Searches for cLFV at Current and Future Colliders

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UNSW
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Motivation

The Standard Model is very successful. . .

. . . but incomplete

In particular neutrinos are massive

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

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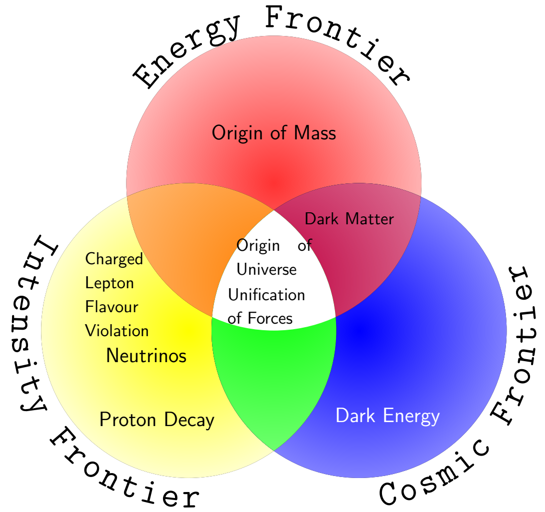

Can high-energy colliders compete with the intensity frontier?

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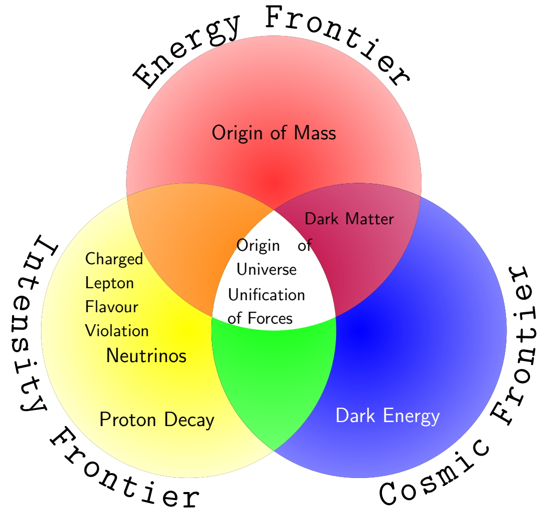


Can high-energy colliders compete with the intensity frontier?

