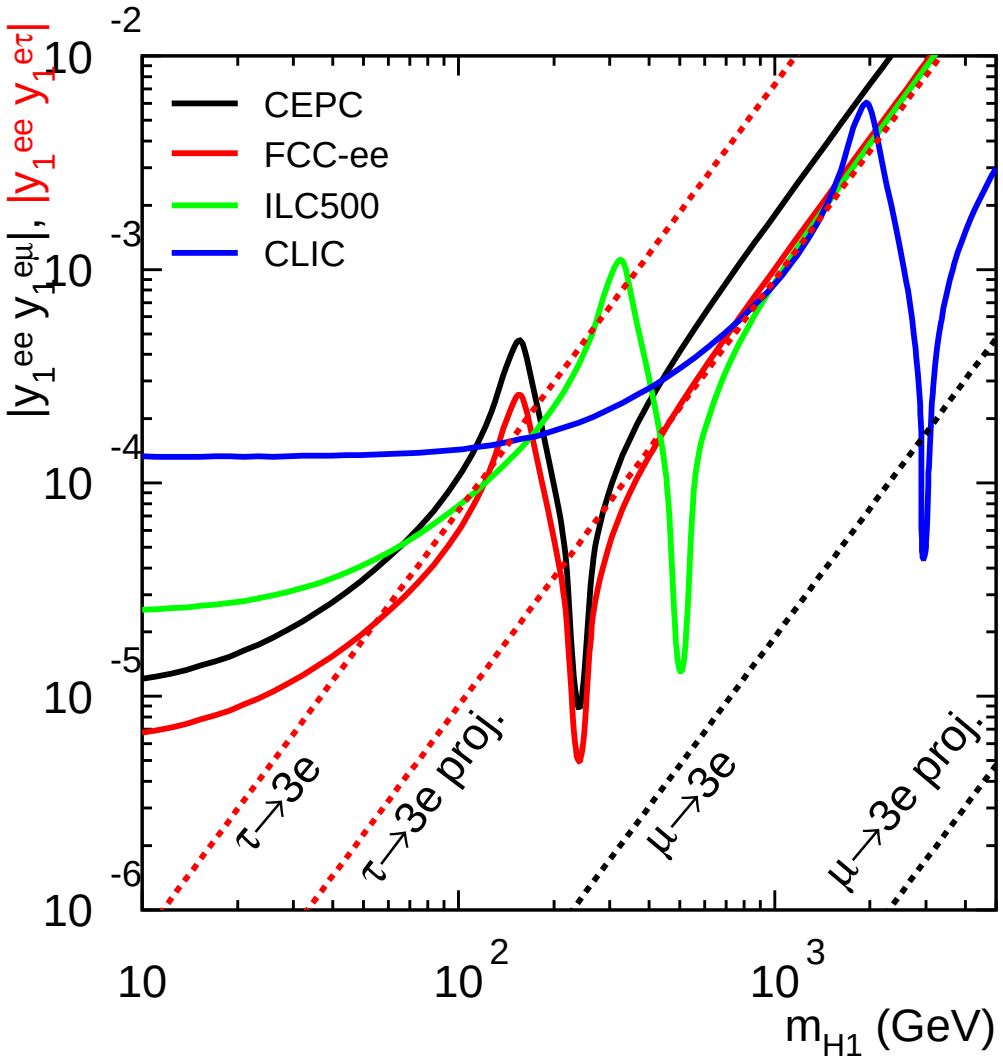
Opposite-sign lepton collider

Lepton colliders

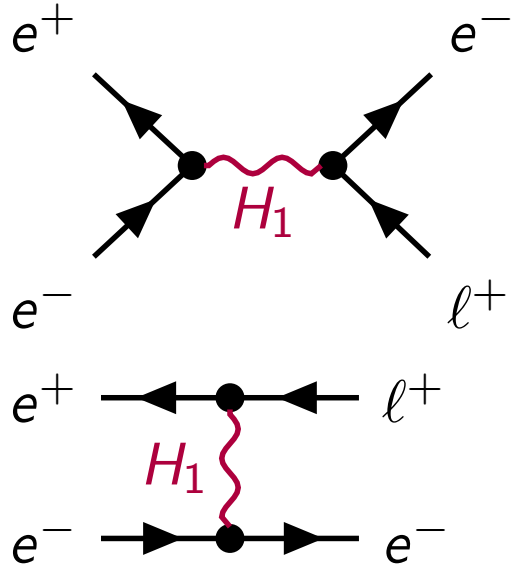
- Cicular Electron Positron Collider (CEPC): 5 ab^{-1} at 240 GeV
- Future Circular Collider (FCC-ee): 16 ab^{-1} at 240 GeV
- International Linear Collider (ILC500): 4 ab^{-1} at 500 GeV
- Compact Linear Collider (CLIC): 5 ab^{-1} at 3 TeV

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

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



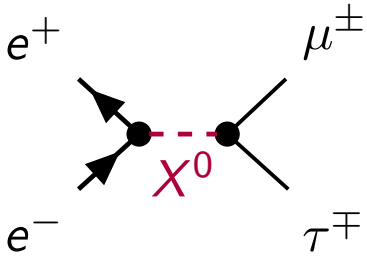
$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{\ell}_i \gamma^\mu P_L \ell_j$$



