Searches for charged lepton flavour violation at colliders

Michael A. Schmidt

18 September 2019

Quy Nhon, Vietnam

based on work in collaboration with
Yi Cai 1510.02486
Yi Cai, German Valencia 1802.09822
Tong Li 1809.07924, 1907.06963

UNSW SYDNEY

Motivation

The Standard Model is very successful. . .

. . . but incomplete

In particular neutrinos are massive

many different possibilities – see Cai, Herrero-Garcia, MS, Vicente, Volkas 1706.08524

Motivation

The Standard Model is very successful. . .

. . . but incomplete

In particular neutrinos are massive

many different possibilities – see Cai, Herrero-Garcia, MS, Vicente, Volkas 1706.08524

Motivation

The Standard Model is very successful. . .

. . . but incomplete

In particular neutrinos are massive

many different possibilities – see Cai, Herrero-Garcia, MS, Vicente, Volkas 1706.08524

$\rightarrow$ need way to discriminate models

Lepton flavour is not conserved

$\rightarrow$ Flavour changing processes are a sensitive probe

- in SM+m_ν suppressed by unitarity, $\mathcal{A} \sim G_F m_\nu^2 \simeq 10^{-26}$
- many neutrino mass models have large charged LFV due to non-unitarity or new contributions, e.g. inverse seesaw, radiative mass models
- could be completely unrelated to neutrino mass, e.g. SUSY

Motivation

The Standard Model is very successful. . .

. . . but incomplete

In particular neutrinos are massive

many different possibilities – see Cai, Herrero-Garcia, MS, Vicente, Volkas 1706.08524

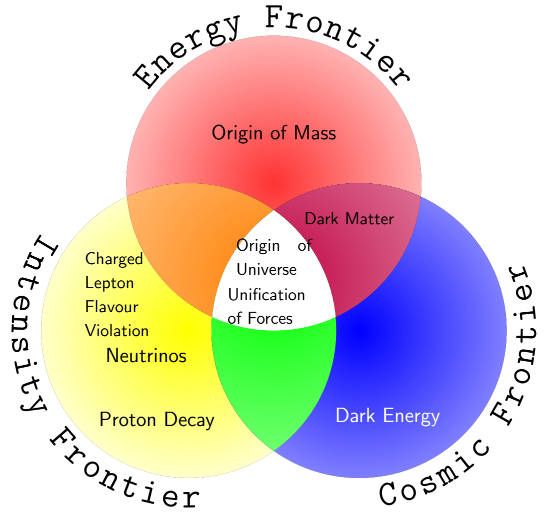
→ need way to discriminate models

Lepton flavour is not conserved

→ Flavour changing processes are a sensitive probe

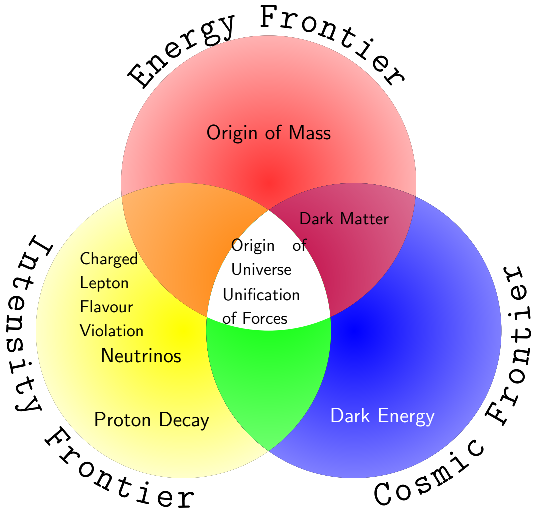
- in SM+m_ν suppressed by unitarity, $\mathcal{A} \sim G_F m_\nu^2 \simeq 10^{-26}$
- many neutrino mass models have large charged LFV due to non-unitarity or new contributions, e.g. inverse seesaw, radiative mass models
- could be completely unrelated to neutrino mass, e.g. SUSY

Motivation



Can high-energy colliders compete with the intensity frontier?

Motivation



Can high-energy colliders compete with the intensity frontier?

cLFV in scattering processes: overview

LHC: $q\bar{q}, gg \to \ell\ell'$

Future lepton colliders: $e^+e^- \to \ell\ell'$

Future lepton colliders: $e^+e^- \to \ell\ell' + X$

Conclusions

LHC: $q\bar{q}, gg \to \ell\ell'$

Relevant effective operators [Cai, MS 1510.02486]

D6 Operators with 2 Quarks and 2 Leptons

Buchmüller, Wyler NPB268(1986)621; Grzadkowski et al 1008.4884; Carpentier, Davidson 1008.0280; Petrov,Zhuridov 1308.6561

Vector

$$\mathcal{Q}_{lq}^{(1)} = (\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q) \qquad \mathcal{Q}_{lq}^{(3)} = (\bar{L}\gamma_\mu \tau^I L)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$\mathcal{Q}_{eu} = (\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ed} = (\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)$$

$$\mathcal{Q}_{lu} = (\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ld} = (\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$$

$$\mathcal{Q}_{qe} = (\bar{Q}\gamma_\mu Q)(\bar{\ell}\gamma^\mu \ell)$$

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

with same-flavour quark

Tensor $$\mathcal{Q}_{lequ}^{(3)} = (\bar{L}^\alpha \sigma_{\mu\nu} \ell)\epsilon_{\alpha\beta}(\bar{Q}^\beta \sigma^{\mu\nu} u)$$

D8 Operators with 2 Gluons and 2 Leptons

$$\mathcal{O}_X^{ij} = \alpha_s G^a_{\mu\nu} G^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* + h.c.) \qquad \mathcal{O}_X^{\prime ij} = i\,\alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* - h.c.)$$

$$\bar{\mathcal{O}}_X^{ij} = i\,\alpha_s G^a_{\mu\nu} G^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* - h.c.) \qquad \bar{\mathcal{O}}_X^{\prime ij} = \alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* + h.c.)$$

$$\mathcal{O}_Y^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j \qquad \mathcal{O}_Z^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

Relevant effective operators [Cai, MS 1510.02486]

D6 Operators with 2 Quarks and 2 Leptons

Buchmüller, Wyler NPB268(1986)621; Grzadkowski et al 1008.4884; Carpentier, Davidson 1008.0280; Petrov,Zhuridov 1308.6561

Vector

$$\mathcal{Q}_{lq}^{(1)} = (\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q) \qquad \mathcal{Q}_{lq}^{(3)} = (\bar{L}\gamma_\mu \tau^I L)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$\mathcal{Q}_{eu} = (\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ed} = (\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)$$

$$\mathcal{Q}_{lu} = (\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ld} = (\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$$

$$\mathcal{Q}_{qe} = (\bar{Q}\gamma_\mu Q)(\bar{\ell}\gamma^\mu \ell)$$

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

with same-flavour quark

Tensor $\mathcal{Q}_{lequ}^{(3)} = (\bar{L}^\alpha \sigma_{\mu\nu} \ell)\epsilon_{\alpha\beta}(\bar{Q}^\beta \sigma^{\mu\nu} u)$

D8 Operators with 2 Gluons and 2 Leptons

$$\mathcal{O}_X^{ij} = \alpha_s G^a_{\mu\nu} G^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* + h.c.) \qquad \mathcal{O}_X^{\prime ij} = i\,\alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* - h.c.)$$

$$\bar{\mathcal{O}}_X^{ij} = i\,\alpha_s G^a_{\mu\nu} G^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* - h.c.) \qquad \bar{\mathcal{O}}_X^{\prime ij} = \alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} (\bar{e}_{Ri} L_j \cdot \phi^* + h.c.)$$

$$\mathcal{O}_Y^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j \qquad \mathcal{O}_Z^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

Relevant effective operators [Cai, MS 1510.02486]

D6 Operators with 2 Quarks and 2 Leptons

Buchmüller, Wyler NPB268(1986)621; Grzadkowski et al 1008.4884; Carpentier, Davidson 1008.0280; Petrov,Zhuridov 1308.6561

Vector

$$\mathcal{Q}_{lq}^{(1)} = (\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q) \qquad \mathcal{Q}_{lq}^{(3)} = (\bar{L}\gamma_\mu \tau^I L)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$\mathcal{Q}_{eu} = (\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ed} = (\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)$$

$$\mathcal{Q}_{lu} = (\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ld} = (\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$$

$$\mathcal{Q}_{qe} = (\bar{Q}\gamma_\mu Q)(\bar{\ell}\gamma^\mu \ell)$$

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

with same-flavour quark

Tensor $\mathcal{Q}_{lequ}^{(3)} = (\bar{L}^\alpha \sigma_{\mu\nu} \ell)\epsilon_{\alpha\beta}(\bar{Q}^\beta \sigma^{\mu\nu} u)$

D8 Operators with 2 Gluons and 2 Leptons

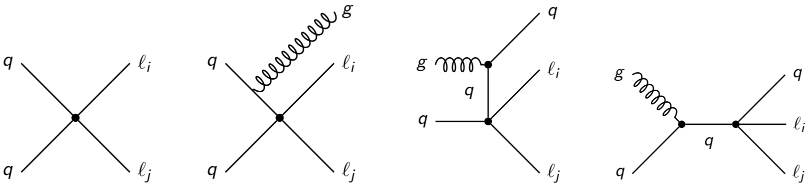
$$\mathcal{O}_X^{ij} = \alpha_s G_{\mu\nu}^a G^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* + h.c.\right) \qquad \mathcal{O}_X^{\prime ij} = i\,\alpha_s G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* - h.c.\right)$$

$$\bar{\mathcal{O}}_X^{ij} = i\,\alpha_s G_{\mu\nu}^a G^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* - h.c.\right) \qquad \bar{\mathcal{O}}_X^{\prime ij} = \alpha_s G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* + h.c.\right)$$

$$\mathcal{O}_Y^{ij} = i\,\alpha_s G_{\mu\rho}^a G_{\sigma\nu}^a \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j \qquad \mathcal{O}_Z^{ij} = i\,\alpha_s G_{\mu\rho}^a G_{\sigma\nu}^a \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

cLFV at the Large Hadron Collider (LHC) [Cai, MS 1510.02486]

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



Signal: opposite-sign different flavour pair of leptons

Several existing searches:

- ATLAS 7 TeV: LFV heavy neutral particle decay to $e\mu$ ATLAS 1103.5559
- CMS 8 TeV: LFV heavy neutral particle decay to $e\mu$ CMS-PAS-EXO-13-002
- ATLAS 7 TeV: LFV in $e\mu$ continuum in $\not{R}$ SUSY ATLAS 1205.0725
- ATLAS 8 TeV: LFV heavy neutral particle decay ATLAS 1503.04430
- CMS 8 TeV: LFV heavy neutral particle decay to $e\mu$ CMS 1604.05239
- ATLAS 13 TeV, 3.2 fb^{-1}: LFV heavy neutral particle decay ATLAS 1607.08079
- ATLAS 13 TeV, 36.1 fb^{-1} ATLAS 1807.06573