Overview

Z boson decays

Higgs boson decay

Top-quark decay

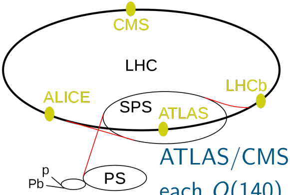
Heavy resonance decay

Scattering at the LHC

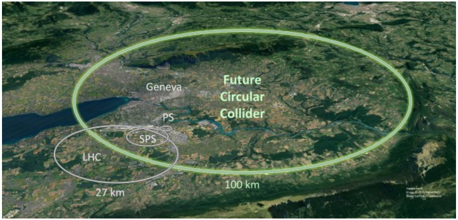
Scattering at future lepton colliders

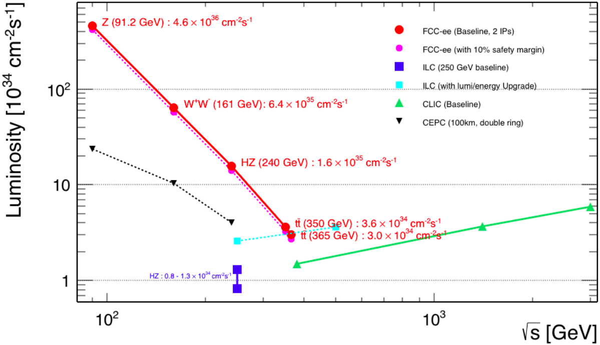
Conclusions

Colliders



ATLAS/CMS
each $O(140)$ fb^{-1}





Ellis 1810.11263

e.g. CEPC quotes

CEPC 1811.10545

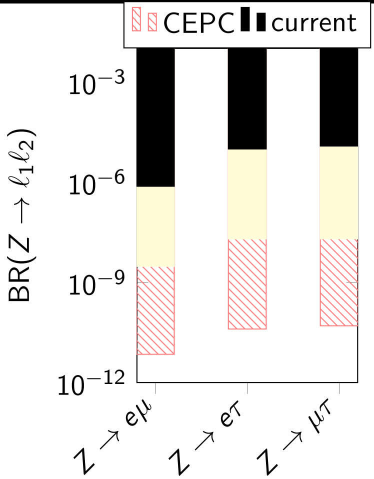
10^6 Higgs bosons

10^{12} Z bosons

LEP: $O(10^7) Z$ bosons

Z boson decays

cLFV Z boson decays



No tree-level FCNC in SM

induced at 1 loop in SM $+m_\nu$

$\propto \frac{G_F m_\nu^2}{16\pi^2} \simeq 10^{-28}$

Observation clear sign of new physics

e.g. due to a leptoquark

today typically less stringent as low-energy precision experiments

but will be more interesting with new Z boson factory

or if there is a signal to disentangle physics

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

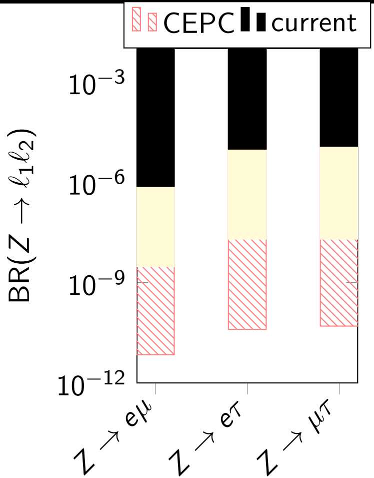
$Z \to \ell\tau$: DELPHI ($\mu\tau$), OPAL ($e\tau$)

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

almost same sensitivity for $\mu\tau$

See also poster on $Z \to \tau\ell$ at ATLAS by Ann-Kathrin Perrevoort

cLFV Z boson decays



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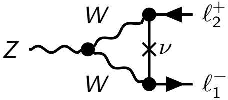

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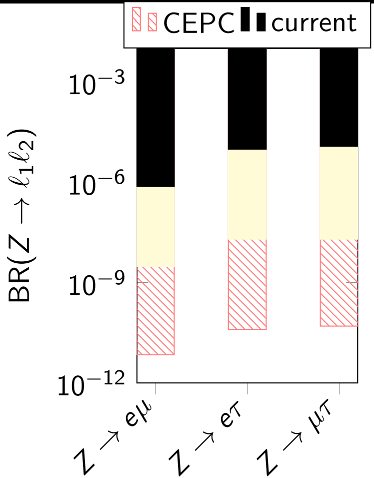

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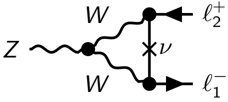

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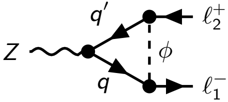

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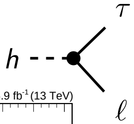
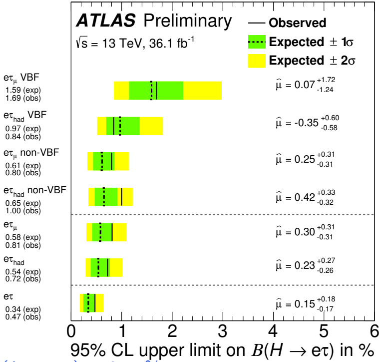
Higgs boson decay

cLFV Higgs decay

Dimension-6 SMEFT operators Grzadkowski et al 1008.4884

$$\mathcal{L} = \left[Y_{ij} + \frac{c_{ij}}{\Lambda^2} \left(H^\dagger H\right) \right] \bar{L}_i P_R \ell_j H + h.c. \rightarrow \left[\frac{m_{ij}}{v} + \frac{c_{ij}}{\sqrt{2}} \frac{v^2}{\Lambda^2} \right] h \bar{\ell}_i P_R \ell_j + h.c.$$





$BR(h \to e\tau) < 0.47\%$

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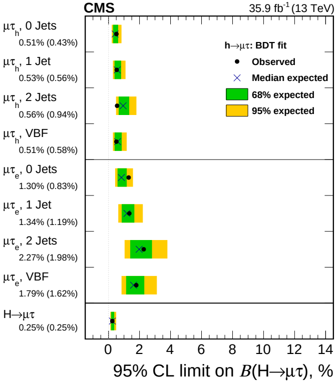
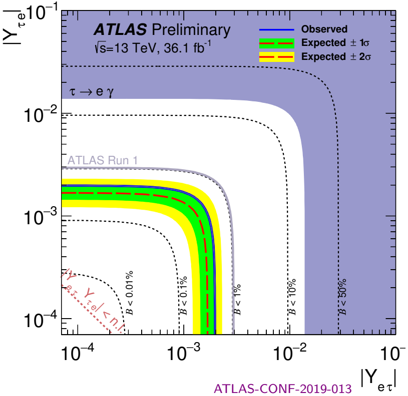