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

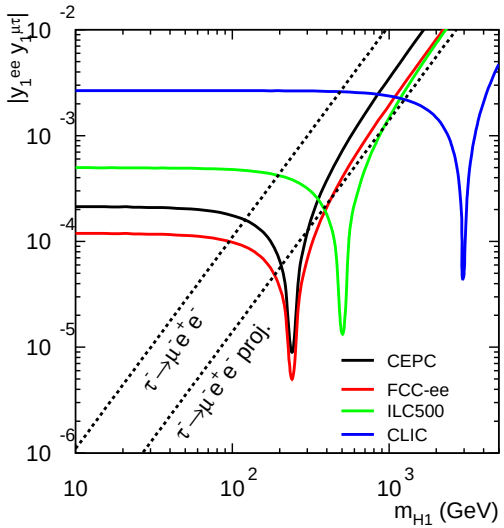
τ efficiency not included in figure
60% τ eff. $\Rightarrow$ 77% (60%) sensitivity reduction for 1 (2) τ leptons

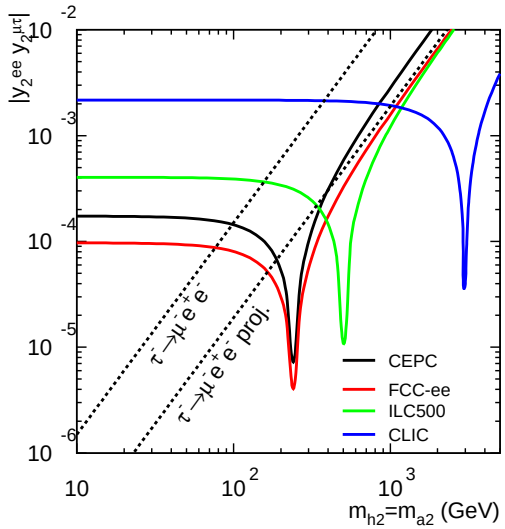
$H_{1\mu}, H_2$: $e^+e^- \to \mu^\pm\tau^\mp$

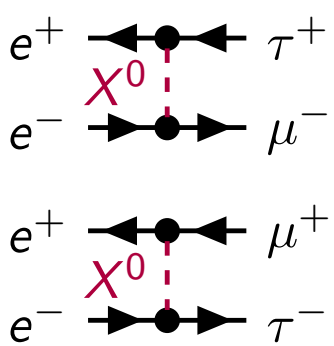


rel. couplings

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







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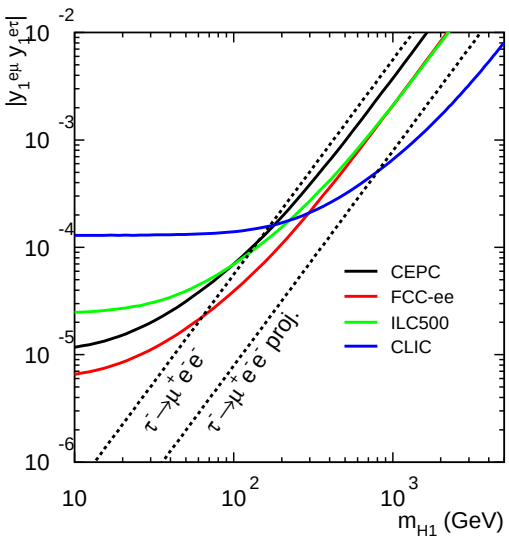
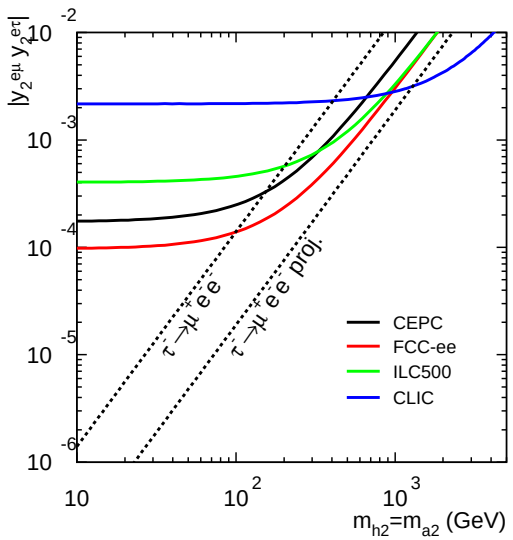
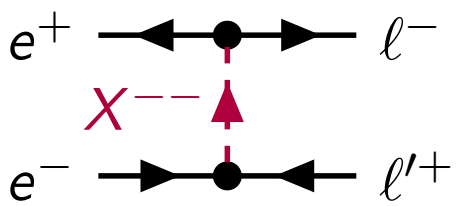