Interesting ATLAS searches [Cai, MS 1510.02486]

Recast limits of most sensitive previous searches

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

Projection to 14 TeV

- Assume 300 fb^{-1}
- Follow searching strategy of exclusive 7 TeV search

Interesting ATLAS searches [Cai, MS 1510.02486]

Recast limits of most sensitive previous searches

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

Projection to 14 TeV

- Assume 300 fb^{-1}
- Follow searching strategy of exclusive 7 TeV search

Interesting ATLAS searches [Cai, MS 1510.02486]

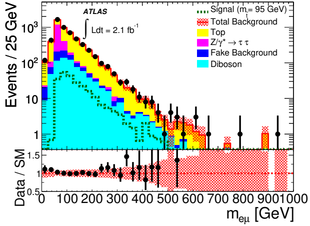
Recast limits of most sensitive previous searches

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

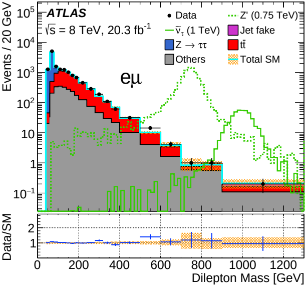
Projection to 14 TeV

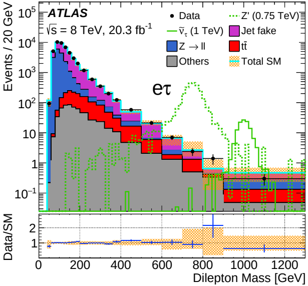
- Assume 300 fb^{-1}
- Follow searching strategy of exclusive 7 TeV search

ATLAS Searches [Cai, MS 1510.02486]

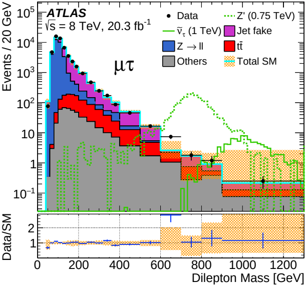


ATLAS 7TeV 1205.0725



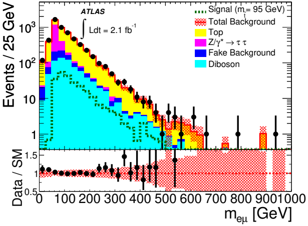


ATLAS 8TeV 1503.04430

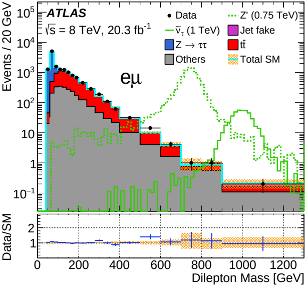


ATLAS 8TeV 1503.04430

ATLAS Searches [Cai, MS 1510.02486]



ATLAS 7TeV 1205.0725



ATLAS 8TeV 1503.04430

- Main backgrounds: $t\bar{t}$, WW, $Z/\gamma^* \to \tau\tau$

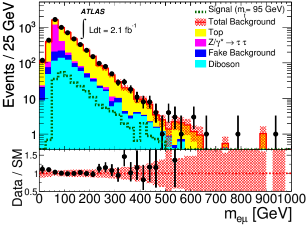
  also W/Z plus jets, WZ/ZZ, single top and $W/Z+\gamma$

$\Rightarrow$ Efficiently reduced in exclusive 7 TeV analysis by rejecting jets and $E_T^{miss} < 20$ GeV

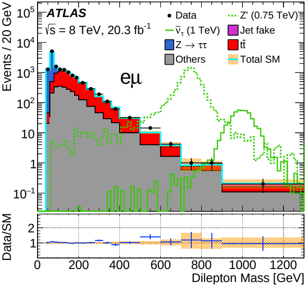
- Modelling of main background agrees with ATLAS
- Fake background estimated from data

$\Rightarrow$ Use background from ATLAS publications

ATLAS Searches [Cai, MS 1510.02486]



ATLAS 7TeV 1205.0725



ATLAS 8TeV 1503.04430

- Main backgrounds: $t\bar{t}$, WW, $Z/\gamma^* \to \tau\tau$

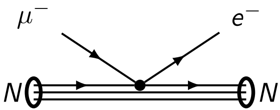
  also W/Z plus jets, WZ/ZZ, single top and $W/Z+\gamma$

$\Rightarrow$ Efficiently reduced in exclusive 7 TeV analysis by rejecting jets and $E_T^{miss} < 20$ GeV

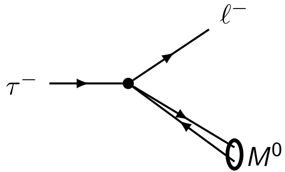
- Modelling of main background agrees with ATLAS
- Fake background estimated from data

$\Rightarrow$ Use background from ATLAS publications

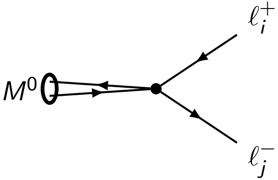
Precision Experiments [Cai, MS 1510.02486]



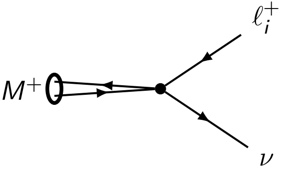
$\mu - e$ conversion in nuclei



$\tau \to \ell M^0$



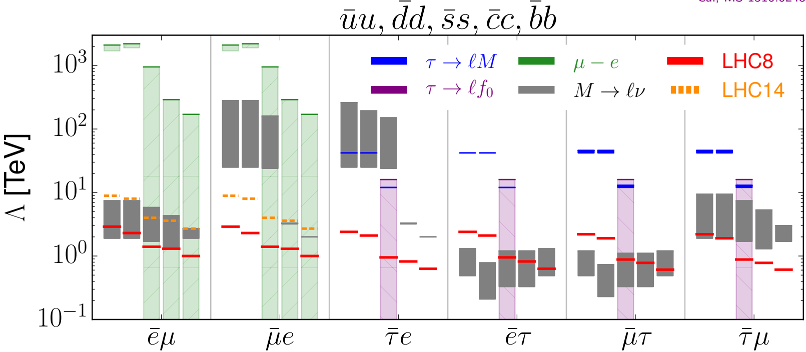
$M^0 \to \ell_i^+ \ell_j^-$



$M^+ \to \ell_i^+ \nu$

cLFV at hadron colliders: quarks

Cai, MS 1510.02486



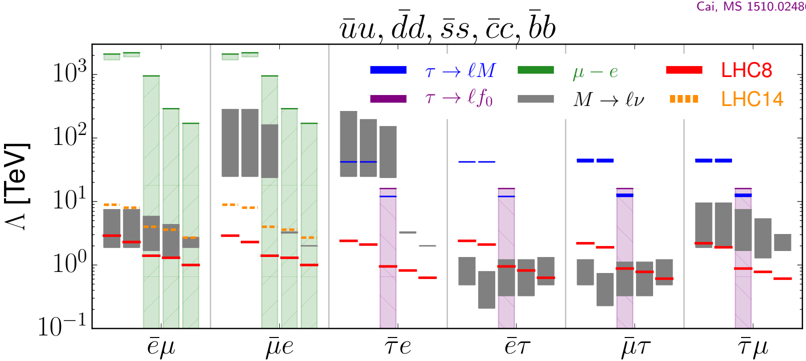
$$\mathcal{Q}_{ledq} = (\bar{L}^\alpha \ell)(\bar{d} Q^\alpha)\,, \qquad \mathcal{Q}^{(1)}_{lequ} = (\bar{L}^\alpha \ell)\epsilon_{\alpha\beta}(\bar{Q}^\beta u)$$

LHC more interesting for vector operators with right-handed quark currents due to weaker constraints from intensity frontier

$$[\bar{q}\gamma_\mu P_R q][\bar{\ell}\gamma_\mu P_{R,L}\ell]$$

cLFV at hadron colliders: quarks

Cai, MS 1510.02486



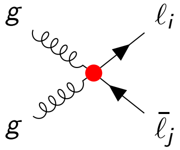
$$\mathcal{Q}_{ledq} = (\bar{L}^{\alpha}\ell)(\bar{d}Q^{\alpha}) \,, \qquad \mathcal{Q}_{lequ}^{(1)} = (\bar{L}^{\alpha}\ell)\epsilon_{\alpha\beta}(\bar{Q}^{\beta}u)$$

LHC more interesting for vector operators with right-handed quark currents due to weaker constraints from intensity frontier

$$[\bar{q}\gamma_{\mu}P_{R}q][\bar{\ell}\gamma_{\mu}P_{R,L}\ell]$$

cLFV at the Large Hadron Collider (LHC): gluons [Cai, MS, Valencia 1802.09822]

Processes at LHC: $pp \to \ell_i \ell_j$



Signal:

opposite-sign different flavour pair of leptons

Most sensitive searches

ATLAS 1607.08079	CMS-PAS-EXO-16-058 1802.01122
13 TeV	13 TeV
3.2 fb^{-1}	35.9 fb^{-1}
$e\mu$, $e\tau$, $\mu\tau$	$e\mu$
inclusive	inclusive

newer ATLAS search: 13 TeV, 36.1 fb^{-1} 1807.06573

EFT scattering amplitudes

$$\mathcal{A}(s) \simeq \frac{s}{\Lambda^2} \xrightarrow{s\to\infty} \infty$$

$\Rightarrow$ Violation of perturbative unitarity

Solutions:

- UV-complete models/simplified models
- apply unitarization procedure, e.g. K-matrix unitarization

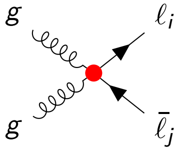
  Wigner 1964; Wigner, Eisenbud 1947; Gupta 1950

  Recent application to monojets: Bell, Busoni, Kobakhidze, Long, MS 1606.02722
- couplings $\to$ form factor

  Baur, Zeppenfeld hep-ph/9309227

$$C \to \frac{C}{1+\frac{\hat{s}}{\Lambda^2}}$$

Processes at LHC: $pp \to \ell_i \ell_j$



Signal:

opposite-sign different flavour pair of leptons

Most sensitive searches

ATLAS 1607.08079	CMS-PAS-EXO-16-058 1802.01122
13 TeV	13 TeV
3.2 fb^{-1}	35.9 fb^{-1}
$e\mu$, $e\tau$, $\mu\tau$	$e\mu$
inclusive	inclusive

newer ATLAS search: 13 TeV, 36.1 fb^{-1} 1807.06573

EFT scattering amplitudes

$$\mathcal{A}(s) \simeq \frac{s}{\Lambda^2} \xrightarrow{s\to\infty} \infty$$

$\Rightarrow$ Violation of perturbative unitarity

Solutions:

- UV-complete models/simplified models
- apply unitarization procedure, e.g. K-matrix unitarization

  Wigner 1964; Wigner, Eisenbud 1947; Gupta 1950

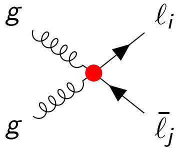
  Recent application to monojets: Bell, Busoni, Kobakhidze, Long, MS 1606.02722
- couplings $\to$ form factor

  Baur, Zeppenfeld hep-ph/9309227

$$C \to \frac{C}{1+\frac{\hat{s}}{\Lambda^2}}$$

cLFV at the Large Hadron Collider (LHC): gluons [Cai, MS, Valencia 1802.09822]

Processes at LHC: $pp \to \ell_i \ell_j$



Signal:
opposite-sign different flavour pair of leptons

Most sensitive searches

ATLAS 1607.08079	CMS-PAS-EXO-16-058 1802.01122
13 TeV	13 TeV
3.2 fb^{-1}	35.9 fb^{-1}
$e\mu$, $e\tau$, $\mu\tau$	$e\mu$
inclusive	inclusive

newer ATLAS search: 13 TeV, 36.1 fb^{-1} 1807.06573

EFT scattering amplitudes

$$\mathcal{A}(s) \simeq \frac{s}{\Lambda^2} \xrightarrow{s\to\infty} \infty$$

$\Rightarrow$ Violation of perturbative unitarity

Solutions:

- UV-complete models/simplified models
- apply unitarization procedure, e.g.
  K-matrix unitarization

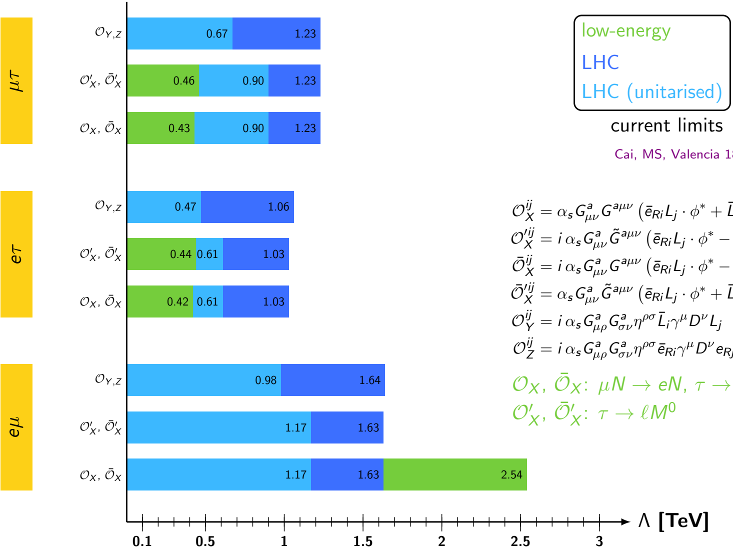
  Wigner 1964; Wigner, Eisenbud 1947; Gupta 1950

  Recent application to monojets: Bell, Busoni, Kobakhidze, Long, MS 1606.02722
- couplings $\to$ form factor

  Baur, Zeppenfeld hep-ph/9309227

$$C \to \frac{C}{1+\frac{\hat{s}}{\Lambda^2}}$$

cLFV at hadron colliders: gluons



current limits

Cai, MS, Valencia 1802.09822

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

$\mathcal{O}_X$, $\bar{\mathcal{O}}_X$: $\mu N \to e N$, $\tau \to \ell M^+ M^-$

$\mathcal{O}'_X$, $\bar{\mathcal{O}}'_X$: $\tau \to \ell M^0$

See also Bhattacharya et al 1802.06082 for a related analysis

Future lepton colliders: $e^+e^- \to \ell\ell'$

Bileptons - seven simplified models [Li,MS 1809.07924]

$\Delta L = 0$

complex scalar $H_2 \sim (2, \frac{1}{2})$

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

LH singlet vector $H_1 \sim (1, 0)$

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

LH triplet vector $H_3 \sim (3, 0)$

$$\mathcal{L} = y_3^{ij} \bar{L}_i \gamma^\mu \vec{\sigma} \cdot H_{3\mu} P_L L_j$$

right-handed vector $H_1' \sim (1, 0)$

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

$\Delta L = 2$

right-handed scalar $\Delta_1 \sim (1, 2)$

$$\mathcal{L} = \lambda_1^{ij} \Delta_1 \ell_i^T C P_R \ell_j + h.c.$$

left-handed scalar $\Delta_3 \sim (3, 1)$

$$\mathcal{L} = -\frac{\lambda_3^{ij}}{\sqrt{2}} L_i^T C i\sigma_2 \vec{\sigma} \cdot \vec{\Delta}_3 P_L L_j + h.c.$$

vector $\Delta_2 \sim (2, \frac{3}{2})$

$$\mathcal{L} = \lambda_2^{ij} \Delta_{2\mu\alpha} L_{i\beta}^T \gamma^\mu P_R \ell_j \epsilon_{\alpha\beta} + h.c.$$

assumption: CP conservation,
symmetric Yukawa couplings (H_2, Δ_2)

related work: Dev, Mohapatra, Zhang 1711.08430, also 1712.03642, 1803.11167

Bileptons - seven simplified models [Li,MS 1809.07924]

$\Delta L = 0$

complex scalar $H_2 \sim (2, \frac{1}{2})$

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

LH singlet vector $H_1 \sim (1, 0)$

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

LH triplet vector $H_3 \sim (3, 0)$

$$\mathcal{L} = y_3^{ij} \bar{L}_i \gamma^\mu \vec{\sigma} \cdot H_{3\mu} P_L L_j$$

right-handed vector $H_1' \sim (1, 0)$

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

$\Delta L = 2$

right-handed scalar $\Delta_1 \sim (1, 2)$

$$\mathcal{L} = \lambda_1^{ij} \Delta_1 \ell_i^T C P_R \ell_j + h.c.$$

left-handed scalar $\Delta_3 \sim (3, 1)$

$$\mathcal{L} = -\frac{\lambda_3^{ij}}{\sqrt{2}} L_i^T C i \sigma_2 \vec{\sigma} \cdot \vec{\Delta}_3 P_L L_j + h.c.$$

vector $\Delta_2 \sim (2, \frac{3}{2})$

$$\mathcal{L} = \lambda_2^{ij} \Delta_{2\mu\alpha} L_{i\beta}^T \gamma^\mu P_R \ell_j \epsilon_{\alpha\beta} + h.c.$$

assumption: CP conservation,
symmetric Yukawa couplings (H_2, Δ_2)

related work: Dev, Mohapatra, Zhang 1711.08430, also 1712.03642, 1803.11167

Bileptons - seven simplified models [Li,MS 1809.07924]

$\Delta L = 0$

complex scalar $H_2 \sim (2, \frac{1}{2})$

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

LH singlet vector $H_1 \sim (1, 0)$

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

LH triplet vector $H_3 \sim (3, 0)$

$$\mathcal{L} = y_3^{ij} \bar{L}_i \gamma^\mu \vec{\sigma} \cdot H_{3\mu} P_L L_j$$

right-handed vector $H_1' \sim (1, 0)$

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

$\Delta L = 2$

right-handed scalar $\Delta_1 \sim (1, 2)$

$$\mathcal{L} = \lambda_1^{ij} \Delta_1 \ell_i^T C P_R \ell_j + h.c.$$

left-handed scalar $\Delta_3 \sim (3, 1)$

$$\mathcal{L} = -\frac{\lambda_3^{ij}}{\sqrt{2}} L_i^T C i \sigma_2 \vec{\sigma} \cdot \vec{\Delta}_3 P_L L_j + h.c.$$

vector $\Delta_2 \sim (2, \frac{3}{2})$

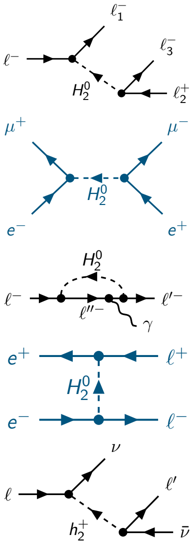
$$\mathcal{L} = \lambda_2^{ij} \Delta_{2\mu\alpha} L_{i\beta}^T \gamma^\mu P_R \ell_j \epsilon_{\alpha\beta} + h.c.$$

assumption: CP conservation,
symmetric Yukawa couplings (H_2, Δ_2)

related work: Dev, Mohapatra, Zhang 1711.08430, also 1712.03642, 1803.11167

Existing (low-energy) precision constraints [Li,MS 1809.07924 1907.06963]

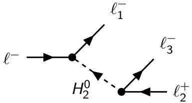
- LFV trilepton decays, $\ell \to \ell_1 \overline{\ell}_2 \overline{\ell}_3$
- Muonium antimuonium conversion, $\mu^+ e^- \to \mu^- e^+$
- anomalous magnetic dipole moments, a_ℓ
- LEP/LHC searches
- lepton flavour non-universality, $\ell \to \ell' \nu \bar{\nu}$
- electroweak precision observables



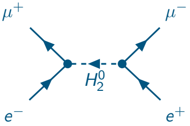
Future sensitivity improvements at e.g. Belle 2, Mu3E, ...

Existing (low-energy) precision constraints [Li,MS 1809.07924 1907.06963]

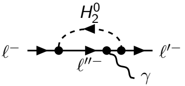
- LFV trilepton decays, $\ell \to \ell_1 \overline{\ell}_2 \overline{\ell}_3$



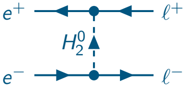
- Muonium antimuonium conversion, $\mu^+ e^- \to \mu^- e^+$



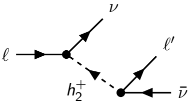
- anomalous magnetic dipole moments, a_ℓ



- LEP/LHC searches



- lepton flavour non-universality, $\ell \to \ell' \nu \bar{\nu}$

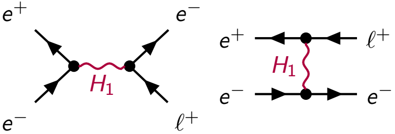


- electroweak precision observables

Future sensitivity improvements at e.g. Belle 2, Mu3E, . . .