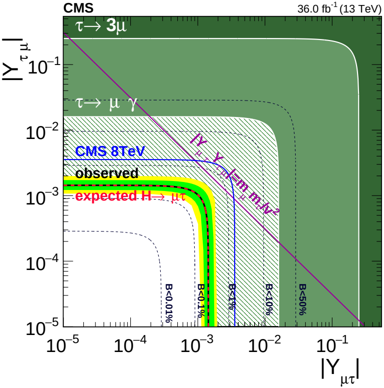
$BR(h \to \mu\tau) < 0.25\%$

CMS 1712.07173

cLFV Higgs decay cont.

$$\sqrt{|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2} = \frac{8\pi\Gamma_H(SM)}{m_H} \frac{BR(H \to \ell\tau)}{1 - BR(H \to \ell\tau)}$$





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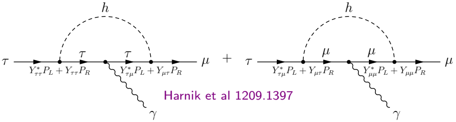
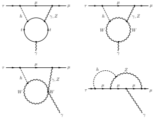


Harnik et al 1209.1397



General (type-III) 2 Higgs doublet model

EFT

$$\mathcal{L} = \left[\frac{m_i}{v}\delta_{ij} + \frac{c_{ij}}{\sqrt{2}}\frac{v^2}{\Lambda^2}\right] h\bar{\ell}_i P_R \ell_j$$

two neutral CP even Higgs

$$\Phi_i = (v_i + \phi_i)/\sqrt{2} \qquad \frac{v_2}{v_1} = t_\beta$$

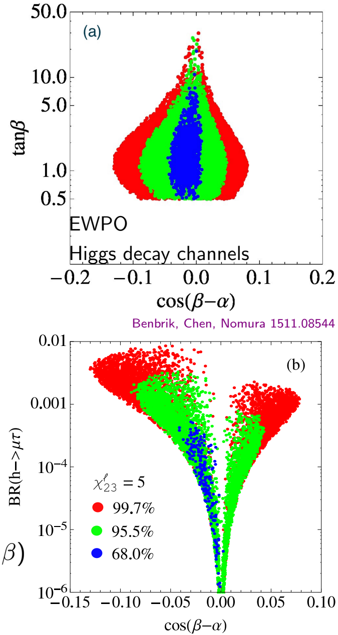
SM Higgs: $h = -s_\alpha\phi_1 + c_\alpha\phi_2$

with Yukawa couplings

$$Y_{ij} = -\frac{s_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} + \frac{\cos(\beta-\alpha)}{c_\beta}\frac{\sqrt{m_i m_j}}{v}\chi^\ell_{ij}$$

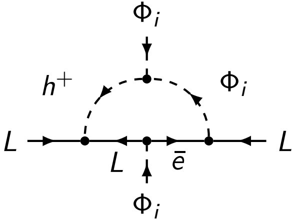
Not suppressed by v^2/Λ^2 → large contribution

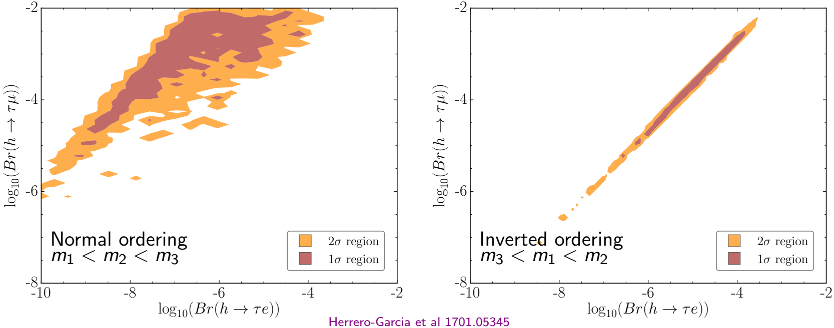
$$BR(h \to \mu\tau) \propto \left(|\chi^\ell_{23}|^2 + |\chi^\ell_{32}|^2\right)\cos^2(\beta-\alpha)(1+\tan^2\beta)$$



Example: Zee model

- Non-zero neutrino masses
- generated at loop level Zee 1980
- Simplest model with 2 Higgs doublets and charged singlet scalar h^+

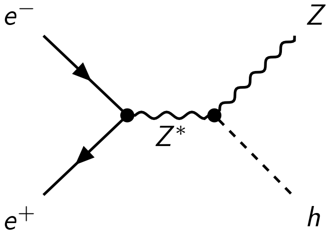


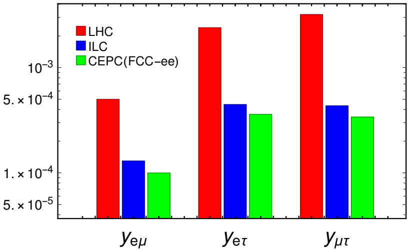


Herrero-Garcia et al 1701.05345

[see Herrero-Garcia et al 1605.06091 for Higgs cLFV in other neutrino mass models]