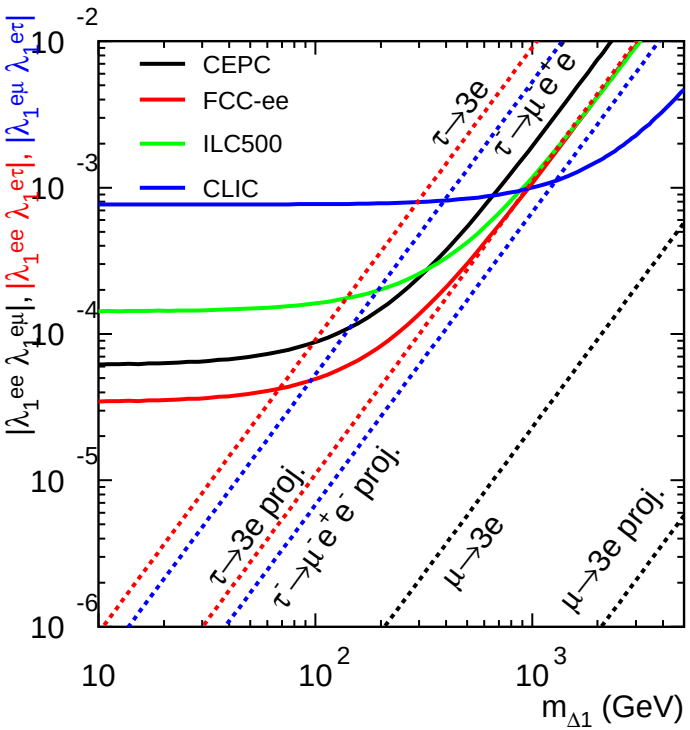


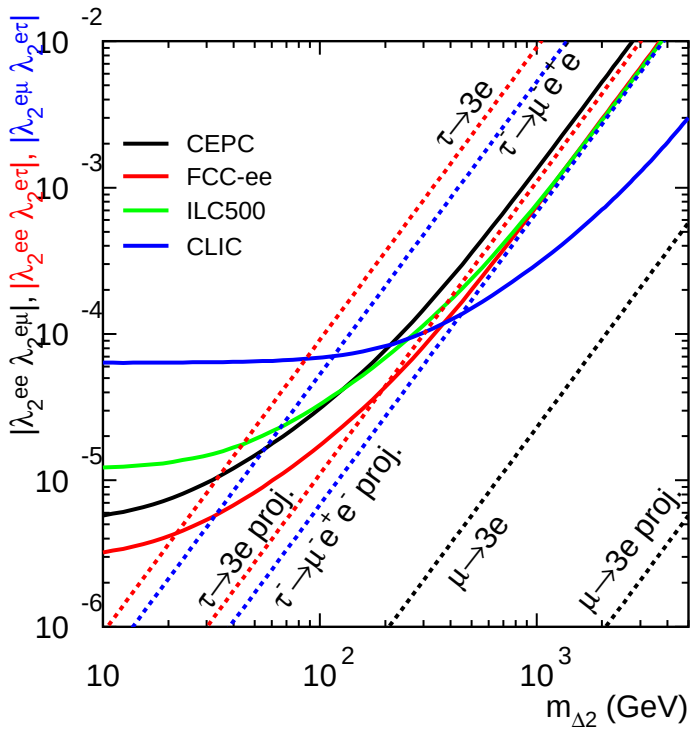
Δ_1, $\Delta_{2\mu}$: $e^+e^- \to \ell^+\ell'^-$



relevant couplings

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

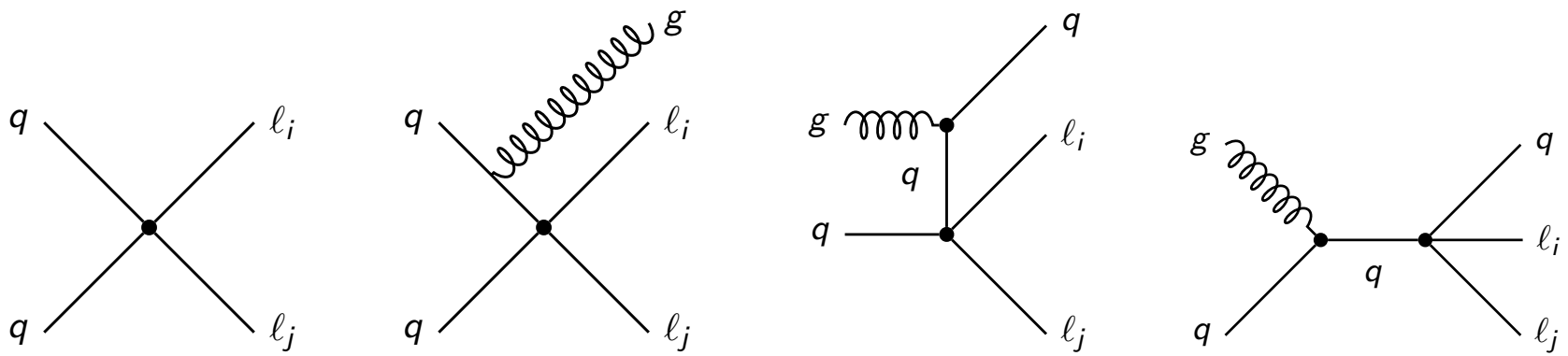




Hadron colliders – LHC

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

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



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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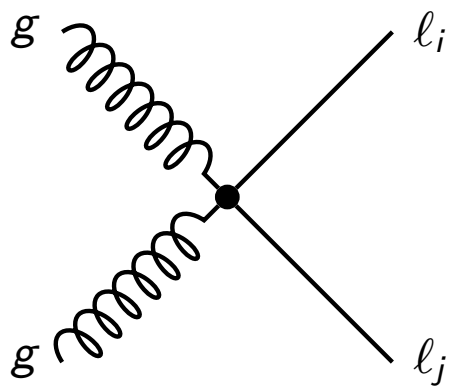
inclusive	exclusive
including arbitrary number of jets	separated by number of jets