Off-shell production $H_{1\mu}$: $e^+e^- \to e^\pm\mu^\mp(e^\pm\tau^\mp)$ [Li,MS 1809.07924]

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



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

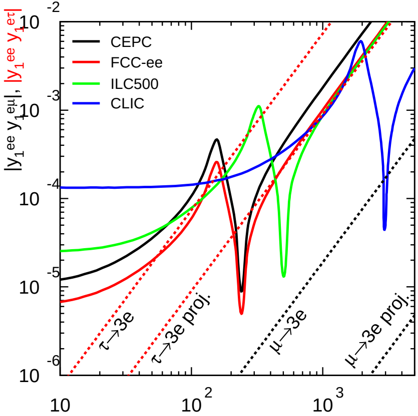
Four collider configurations:

CEPC: 5 ab^{-1} at 240 GeV

FCC-ee: 16 ab^{-1} at 240 GeV

ILC500: 4 ab^{-1} at 500 GeV

CLIC: 5 ab^{-1} at 3 TeV

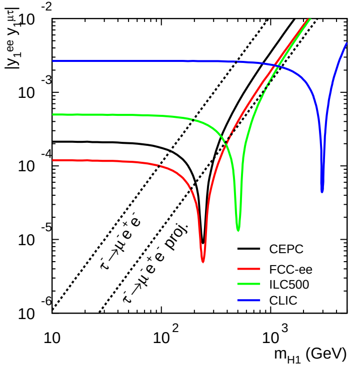


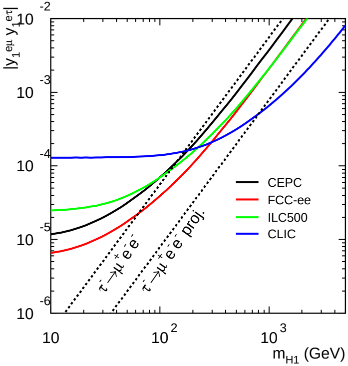
same result for $H'_{1\mu}/H_{3\mu}$

τ efficiency not included in figure

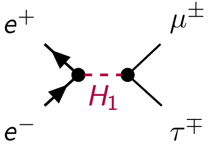
60% τ eff. $\Rightarrow$ 77% sensitivity reduction for 1 τ

$H_{1\mu}$: $e^+e^- \to \mu^\pm\tau^\mp$ [Li,MS 1809.07924]



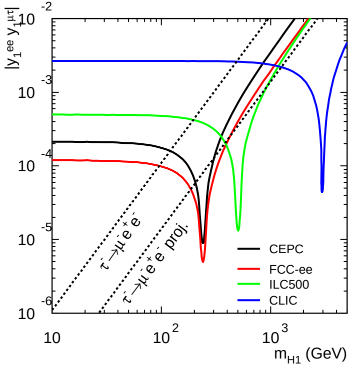


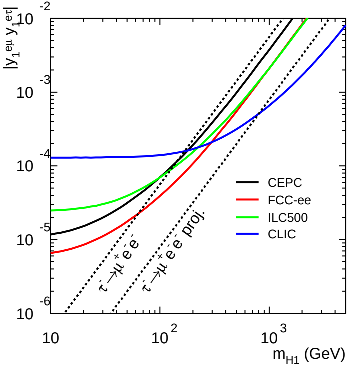
rel. couplings $|y_1^{ee} y_1^{\mu\tau}|$



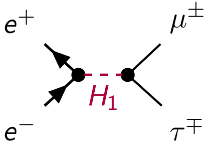
rel. couplings $|y^{e\mu} y^{e\tau}|$

$H_{1\mu}$: $e^+e^- \to \mu^\pm\tau^\mp$ [Li,MS 1809.07924]

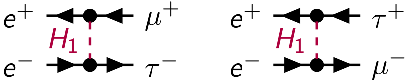


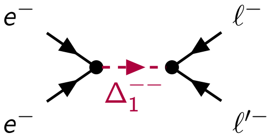


rel. couplings $|y_1^{ee} y_1^{\mu\tau}|$

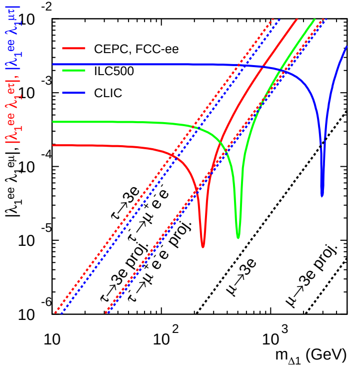


rel. couplings $|y^{e\mu} y^{e\tau}|$





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



same centre of mass energies

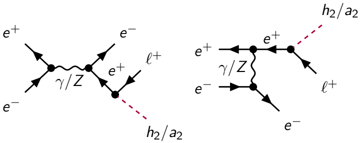
smaller integrated luminosity
$\mathcal{L} = 500\,\mathrm{fb}^{-1}$

Future lepton colliders:

$e^+e^- \to \ell\ell' + X$

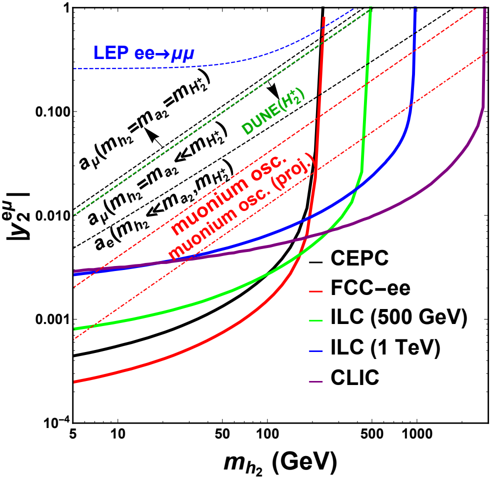
On-shell production H_2: $e^+e^- \to e^\pm\mu^\mp + h_2/a_2$ [Li,MS 1907.06963]

$$\mathcal{L} = y_2^{ij} H_{2\alpha} \bar{L}_i^\alpha P_R \ell_j + h.c.$$



Cuts: $p_T > 10$ GeV and $|\eta| < 2.5$
100% h/a reconstruction efficiency

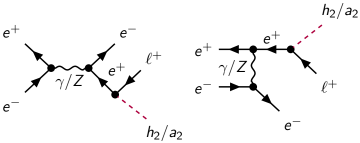
Five collider configurations:
CEPC: 5 ab^{-1} at 240 GeV
FCC-ee: 16 ab^{-1} at 240 GeV
ILC (500 GeV): 4 ab^{-1} at 500 GeV
ILC (1TeV): 1 ab^{-1} at 1 TeV
CLIC: 5 ab^{-1} at 3 TeV



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

On-shell production H_2: $e^+e^- \to e^\pm\mu^\mp + h_2/a_2$ [Li,MS 1907.06963]

$$\mathcal{L} = y_2^{ij} H_{2\alpha} \bar{L}_i^\alpha P_R \ell_j + h.c.$$



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

10% h/a reconstruction efficiency

Five collider configurations:

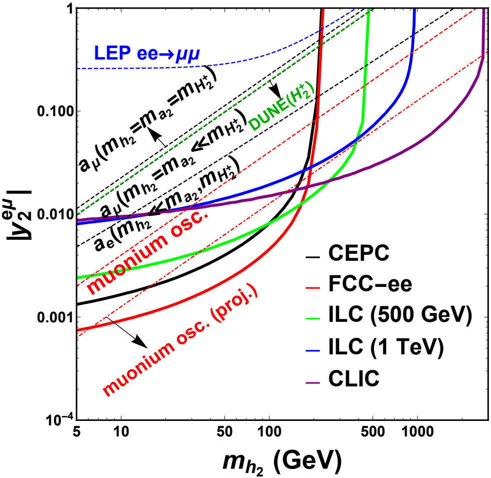
CEPC: 5 ab^{-1} at 240 GeV

FCC-ee: 16 ab^{-1} at 240 GeV

ILC (500 GeV): 4 ab^{-1} at 500 GeV

ILC (1TeV): 1 ab^{-1} at 1 TeV

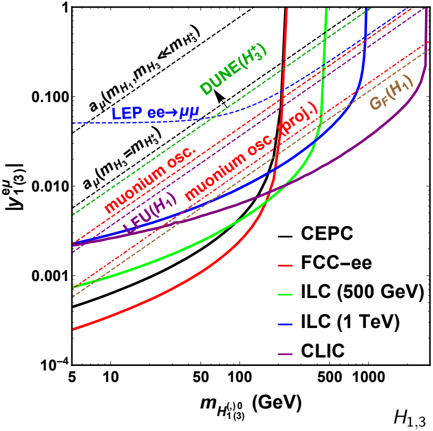
CLIC: 5 ab^{-1} at 3 TeV

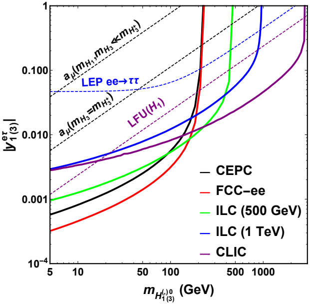


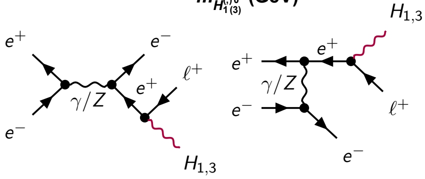
τ efficiency not included in figure

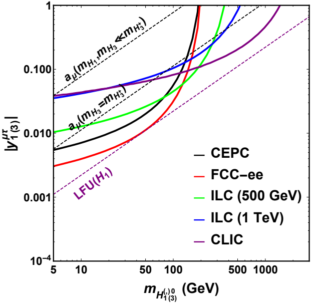
60% τ eff. $\Rightarrow$ 77% sensitivity reduction for 1 τ

On-shell production $H_{1,3\mu}$: $e^+e^- \to \ell^\pm \ell'^\mp + H_{1,3}$ [Li,MS 1907.06963]









$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{L}_i \gamma^\mu P_L L_j + y_3^{ij} \bar{L}_i \gamma^\mu \vec{\sigma} \cdot H_{3\mu} P_L L_j$$

Conclusions

Conclusions

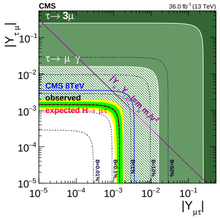
colliders complementary way to search for charged LFV