Future lepton collider





Qin et al 1711.07243

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

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

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

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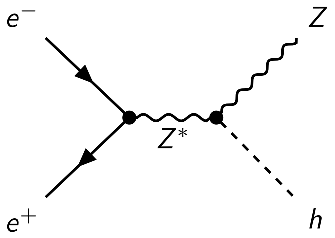

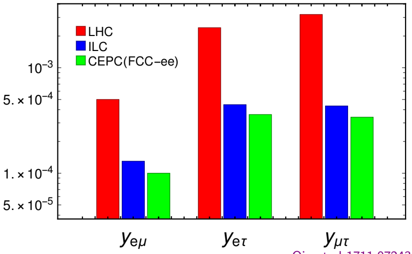

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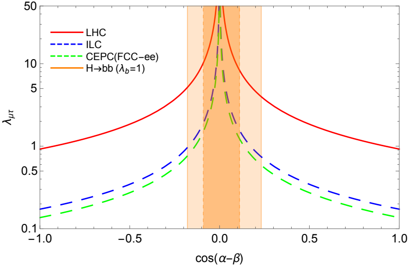
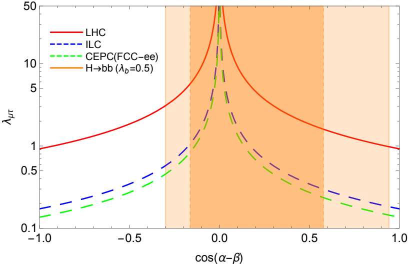


Qin et al 1711.07243



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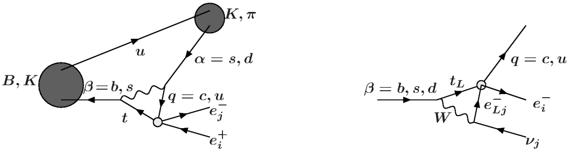
Top-quark decay

cLFV top-quark [Davidson et al 1507.07163]

described by D6 operators with 1 top quark and 2 charged leptons

$$\mathcal{L} = 2\sqrt{2}G_F \sum_i \epsilon_i \mathcal{O}_i$$

e.g. $\mathcal{O}^{AV}_{LL,RR,LR,RL} = (\bar{\ell}_i \gamma^\alpha P_X \ell_j)(\bar{u}_q \gamma_\alpha P_Y t)$



Davidson et al 1507.07163

- HERA $\sigma(e^\pm p \to e^\pm t + X) \leq 0.3pb$
- $K \to e\mu$, $\mu \to e\gamma$
- radiative corrections

$e\mu$ op's: most $|\epsilon| \lesssim O(10^{-3} - 10^{-2})$, some $O(1)$

$\tau\ell$ op's $O(1 - 100)$ $|\epsilon^{ut}_{S+P,L}| \leq 0.03$

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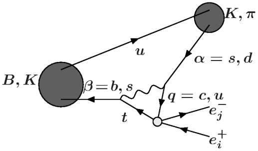
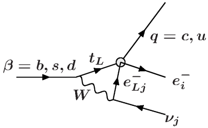
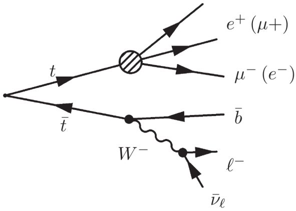




Davidson et al 1507.07163

top pair production



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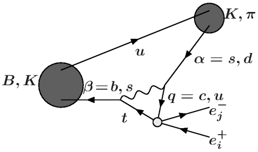

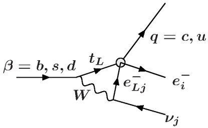

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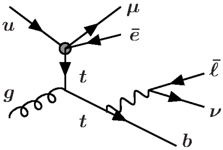
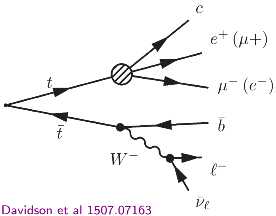
single top quark production (more diag's)



cLFV top quark decay: top-quark pair production



Davidson et al 1507.07163

cross section

$$\sigma = 2\sigma_{t\bar{t}}\, BR(t \to \ell \nu b) \times BR(t \to \ell^\pm \ell'^\mp q)$$

$$BR(t \to \ell^\pm \ell'^\mp + q) \simeq 0.0027 \sum_{X,Y} |\epsilon_{XY}|^2$$

Main backgrounds:

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

Multi-variate analysis w/ 14 var's using BDT

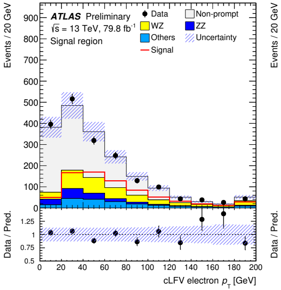
observed [expected] limit

$$BR(t \to \ell\ell' q) < 1.86[1.36^{+0.61}_{-0.37}] \times 10^{-5}$$

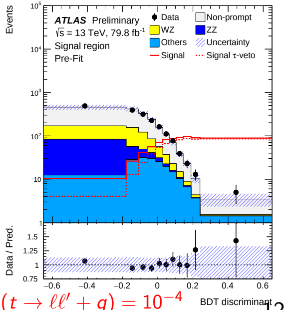
$$BR(t \to e\mu q) < 6.6[4.8^{+2.1}_{-1.4}] \times 10^{-5}$$

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

low-energy lim's stronger for most $e\mu$ op's: $\epsilon_{LL,RL}$, $\epsilon_{S\pm P,R}$, $\epsilon_{T,R}$



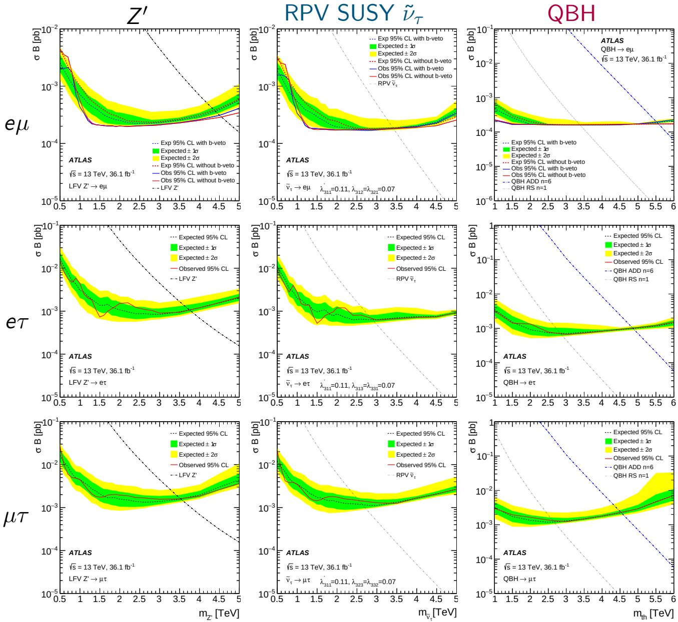
ATLAS-CONF-2018-044



$BR(t \to \ell\ell' + q) = 10^{-4}$

Heavy resonance decay

Heavy resonance: Z', RPV SUSY $\tilde{\nu}_\tau$, quantum black hole



Z'

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

RPV SUSY $\tilde{\nu}_\tau$

$$W = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k$$

QBH

ADD (universal ED)

RS (warped ED)

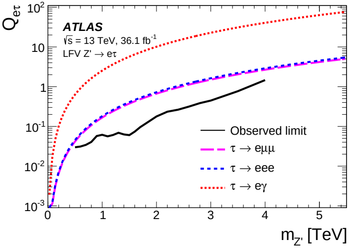
n number of ED

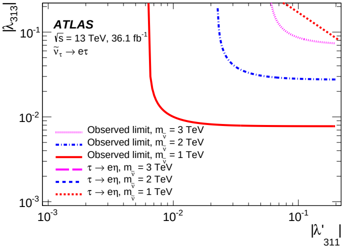
ATLAS 1807.06573

Heavy resonance: Z', RPV SUSY $\tilde{\nu}_\tau$ cont.