Gluon initial state Cai,MS,Valencia 1802.09822

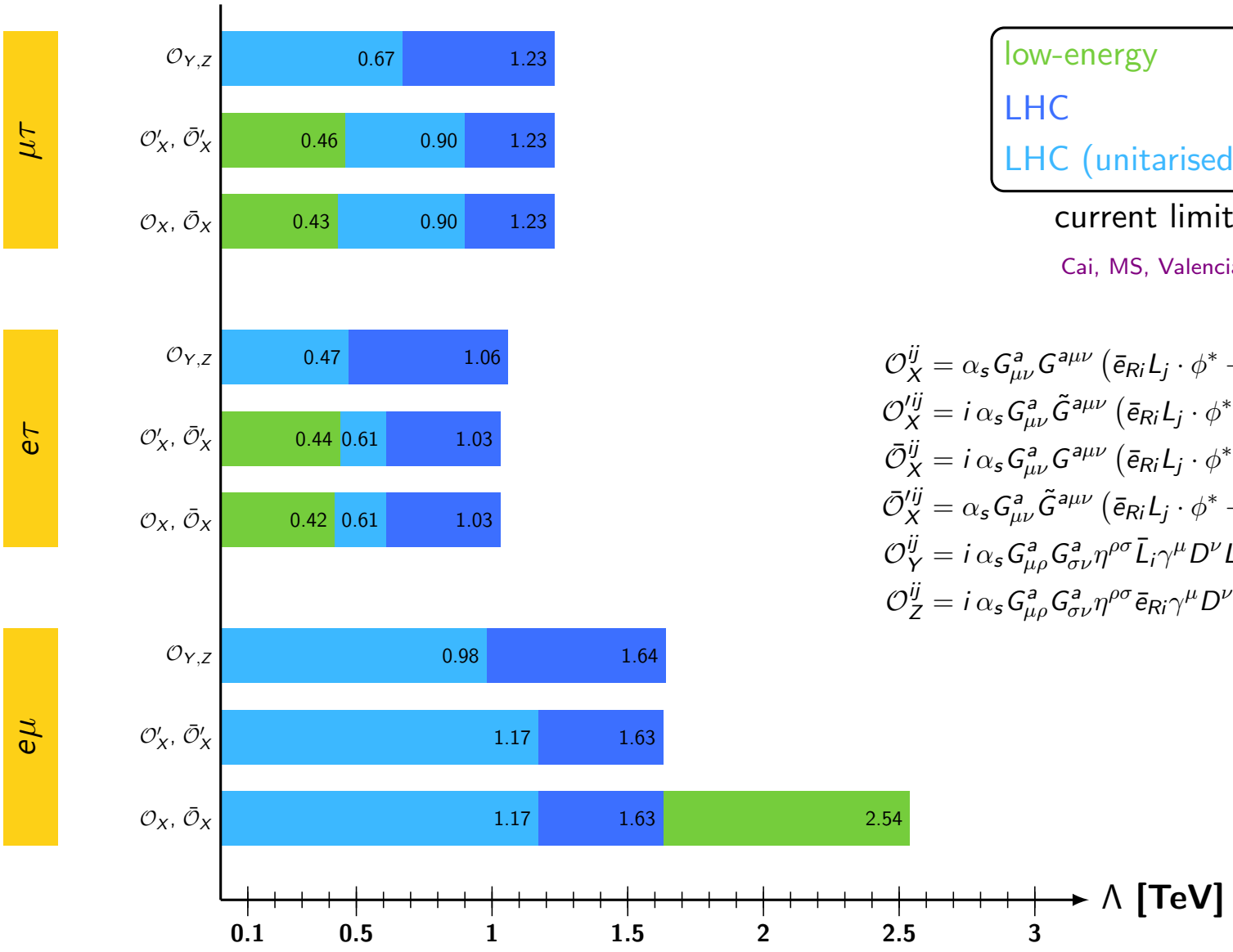
CMS-PAS-EXO-16-058	ATLAS 1607.08079
13 TeV	13 TeV
35.9 fb^{-1}	3.2 fb^{-1}
$e\mu$	$e\tau$, $\mu\tau$

14 TeV projection

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



Charged LFV at the LHC: gluons



low-energy
LHC
LHC (unitarised)