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

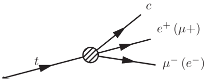
$\tau \leftrightarrow \ell$ flavour complementary sensitivity at colliders

colliders test more Lorentz structures

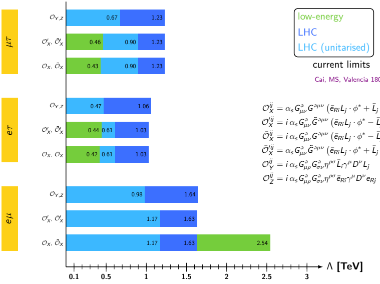
best for operators which are difficult to constrain at low energy



cLFV Higgs decay



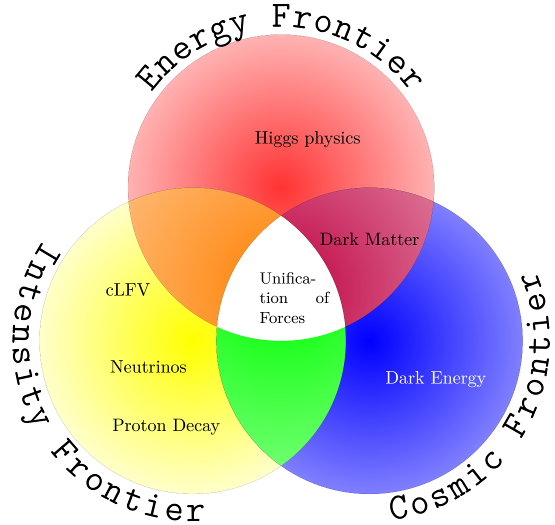
cLFV top decay



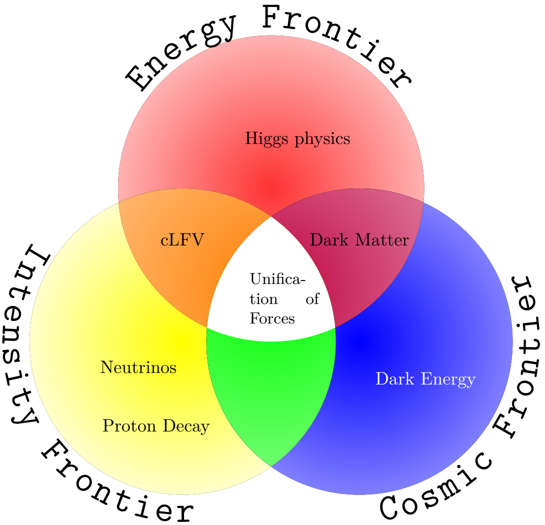
$$\mathcal{O}_X^{ij} = \alpha_s G^a_{\mu\nu} G^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* + \bar{L}_j \cdot \phi e_{Ri}\right)$$
$$\mathcal{O}_X^{\prime ij} = i\, \alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* - \bar{L}_j \cdot \phi e_{Ri}\right)$$
$$\bar{\mathcal{O}}_X^{ij}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

cLFV scattering with initial state gluons

Conclusions cont.



Conclusions cont.



Neutrino masses

Classification in terms of effective $\Delta L = 2$ operators

Babu, Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344 Bonnet, Hernandez, Ota, Winter 0907.3143

$\rightarrow$ no information on $\Delta L = 0$ processes

Systematic construction of models

Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas (in prep)
Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629

Volkas (NuFact 2019): "exploding! $\Delta L = 2$ operators" ..."1000s of models"

$\rightarrow$ too many models!

Hybrid scheme Herrero-Garcia, MS 1903.10552

- SM + one particle with $L \neq 0$ and renormalizable $\Delta L = 0$ op.
- add $\Delta L = 2$ operator with this particle
- neutrino masses in terms of both operators
- L-conserving pheno in terms of $\Delta L = 0$ operator

Neutrino masses

Classification in terms of effective $\Delta L = 2$ operators
Babu, Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344 Bonnet, Hernandez, Ota, Winter 0907.3143

$\rightarrow$ no information on $\Delta L = 0$ processes

Systematic construction of models
Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas (in prep)
Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629

Volkas (NuFact 2019): "exploding! $\Delta L = 2$ operators" ..."1000s of models"

$\rightarrow$ too many models!

Hybrid scheme Herrero-Garcia, MS 1903.10552

- SM + one particle with $L \neq 0$ and renormalizable $\Delta L = 0$ op.
- add $\Delta L = 2$ operator with this particle
- neutrino masses in terms of both operators
- L-conserving pheno in terms of $\Delta L = 0$ operator

Neutrino masses

Classification in terms of effective $\Delta L = 2$ operators
Babu, Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344 Bonnet, Hernandez, Ota, Winter 0907.3143

$\rightarrow$ no information on $\Delta L = 0$ processes

Systematic construction of models
Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas (in prep)
Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629

Volkas (NuFact 2019): "exploding! $\Delta L = 2$ operators" ..."1000s of models"

$\rightarrow$ too many models!

Hybrid scheme **Herrero-Garcia, MS 1903.10552**

- SM + one particle with $L \neq 0$ and renormalizable $\Delta L = 0$ op.
- add $\Delta L = 2$ operator with this particle
- neutrino masses in terms of both operators
- L-conserving pheno in terms of $\Delta L = 0$ operator

TeV Particle Astrophysics 2019

Sydney, 2 - 6 Dec, 2019

Deadlines:

Abstract submission: 23 Sep 2019 ($\rightarrow$ 7 Oct 2019)

Registration: 15 Nov [early bird 18 Oct]

Satellite meetings:

Second Sydney spring school, UNSW, 26-29 Nov 2019

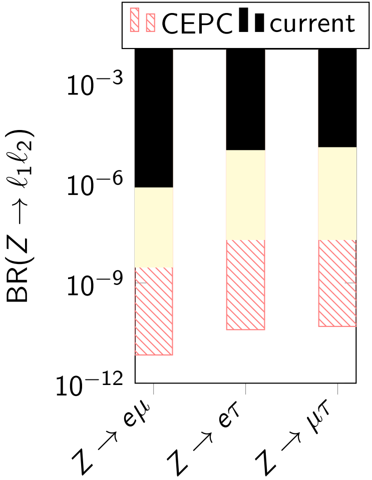
pre-TevPA CTA workshop, University of Adelaide, 28-29 Nov 2019

LOC: **Archil Kobakhidze (USyd)**, Csaba Balazs (Monash), Nicole Bell (UMelb), Celine Boehm (USyd), Roland Crocker (ANU), Paul Jackson (Adelaide), Geraint Lewis (USyd), Tara Murphy (USyd), Gavin Rowell (Adelaide), Martin White (Adelaide), Yvonne Wong (UNSW)

Backup slides

Other searches

Searches for cLFV in decays of Z and Higgs boson

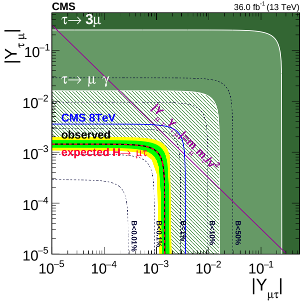


$Z \to e\mu$: ATLAS 1408.5774, CMS EXO-13-005

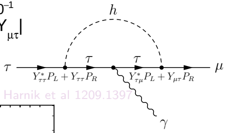
$Z \to \ell\tau$: DELPHI ($\mu\tau$), OPAL ($e\tau$)

ATLAS, 13 TeV, 36.1 fb^{-1} 1804.09568

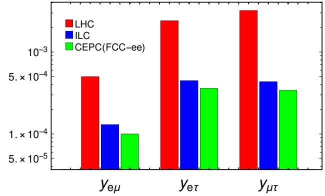
almost same sensitivity for $\mu\tau$



CMS 1712.07173



Harnik et al 1209.1397



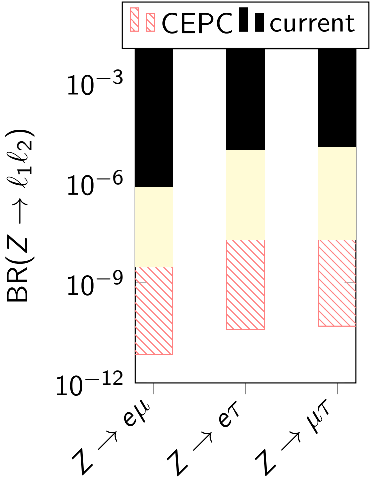
Qin et al 1711.07243

LHC CMS-PAS-HIG-16-005, CMS 1607.03561

ILC $\sqrt{s} = 250$ GeV, 4 polarizations, $\mathcal{L} = 2$ ab^{-1}

CEPC $\sqrt{s} = 240$ GeV, $\mathcal{L} = 5$ ab^{-1}

Searches for cLFV in decays of Z and Higgs boson

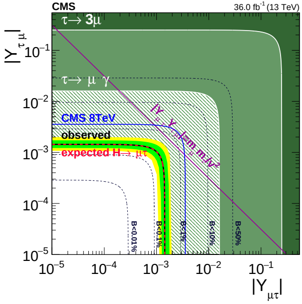


$Z \to e\mu$: ATLAS 1408.5774, CMS EXO-13-005

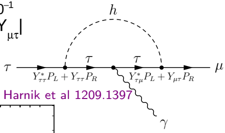
$Z \to \ell\tau$: DELPHI ($\mu\tau$), OPAL ($e\tau$)

ATLAS, 13 TeV, 36.1 fb^{-1} 1804.09568

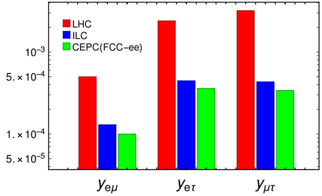
almost same sensitivity for $\mu\tau$



CMS 1712.07173



Harnik et al 1209.1397



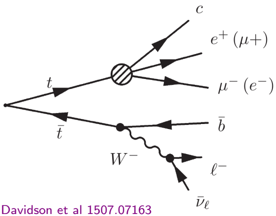
Qin et al 1711.07243

LHC CMS-PAS-HIG-16-005, CMS 1607.03561

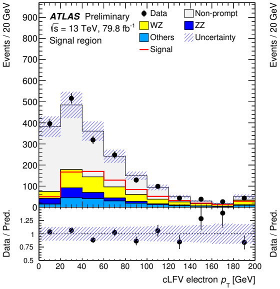
ILC $\sqrt{s} = 250$ GeV, 4 polarizations, $\mathcal{L} = 2$ ab^{-1}

CEPC $\sqrt{s} = 240$ GeV, $\mathcal{L} = 5$ ab^{-1}

Searches for cLFV in decays of top and heavy resonance



Davidson et al 1507.07163



ATLAS-CONF-2018-044

cross section $\sigma \propto \sum_{X,Y} |\epsilon_{XY}|^2$

Main backgrounds:

- $t\bar{t}$ with non-prompt lepton
- $Z+$ jets

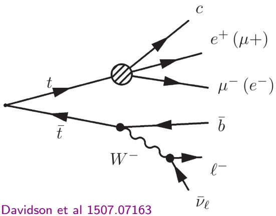
Multi-variate analysis w/ 13 var's using BDT

observed limit

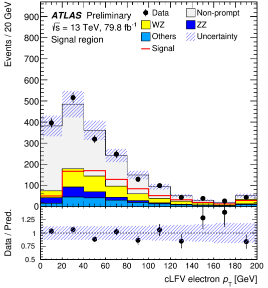
$$BR(t \to \ell\ell'[e\mu]q) < 1.86[6.6] \times 10^{-5}$$

$\to |\epsilon| \lesssim 0.1$, more stringent for $t \to \tau + X$

Searches for cLFV in decays of top and heavy resonance



Davidson et al 1507.07163



ATLAS-CONF-2018-044

cross section $\sigma \propto \sum_{X,Y} |\epsilon_{XY}|^2$

Main backgrounds:

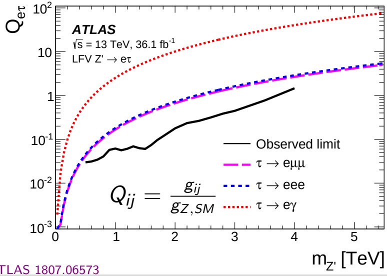
- $t\bar{t}$ with non-prompt lepton
- $Z+$ jets

Multi-variate analysis w/ 13 var's using BDT

observed limit

$$BR(t \to \ell\ell'[e\mu]q) < 1.86[6.6] \times 10^{-5}$$

$\to |\epsilon| \lesssim 0.1$, more stringent for $t \to \tau + X$



$$Q_{ij} = \frac{g_{ij}}{g_{Z,SM}}$$

ATLAS 1807.06573

Scalar Operators

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

Relevant Wilson coefficients $\Xi^{u,d}$ of SM EFT

$$-\mathcal{L} = \Xi^{d}_{ij,kk}\left(\mathcal{Q}_{ledq}\right)_{ij,kk} + \Xi^{u}_{ij,kk}\left(\mathcal{Q}^{(1)}_{lequ}\right)_{ij,kk} + \mathrm{h.c.}\ .$$

Effective four fermion Lagrangian

$$\begin{aligned}\mathcal{L}_{4f} &= \Xi^{Cd}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Rk}u_{Ll}) + \Xi^{Nd}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{d}_{Rk}d_{Ll}) \\ &\quad + \Xi^{Cu}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Lk}u_{Rl}) + \Xi^{Nu}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{u}_{Lk}u_{Rl})\ .\end{aligned}$$

We do not consider top quark because of different phenomenology.