Z' | RPV SUSY $\tilde{\nu}_\tau$

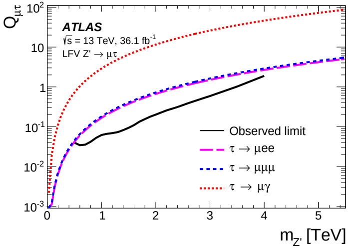
$e\tau$

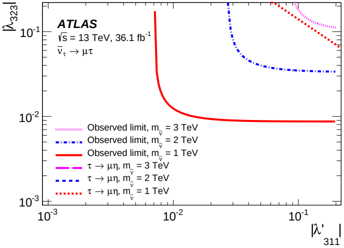




ATLAS 1807.06573

$\mu\tau$





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$$W = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k$$

Scattering at the LHC

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

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with same-flavour quark

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D8 Operators with 2 Gluons and 2 Leptons

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

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Relevant effective operators [Cai, MS 1510.02486]

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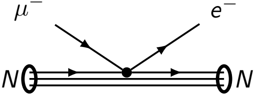
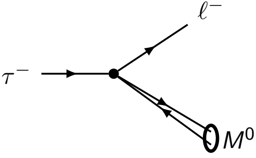
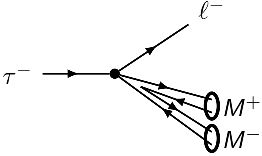
Precision Experiments [Cai, MS 1510.02486]



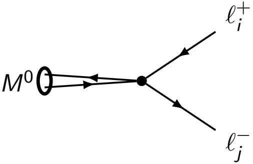
$\mu - e$ conversion in nuclei



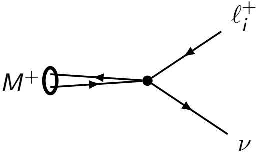
$\tau \to \ell M^0$



$\tau \to \ell M^+ M^-$



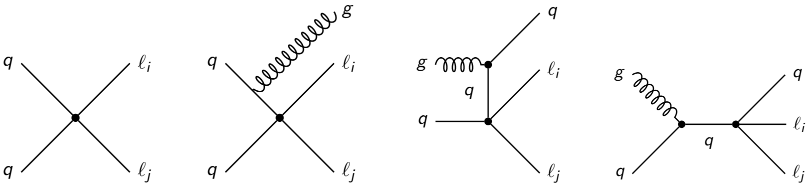
$M^0 \to \ell_i^+ \ell_j^-$



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

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

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



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

Projection to 14 TeV

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

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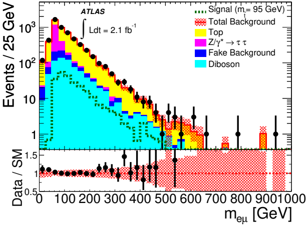
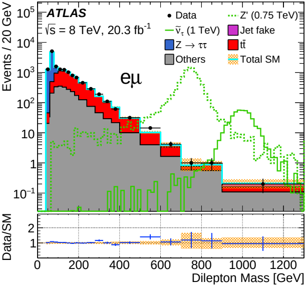
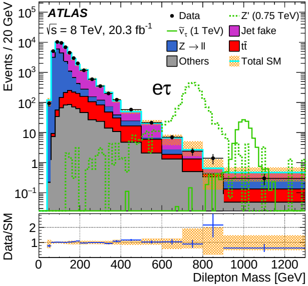


ATLAS 7TeV 1205.0725





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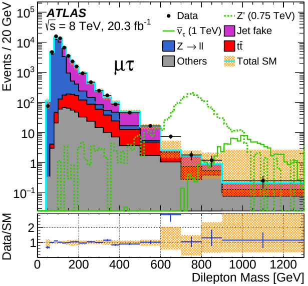

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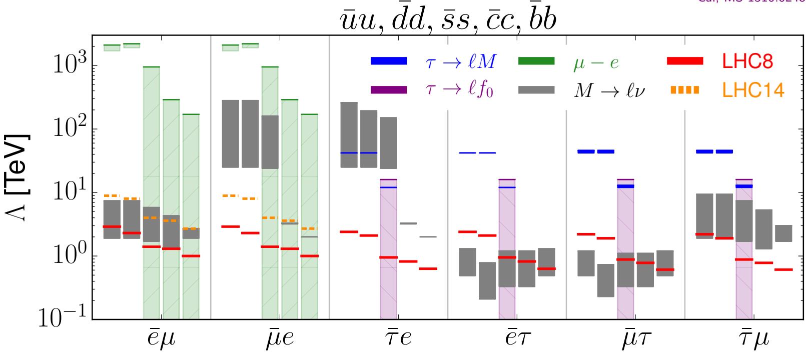
cLFV at hadron colliders: quarks