current limits

Cai, MS, Valencia 1802.09822

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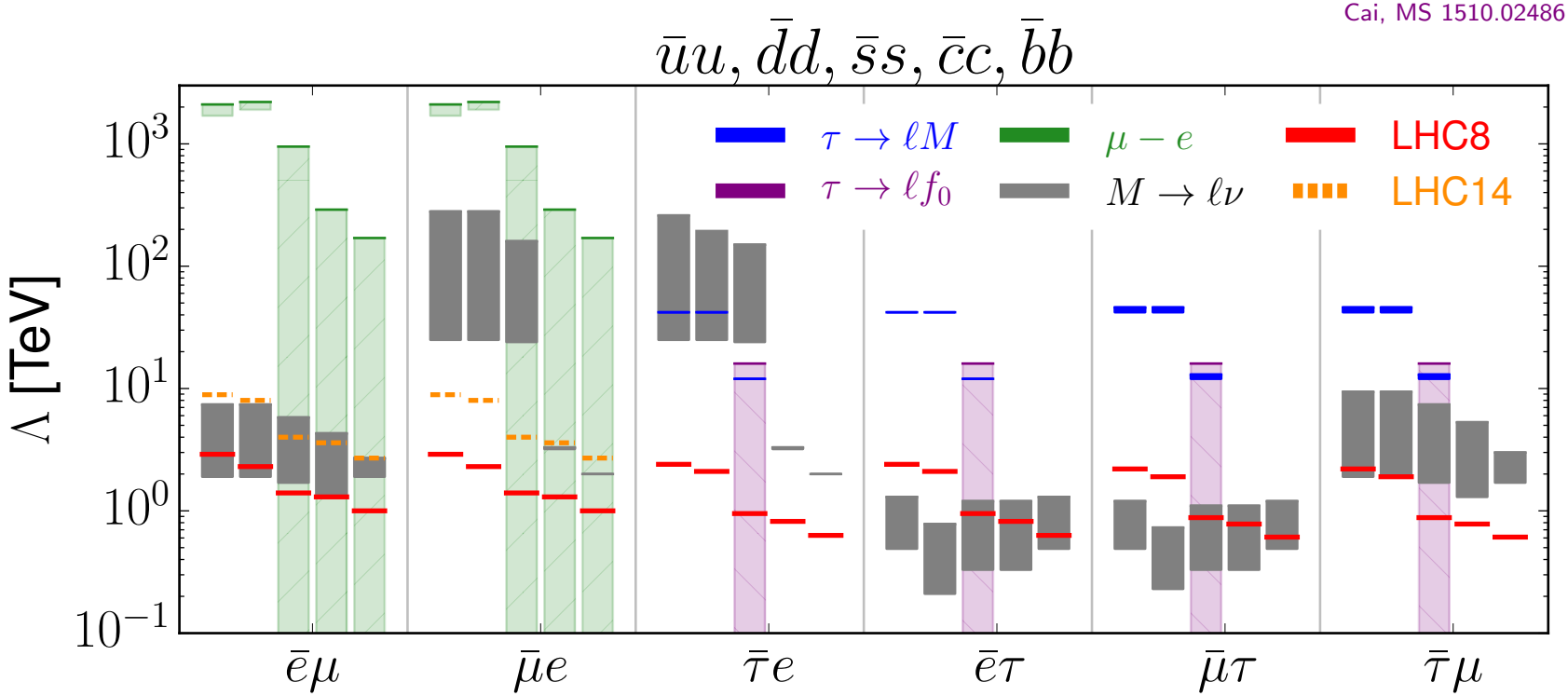
$$\mathcal{O}^{ij}_Y = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j$$
$$\mathcal{O}^{ij}_Z = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