Scalar Operators

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

Relevant Wilson coefficients $\Xi^{u,d}$ of SM EFT

$$-\mathcal{L} = \Xi^d_{ij,kk}\left(\mathcal{Q}_{ledq}\right)_{ij,kk} + \Xi^u_{ij,kk}\left(\mathcal{Q}^{(1)}_{lequ}\right)_{ij,kk} + \mathrm{h.c.}\ .$$

Effective four fermion Lagrangian

$$\begin{aligned}\mathcal{L}_{4f} = {} & \Xi^{Cd}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Rk} u_{Ll}) + \Xi^{Nd}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{d}_{Rk} d_{Ll}) \\ & + \Xi^{Cu}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Lk} u_{Rl}) + \Xi^{Nu}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{u}_{Lk} u_{Rl})\ .\end{aligned}$$

Thus the most general four fermion coefficients are

$$\begin{aligned}\Xi^{Nd}_{ij,kl} &= U^{\ell *}_{ii'}\, V^d_{lk}\, \Xi^d_{ij,kk} & \qquad \Xi^{Cd}_{ij,kl} &= U^{\nu *}_{ii'}\, V^u_{lk}\, \Xi^d_{i'j,kk} \\ \Xi^{Nu}_{ij,kl} &= -U^{\ell *}_{ii'}\, V^{u*}_{kl}\, \Xi^u_{ij,ll} & \qquad \Xi^{Cu}_{ij,kl} &= U^{\nu *}_{ii'}\, V^{d*}_{kl}\, \Xi^u_{i'j,ll}\end{aligned}$$

In general there is quark flavour violation.

We do not consider top quark because of different phenomenology.

Scalar Operators

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

Relevant Wilson coefficients $\Xi^{u,d}$ of SM EFT

$$-\mathcal{L} = \Xi^d_{ij,kk} \left(\mathcal{Q}_{ledq}\right)_{ij,kk} + \Xi^u_{ij,kk} \left(\mathcal{Q}^{(1)}_{lequ}\right)_{ij,kk} + \text{h.c.}\ .$$

Effective four fermion Lagrangian

$$\begin{aligned}\mathcal{L}_{4f} = {} & \Xi^{Cd}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Rk} u_{Ll}) + \Xi^{Nd}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{d}_{Rk} d_{Ll}) \\ & + \Xi^{Cu}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Lk} u_{Rl}) + \Xi^{Nu}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{u}_{Lk} u_{Rl})\ .\end{aligned}$$

Choose basis in which charged lepton mass matrix is diagonal as well as $\Xi^{N?}_{ij,kk}$

$$\begin{aligned}\Xi^{Nd}_{ij,kl} &= \delta_{kl}\Xi^d_{ij,kk} & \qquad \Xi^{Cd}_{ij,kl} &= U^*_{ii'} V^*_{kl} \Xi^d_{i'j,kk} \\ \Xi^{Nu}_{ij,kl} &= -\delta_{kl}\Xi^u_{ij,kk} & \qquad \Xi^{Cu}_{ij,kl} &= U^*_{ii'} V^*_{kl} \Xi^u_{i'j,ll}\end{aligned}$$

$\Rightarrow$ No tree-level FCNC processes.

We do not consider top quark because of different phenomenology.

Scalar Operators

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

Relevant Wilson coefficients $\Xi^{u,d}$ of SM EFT

$$-\mathcal{L} = \Xi^d_{ij,kk}\left(\mathcal{Q}_{ledq}\right)_{ij,kk} + \Xi^u_{ij,kk}\left(\mathcal{Q}^{(1)}_{lequ}\right)_{ij,kk} + \mathrm{h.c.}\ .$$

Effective four fermion Lagrangian

$$\begin{aligned}\mathcal{L}_{4f} = {} & \Xi^{Cd}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Rk}u_{Ll}) + \Xi^{Nd}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{d}_{Rk}d_{Ll}) \\ & + \Xi^{Cu}_{ij,kl}(\bar{\nu}_{Li}\ell_{Rj})(\bar{d}_{Lk}u_{Rl}) + \Xi^{Nu}_{ij,kl}(\bar{\ell}_{Li}\ell_{Rj})(\bar{u}_{Lk}u_{Rl})\ .\end{aligned}$$

Choose basis in which charged lepton mass matrix is diagonal as well as $\Xi^{N?}_{ij,kk}$

$$\Xi^{Nd}_{ij,kl} = \delta_{kl}\Xi^d_{ij,kk} \qquad \Xi^{Cd}_{ij,kl} = U^*_{ii'}V^*_{kl}\Xi^d_{i'j,kk}$$

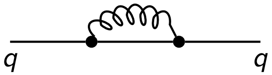
$$\Xi^{Nu}_{ij,kl} = -\delta_{kl}\Xi^u_{ij,kk} \qquad \Xi^{Cu}_{ij,kl} = U^*_{ii'}V^*_{kl}\Xi^u_{i'j,ll}$$

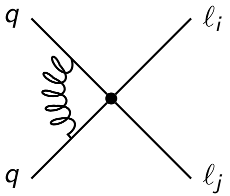
$\Rightarrow$ No tree-level FCNC processes.

We do not consider top quark because of different phenomenology.

Renormalization Group Corrections

- Main effect are QCD corrections





- Following the standard discussion at NLO

Buchalla,Buras, Lautenbacher hep-ph/9512380

$$\Xi(\mu) = \Xi(\mu_0) \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right)^{\frac{\gamma_0}{2\beta_0}}$$

with coefficients

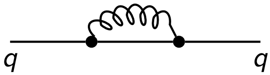
$$\beta_0 = 11 - 2n_F/3 \quad \text{and} \quad \gamma_0 = 6C_2(3) = 8$$

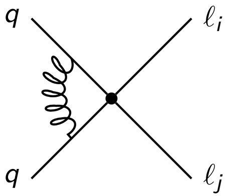
- Wilson coefficients become larger at smaller scales.

$\Rightarrow$ Increases reach of precision experiments

Renormalization Group Corrections

- Main effect are QCD corrections





- Following the standard discussion at NLO

Buchalla,Buras, Lautenbacher hep-ph/9512380

$$\Xi(\mu) = \Xi(\mu_0) \left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right)^{\frac{\gamma_0}{2\beta_0}}$$

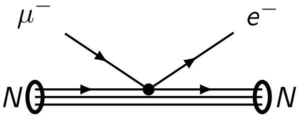
with coefficients

$$\beta_0 = 11 - 2n_F/3 \quad \text{and} \quad \gamma_0 = 6C_2(3) = 8$$

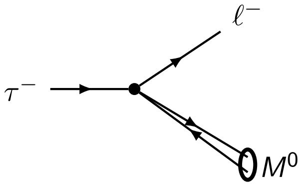
- Wilson coefficients become larger at smaller scales.

$\Rightarrow$ Increases reach of precision experiments

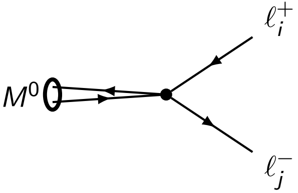
Precision Experiments



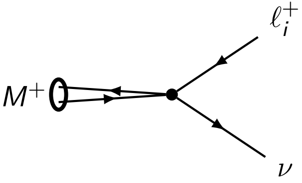
$\mu - e$ conversion in nuclei



$\tau \to \ell M^0$



$M^0 \to \ell_i^+ \ell_j^-$

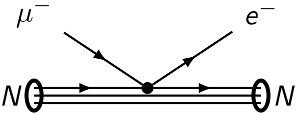


$M^+ \to \ell_i^+ \nu$

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in

Gonzalez, Gutsche, Helo, Kovalenko, Lyubovitskij, Schmidt 1303.0596



Dimensionless $\mu - e$ conversion rate

$$R_{\mu e}^{(A,Z)} \equiv \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

with muon conversion rate

$$\Gamma(\mu^- + (A,Z) \to e^- + (A,Z)) = \left|\Xi_{ij,kl}^{Nu,Nd}\right|^2 \times \mathcal{F} \times \frac{p_e E_e \left(\mathcal{M}_p + \mathcal{M}_n\right)^2}{2\pi}$$

$\mathcal{F}$ depends on mediation mechanism

No dependence on phase of Ξ if there is only one operator.