Cai, MS 1510.02486



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

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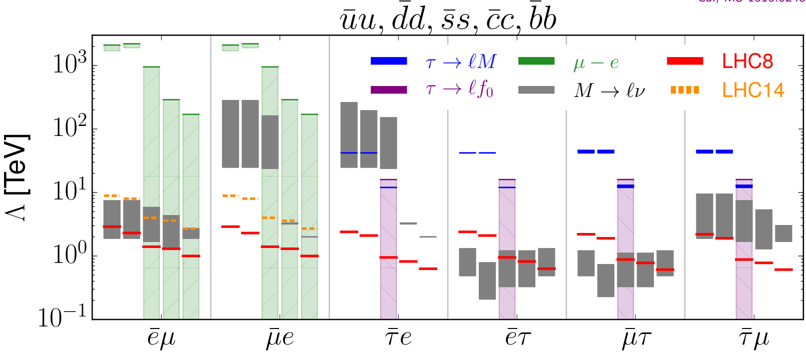

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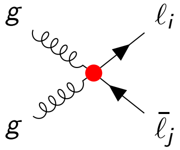

Signal:

opposite-sign different flavour pair of leptons

Most sensitive searches

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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

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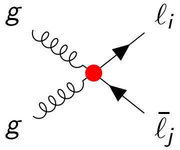

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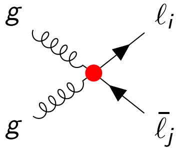

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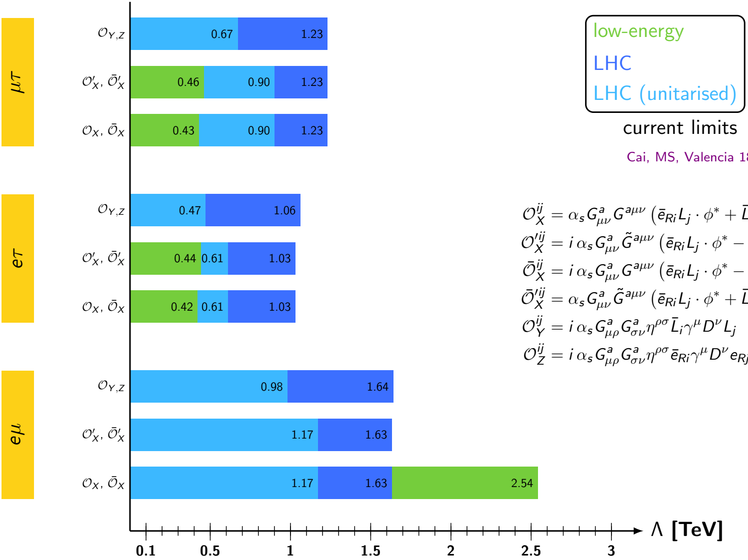

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See also Bhattacharya et al 1802.06082 for a related analysis

Scattering at future lepton colliders

Bileptons - seven simplified models [Li,MS 1809.07924]

$\Delta L = 0$

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

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

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

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$\Delta L = 2$

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

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

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

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assumption: real and symmetric Yukawa coupling matrices

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

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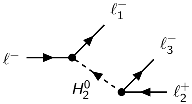
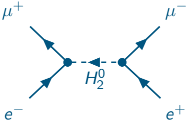
Existing (low-energy) precision constraints [Li,MS 1809.07924]

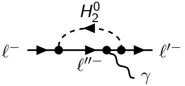
- LFV trilepton decays, $\ell \to \ell_1 \bar{\ell}_2 \bar{\ell}_3$



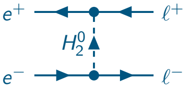
- Muonium antimuonium conversion, $\mu^+ e^- \to \mu^- e^+$



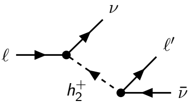
- anomalous magnetic (and electric) dipole moments, a_ℓ



- LEP/LHC searches



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



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

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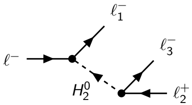

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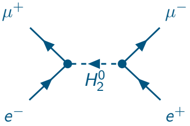

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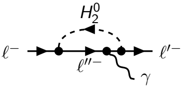

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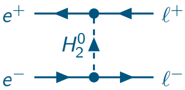

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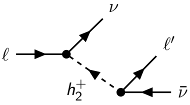

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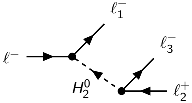

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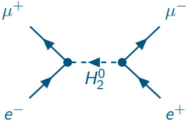

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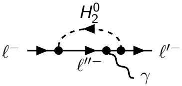

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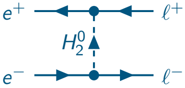

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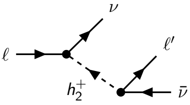
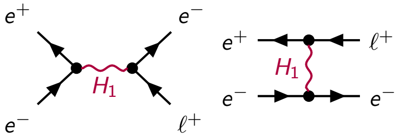


Future sensitivity improvements at e.g. Belle 2, Mu3E, . . .