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 $G\tilde{G}$

Thank you

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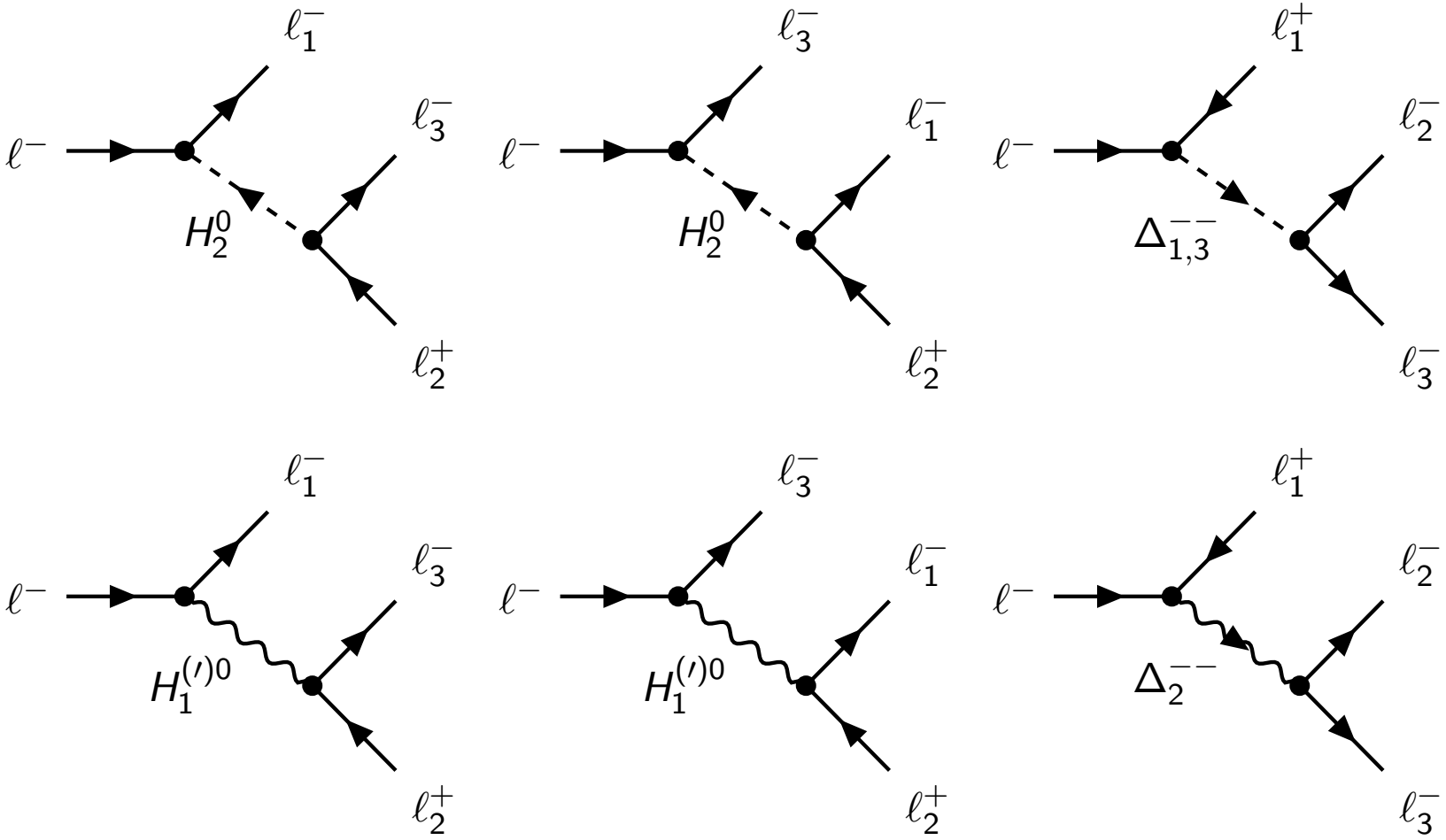
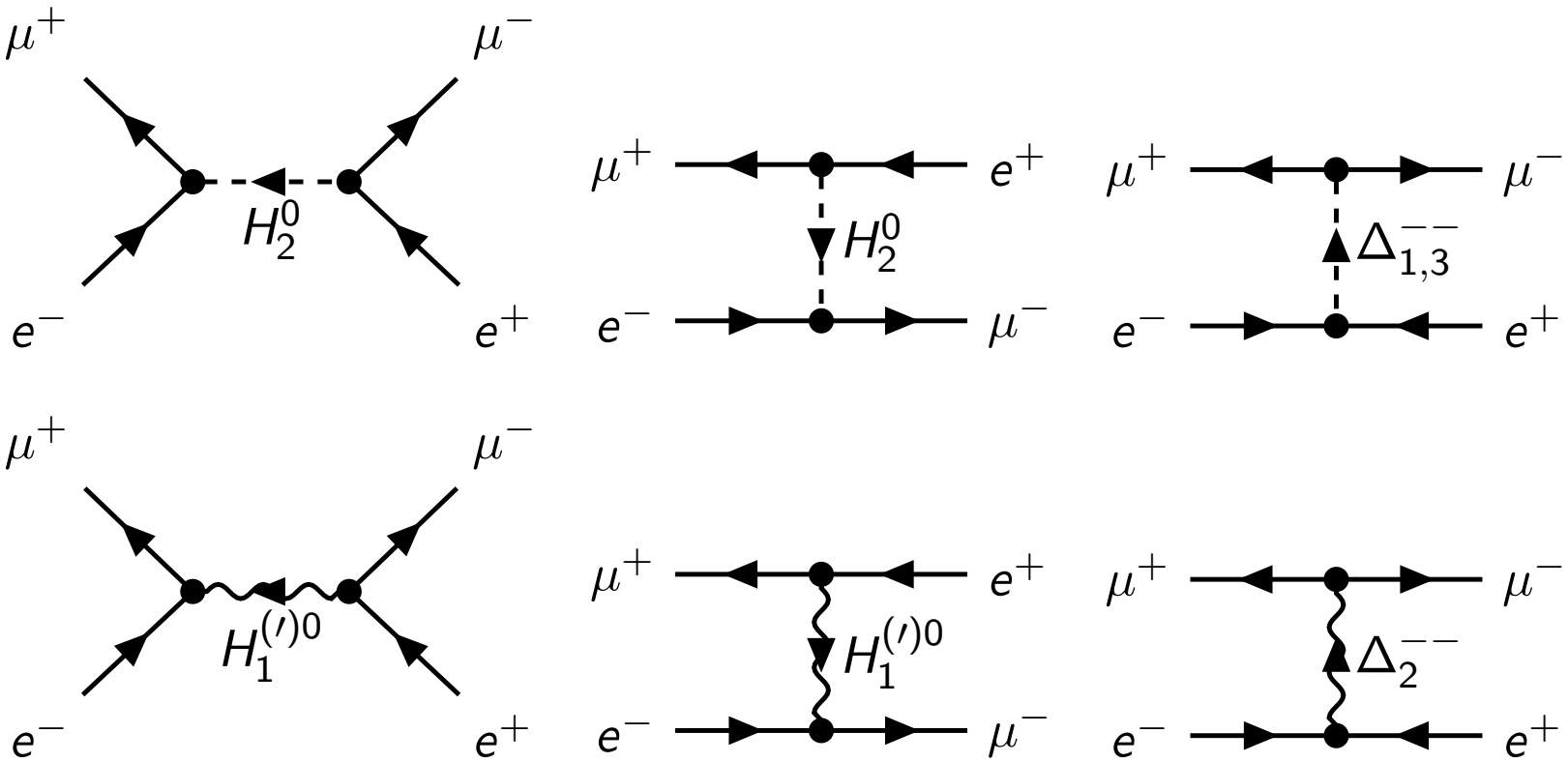
Backup Slides