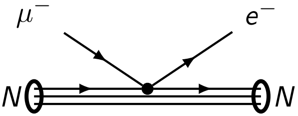
Strongest limit for first generation quarks,

but non-negligible for other quarks if pure direct nuclear mediation

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in

Gonzalez, Gutsche, Helo, Kovalenko, Lyubovitskij, Schmidt 1303.0596



	^{48}Ti	^{197}Au	^{208}Pb
$R_{\mu e}^{\max}$	4.3×10^{-11}	7.0×10^{-13}	4.6×10^{-11}
$\bar{u}u$	1100 [870]	2100 [1700]	760 [610]
$\bar{d}d$	1100 [930]	2200 [1900]	780 [680]
$\bar{s}s$	480 [-]	950 [-]	340 [-]
$\bar{c}c$	150 [-]	290 [-]	110 [-]
$\bar{b}b$	84 [-]	170 [-]	61 [-]

Direct nuclear mediation [Meson mediation]

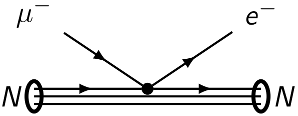
Strongest limit for first generation quarks,

but non-negligible for other quarks if pure direct nuclear mediation

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in

Gonzalez, Gutsche, Helo, Kovalenko, Lyubovitskij, Schmidt 1303.0596



	^{48}Ti	^{197}Au	^{208}Pb
$R_{\mu e}^{\max}$	4.3×10^{-11}	7.0×10^{-13}	4.6×10^{-11}
$\bar{u}u$	1100 [870]	2100 [1700]	760 [610]
$\bar{d}d$	1100 [930]	2200 [1900]	780 [680]
$\bar{s}s$	480 [-]	950 [-]	340 [-]
$\bar{c}c$	150 [-]	290 [-]	110 [-]
$\bar{b}b$	84 [-]	170 [-]	61 [-]

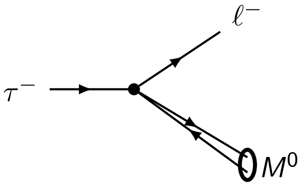
Direct nuclear mediation [Meson mediation]

Strongest limit for first generation quarks,

but non-negligible for other quarks if pure direct nuclear mediation

LFV Semileptonic τ Decays

- Only light quarks u,d,s
- Weak dependence on phase
- f_0: φ_m parameterises quark content
- Quark FCNC parameterised by λ



$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

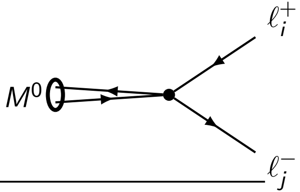
decay	$\mathrm{Br}_i^{\mathrm{max}}$	cutoff scale Λ [TeV]		
		$\Xi^u_{ij,uu}$	$\Xi^d_{ij,dd}$	$\Xi^d_{ij,ss}$
$\tau^- \to e^- \pi^0$	8.0×10^{-8}	10	10	-
$\tau^- \to e^- \eta$	9.2×10^{-8}	34	34	7.9
$\tau^- \to e^- \eta'$	1.6×10^{-7}	42	42	12
$\tau^- \to e^- K^0_S$	2.6×10^{-8}	-	$7.8\sqrt{\lambda}$	$7.8\sqrt{\lambda}$
$\tau^- \to e^- (f_0(980) \to \pi^+\pi^-)$	3.2×10^{-8}	$13\sqrt{\sin\varphi_m}$	$13\sqrt{\sin\varphi_m}$	$16\sqrt{\cos\varphi_m}$
$\tau^- \to \mu^- \pi^0$	1.1×10^{-7}	$9.0 - 9.6$	$9.0 - 9.6$	-
$\tau^- \to \mu^- \eta$	6.5×10^{-8}	$36 - 38$	$36 - 38$	$8.4 - 8.9$
$\tau^- \to \mu^- \eta'$	1.3×10^{-7}	$42 - 46$	$42 - 46$	$12 - 13$
$\tau^- \to \mu^- K^0_S$	2.3×10^{-8}	-	$(7.8 - 8.3)\sqrt{\lambda}$	$(7.8 - 8.3)\sqrt{\lambda}$
$\tau^- \to \mu^- (f_0(980) \to \pi^+\pi^-)$	3.4×10^{-8}	$(12 - 14)\sqrt{\sin\varphi_m}$	$(12 - 14)\sqrt{\sin\varphi_m}$	$(15 - 16)\sqrt{\cos\varphi_m}$

Leptonic Neutral Meson Decays $M^0 \to \ell_i^+ \ell_j^-$

Quark FCNC parameterised by λ

$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

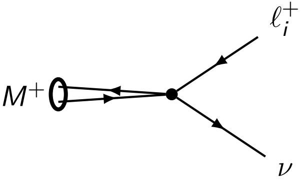
For $\lambda = 0$ only constraints from $\pi^0, \eta^{(\prime)}$ decays



decay	$\mathrm{Br}_i^{\max}$	cutoff scale Λ [TeV]				
		$\Xi^u_{ij,uu}$	$\Xi^d_{ij,dd}$	$\Xi^d_{ij,ss}$	$\Xi^u_{ij,cc}$	$\Xi^d_{ij,bb}$
$\pi^0 \to \mu^+ e^-$	3.8×10^{-10}	2.2	2.2	-	-	-
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	1.2	1.2	-	-	-
$\pi^0 \to \mu^+ e^- + \mu^- e^+$	3.6×10^{-10}	2.6	2.6	-	-	-
$\eta \to \mu^+ e^- + \mu^- e^+$	6×10^{-6}	0.52	0.52	0.12	-	-
$\eta' \to e\mu$	4.7×10^{-4}	0.091	0.091	0.026	-	-
$K_L^0 \to e^\pm \mu^\mp$	4.7×10^{-12}	-	$86\sqrt{\lambda}$	$86\sqrt{\lambda}$	-	-
$D^0 \to e^\pm \mu^\mp$	2.6×10^{-7}	$6.4\sqrt{\lambda}$	-	-	$6.4\sqrt{\lambda}$	-
$B^0 \to e^\pm \mu^\mp$	2.8×10^{-9}	-	$10\sqrt{\lambda}$	-	-	$6.6\sqrt{\lambda}$
$B^0 \to e^\pm \tau^\mp$	2.8×10^{-5}	-	$0.97\sqrt{\lambda}$	-	-	$0.62\sqrt{\lambda}$
$B^0 \to \mu^\pm \tau^\mp$	2.2×10^{-2}	-	$0.18\sqrt{\lambda}$	-	-	$0.12\sqrt{\lambda}$

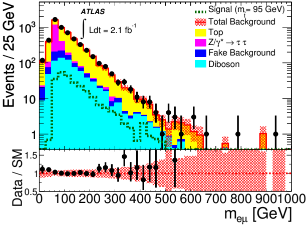
Leptonic Charged Meson Decays $M^+ \to \ell_i^+ \nu$

- $R_M = \frac{\mathrm{Br}(M^+ \to e^+ \nu)}{\mathrm{Br}(M^+ \to \mu^+ \nu)}$
- Theoretical error for R_π (R_K) about 5%
- Improvement by factor 20 (2) possible
- **✓** indicates constraints
- Second index of Λ corresponds to charged lepton

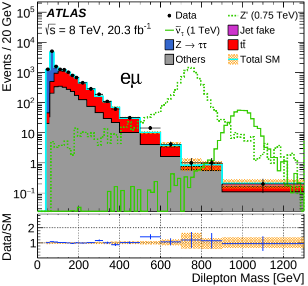


decay	constraint	cutoff scale Λ [TeV]		Wilson coefficients				
		$\Lambda_{\mu e, e\mu, e\tau}$	$\Lambda_{\tau e, \tau\mu, \mu\tau}$	$\Xi^u_{ij,uu}$	$\Xi^d_{ij,dd}$	$\Xi^d_{ij,ss}$	$\Xi^u_{ij,cc}$	$\Xi^d_{ij,bb}$
R_π	$R_\pi^{exp} \pm 5\%$	$25 - 280$	$25 - 260$	**✓**	**✓**	-	-	-
R_K	$R_K^{exp} \pm 5\%$	$24 - 160$	$24 - 150$	✓	-	**✓**	-	-
$\mathrm{Br}(D^+ \to e^+ \nu)$	$< 8.8 \times 10^{-6}$	$2.8 - 2.9$	2.9	-	✓	-	✓	-
$\mathrm{Br}(D_s^+ \to e^+ \nu)$	$< 8.3 \times 10^{-5}$	$3.2 - 3.3$	$3.2 - 3.3$	-	-	✓	**✓**	-
$\mathrm{Br}(B^+ \to e^+ \nu)$	$< 9.8 \times 10^{-7}$	2.0	2.0	✓	-	-	-	**✓**
$\mathrm{Br}(\pi^+ \to \mu^+ \nu)$	$\mathrm{Br}^{exp} \pm 5\%$	$1.9 - 7.4$	$1.9 - 9.4$	**✓**	**✓**	-	-	-
$\mathrm{Br}(K^+ \to \mu^+ \nu)$	$\mathrm{Br}^{exp} \pm 5\%$	$1.7 - 5.8$	$1.7 - 7.4$	✓	-	**✓**	-	-
$\mathrm{Br}(D^+ \to \mu^+ \nu)$	$(3.82 \pm 0.33) \times 10^{-4}$	$1.1 - 2.7$	$1.1 - 3.4$	-	✓	-	✓	-
$\mathrm{Br}(D_s^+ \to \mu^+ \nu)$	$(5.56 \pm 0.25) \times 10^{-3}$	$1.3 - 4.3$	$1.3 - 5.3$	-	-	✓	**✓**	-
$\mathrm{Br}(B^+ \to \mu^+ \nu)$	$< 1.0 \times 10^{-6}$	$1.9 - 2.7$	$1.7 - 3.0$	✓	-	-	-	**✓**
$\mathrm{Br}(D^+ \to \tau^+ \nu)$	$< 1.2 \times 10^{-3}$	$0.21 - 0.78$	$0.23 - 0.73$	-	**✓**	-	✓	-
$\mathrm{Br}(D_s^+ \to \tau^+ \nu)$	$(5.54 \pm 0.24) \times 10^{-2}$	$0.33 - 1.2$	$0.33 - 1.1$	-	-	**✓**	**✓**	-
$\mathrm{Br}(B^+ \to \tau^+ \nu)$	$(1.14 \pm 0.27) \times 10^{-4}$	$0.49 - 1.3$	$0.49 - 1.2$	**✓**	-	-	-	**✓**

SM Background



ATLAS 7TeV 1205.0725



ATLAS 8TeV 1503.04430

- Main backgrounds: $t\bar{t}$, WW, $Z/\gamma^* \to \tau\tau$

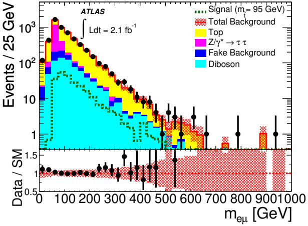
  also W/Z plus jets, WZ/ZZ, single top and $W/Z + \gamma$

$\Rightarrow$ Efficiently reduced in exclusive 7 TeV analysis by rejecting jets and $E_T^{miss} < 20$ GeV

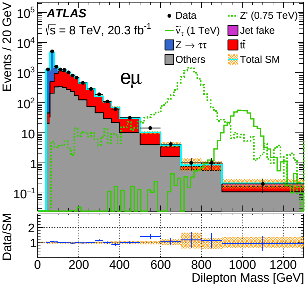
- Modelling of main background agrees with ATLAS
- Fake background estimated from data

$\Rightarrow$ Use background from ATLAS publications

SM Background



ATLAS 7TeV 1205.0725



ATLAS 8TeV 1503.04430

- Main backgrounds: $t\bar{t}$, WW, $Z/\gamma^* \to \tau\tau$

  also W/Z plus jets, WZ/ZZ, single top and $W/Z + \gamma$

$\Rightarrow$ Efficiently reduced in exclusive 7 TeV analysis by rejecting jets and $E_T^{miss} < 20$ GeV

- Modelling of main background agrees with ATLAS
- Fake background estimated from data

$\Rightarrow$ Use background from ATLAS publications

Selection Criteria

Same selection criteria as in ATLAS 7 and 8 TeV analyses.