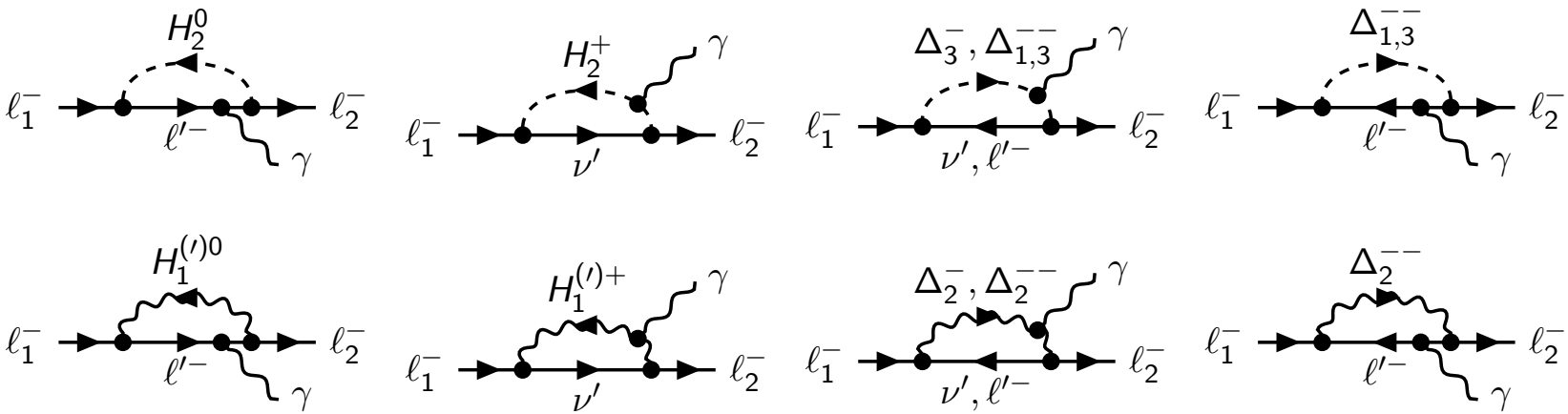
Tri-lepton decays



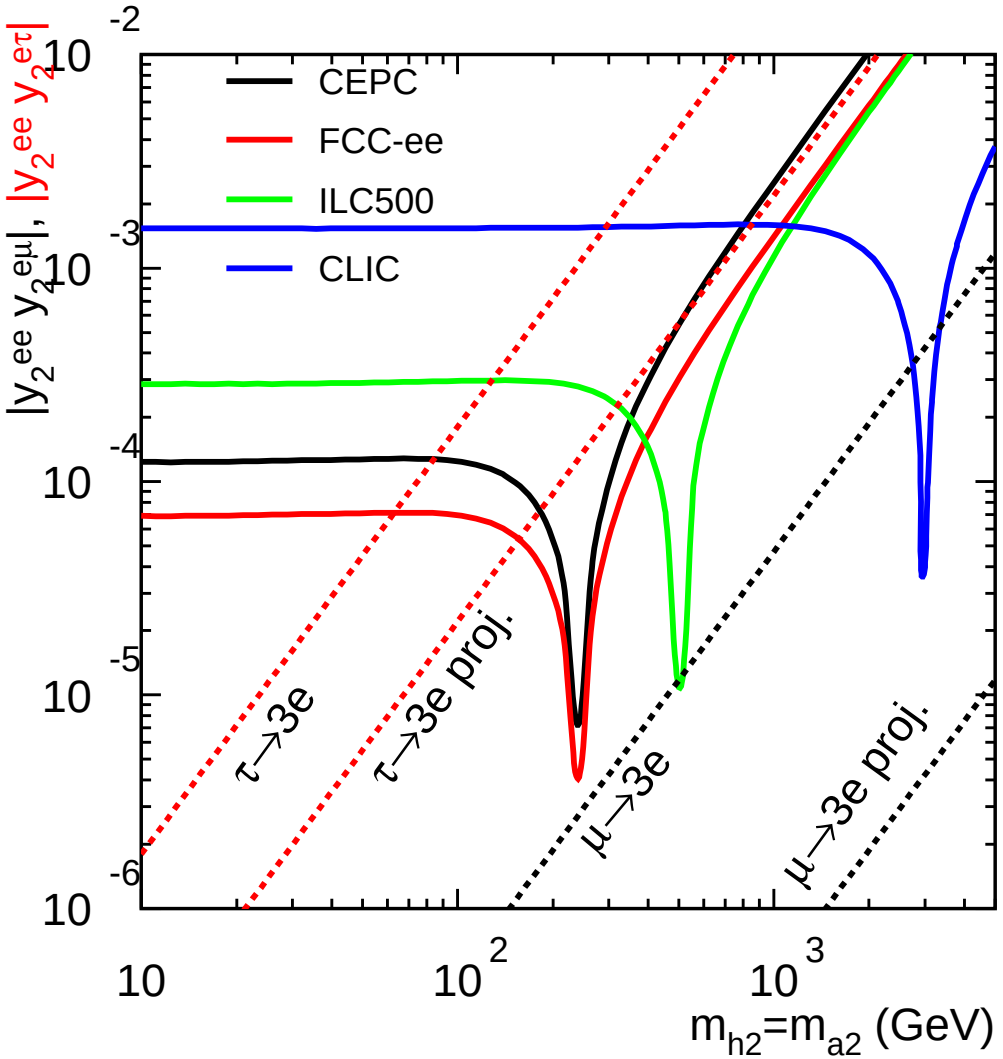
Muonium-Antimuonium Conversion



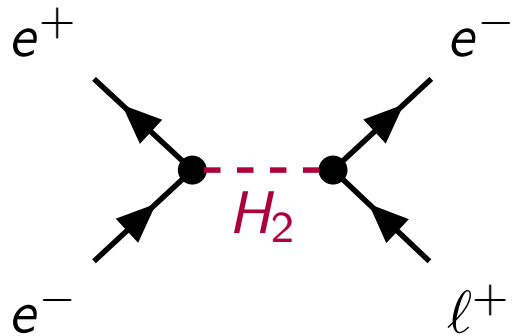
Radiative lepton decays

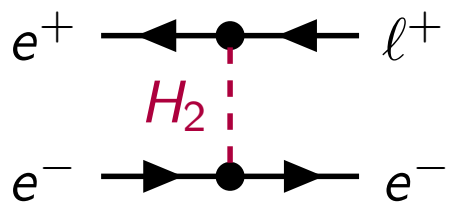


H_2: $e^+e^- \to e^\pm\mu^\mp(e^\pm\tau^\mp)$

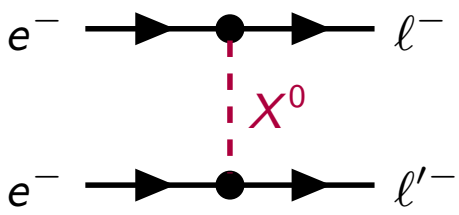


$$\mathcal{L} = y_2^{ij} H_2^0 \bar{\ell}_i P_R \ell_j + h.c.$$