- oppositely charged leptons
- Electrons: $E_T > 25$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$, tight identification criteria
- Muons: $p_T > 25$ GeV, $|\eta| < 2.4$
- Tau: $E_T > 25$ GeV, $0.03 < |\eta| < 2.47$
- Lepton isolation: scalar sum of lepton p_T within cone of $\Delta R = 0.2(0.4)$ is less than 10% (6%) of lepton p_T for 7 (8) TeV search
- Jets reconstructed anti-k_T algorithm with radius parameter 0.4
- 7 TeV analysis: jets rejected if $p_T > 30$ GeV or $E_T^{miss} < 25$ GeV
- Invariant mass of lepton pair: $> 100(200)$ GeV in 7(8) TeV analysis
- azimuthal angle difference $\Delta\phi > 3(2.7)$ in 7 (8) TeV analysis

14 TeV projection

Same as 7 TeV exclusive analysis and $p_T(\ell) > 300$ GeV and $E_T^{miss} < 20$ GeV

Limits from LHC on Cutoff Scale in TeV

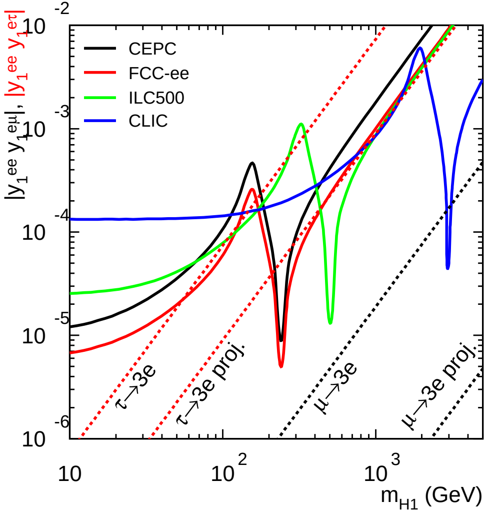
$\bar{q}q$ \ $\bar{\ell}_i\ell_j$	$\bar{e}\mu$			$\bar{e}\tau$	$\bar{\mu}\tau$
	7 TeV	8 TeV	14 TeV	8 TeV	8 TeV
$\bar{u}u$	2.6	2.9	8.9	2.4	2.2
$\bar{d}d$	2.3	2.3	8.0	2.1	1.9
$\bar{s}s$	1.1	1.4	4.0	0.95	0.88
$\bar{c}c$	0.97	1.3	3.6	0.82	0.78
$\bar{b}b$	0.74	1.0	2.7	0.63	0.61

- 8 TeV analysis gives only a slight improvement compared to 7 TeV despite 10 times more data because of large background
- $e\tau$ and $\mu\tau$ limits weaker than $e\mu$ because of low τ-tagging rate and higher fake background
- 14 TeV projection: same search strategy as 7 TeV exclusive search

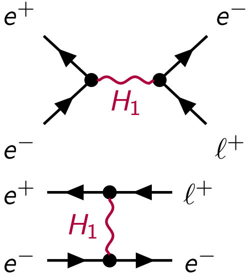
cLFV D8 operator with 2 gluons and 2 leptons

process	exp. limit	operator	Λ [TeV]
	$e\mu$		
Br($\mu^- \, {}^{48}_{22}\mathrm{Ti} \to e^- \, {}^{48}_{22}\mathrm{Ti}$)	$< 4.3 \times 10^{-12}$	$\mathcal{O}_X$, $\bar{\mathcal{O}}_X$	2.11
Br($\mu^- \, {}^{197}_{79}\mathrm{Au} \to e^- \, {}^{197}_{79}\mathrm{Au}$)	$< 7 \times 10^{-13}$	$\mathcal{O}_X$, $\bar{\mathcal{O}}_X$	2.54
	$e\tau$		
Br($\tau^+ \to e^+\pi^+\pi^-$)	$< 2.3 \times 10^{-8}$	$\mathcal{O}_X$, $\bar{\mathcal{O}}_X$	0.42
Br($\tau^- \to e^- K^+ K^-$)	$< 3.4 \times 10^{-8}$	$\mathcal{O}_X$, $\bar{\mathcal{O}}_X$	0.37
Br($\tau^- \to e^-\eta$)	$< 9.2 \times 10^{-8}$	$\mathcal{O}'_X$, $\bar{\mathcal{O}}'_X$	0.40
Br($\tau^- \to e^-\eta'$)	$< 1.6 \times 10^{-7}$	$\mathcal{O}'_X$, $\bar{\mathcal{O}}'_X$	0.44
	$\mu\tau$		
Br($\tau^- \to \mu^-\pi^+\pi^-$)	$< 2.1 \times 10^{-8}$	$\mathcal{O}_X$, $\bar{\mathcal{O}}_X$	0.43
Br($\tau^- \to \mu^- K^+ K^-$)	$< 4.4 \times 10^{-8}$	$\mathcal{O}_X$, $\bar{\mathcal{O}}_X$	0.36
Br($\tau^- \to \mu^-\eta$)	$< 6.5 \times 10^{-8}$	$\mathcal{O}'_X$, $\bar{\mathcal{O}}'_X$	0.42
Br($\tau^- \to \mu^-\eta'$)	$< 1.3 \times 10^{-7}$	$\mathcal{O}'_X$, $\bar{\mathcal{O}}'_X$	0.46

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



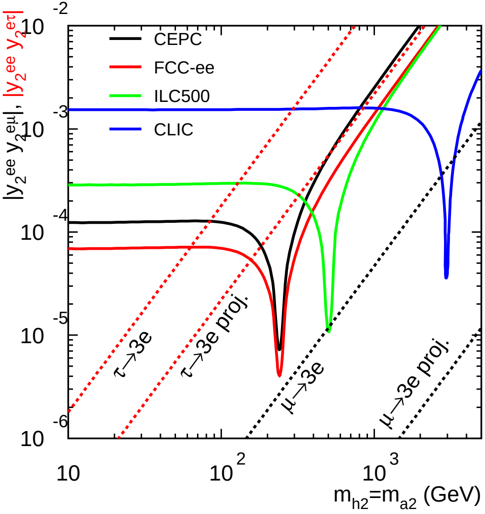
$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{\ell}_i \gamma^\mu P_L \ell_j$$



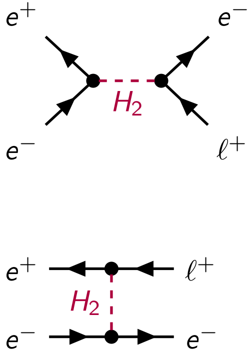
same result for right-handed $H'_{1\mu}$

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

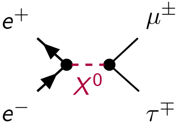
H_2: $e^+e^- \to e^\pm\mu^\mp(e^\pm\tau^\mp)$



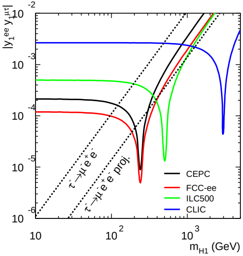
$$\mathcal{L} = y_2^{ij} H_2^0 \bar{\ell}_i P_R \ell_j + h.c.$$

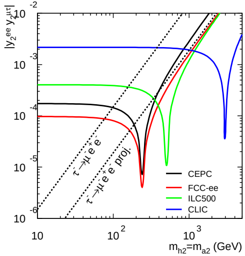


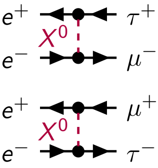
$H_{1\mu}, H_2$: $e^+e^- \to \mu^\pm\tau^\mp$



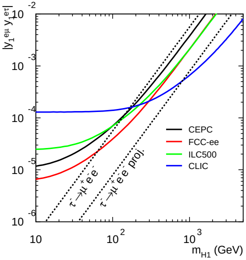
rel. couplings
$|y^{ee}y^{\mu\tau}|$

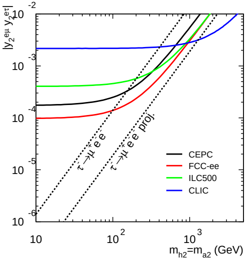




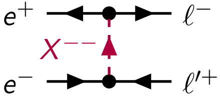


rel. couplings
$|y^{e\mu}y^{e\tau}|$



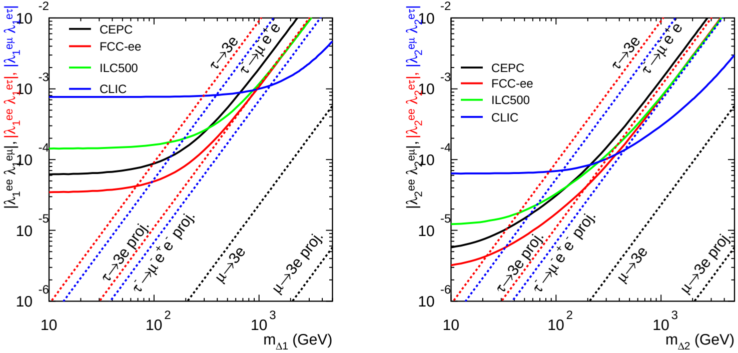


Δ_1, $\Delta_{2\mu}$: $e^+e^- \to \ell^+\ell'^-$

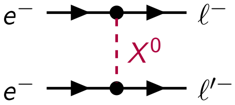


relevant couplings

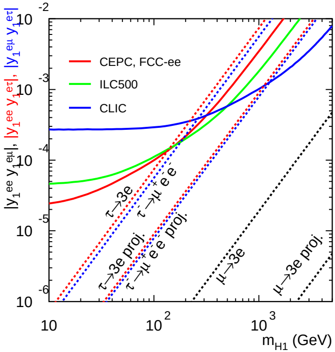
$|\lambda^{ee}\lambda^{e\ell}|$ and $|\lambda^{e\mu}\lambda^{e\tau}|$

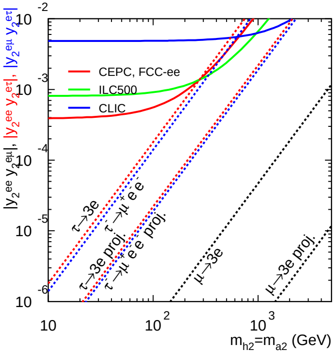


$H_{1\mu}$, H_2: $e^- e^- \to \ell^- \ell'^-$

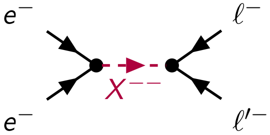


relevant couplings
$|y^{ee} y^{e\ell}|$ and $|y^{e\mu} y^{e\tau}|$





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



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