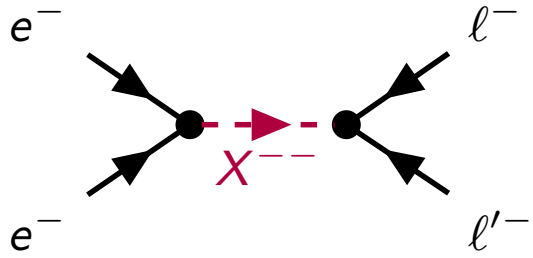




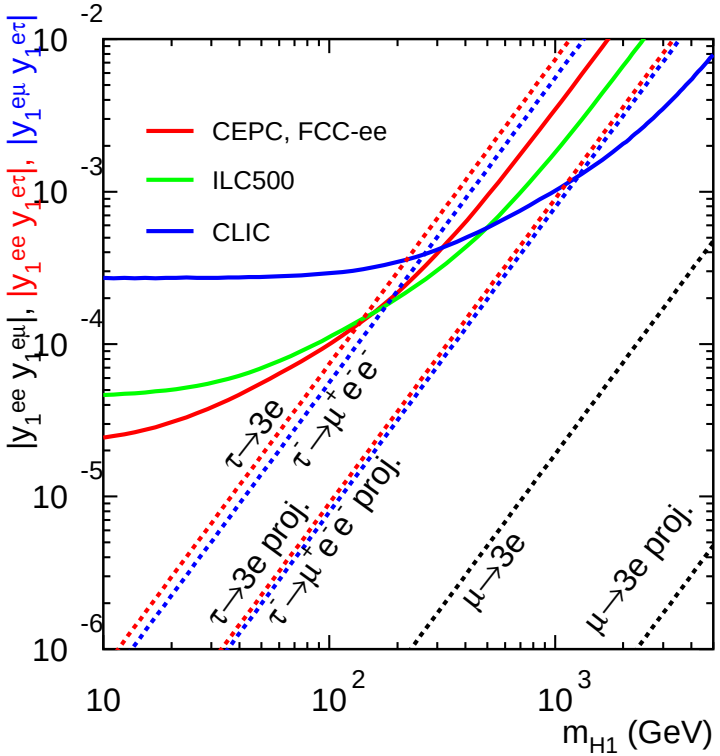
Same-sign lepton collider: $H_{1\mu}$, Δ_1: $e^-e^- \to \ell^-\ell'^-$

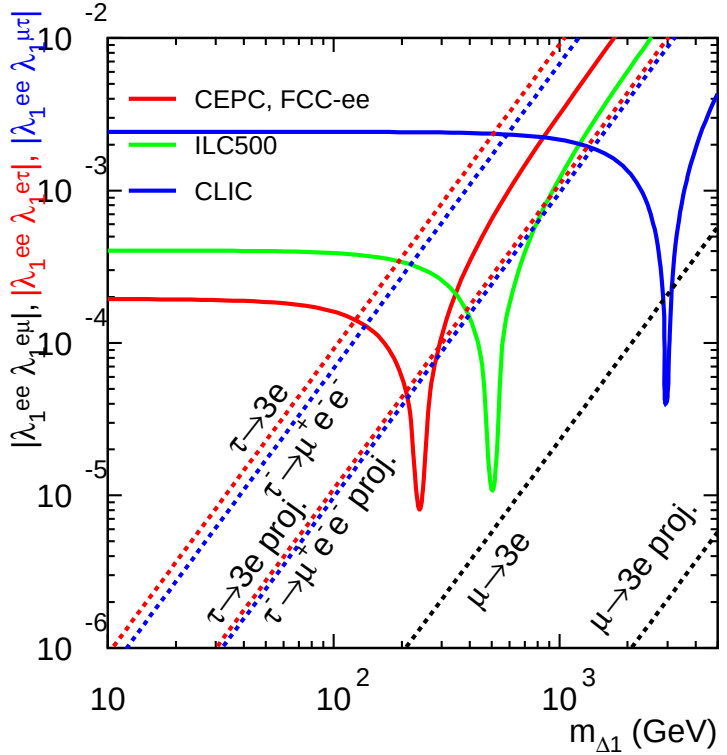


couplings $|y_1^{ee} y_1^{e\ell}|$ and $|y_1^{e\mu} y_1^{e\tau}|$



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





assuming luminosity of $500\mathrm{fb}^{-1}$