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 $|\eta| < 2.5$

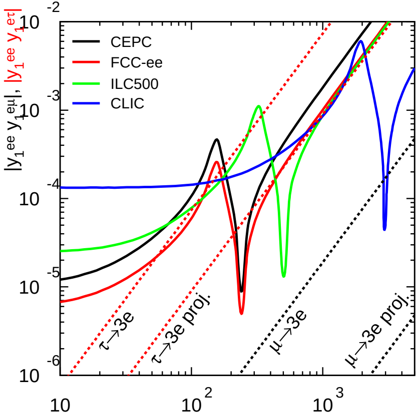
Four collider configurations:

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

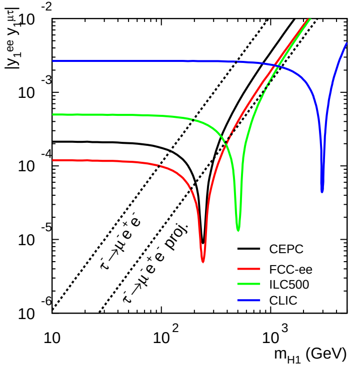


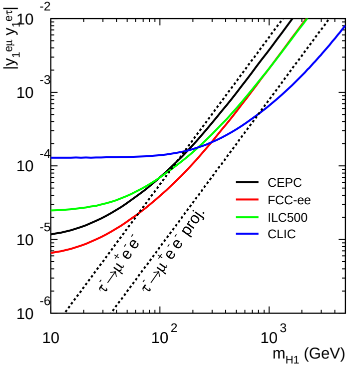
same result for $H'_{1\mu}/H_{3\mu}$

τ efficiency not included in figure

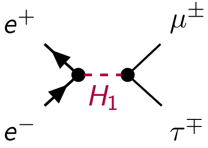
60% τ eff. $\Rightarrow$ 77% sensitivity reduction for 1 τ

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





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



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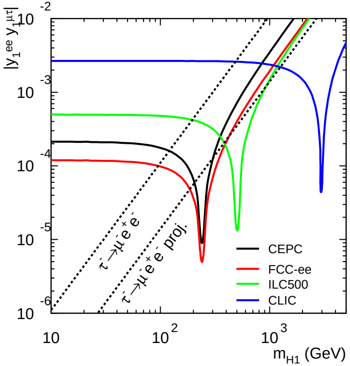
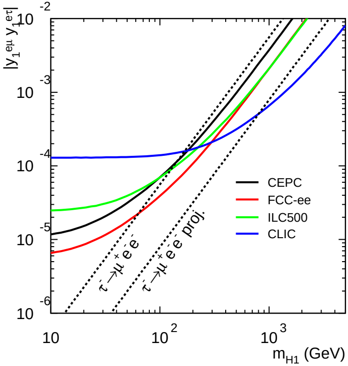
$H_{1\mu}$: $e^+e^- \to \mu^\pm\tau^\mp$ [Li,MS 1809.07924]





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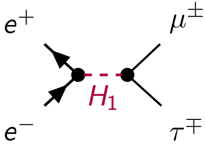

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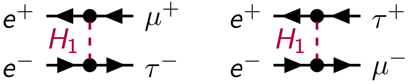
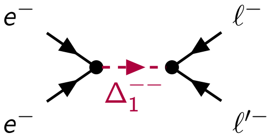
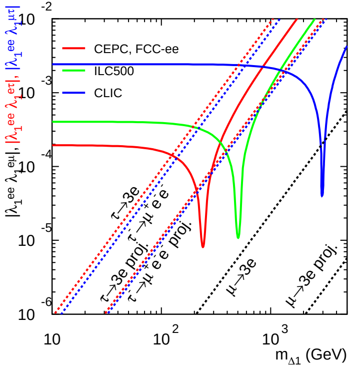


Same-sign lepton collider - Δ_1: $e^- e^- \to \ell^- \ell'^-$ [Li,MS 1809.07924]



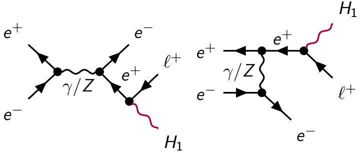
relevant couplings
$|\lambda_1^{ee}\lambda_1^{e\ell}|$ and $|\lambda_1^{ee}\lambda_1^{\mu\tau}|$



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

On-shell production $H_{1\mu}$: $e^+e^- \to e^\pm\mu^\mp(e^\pm\tau^\mp) + H_1$ [Li,MS in preparation]

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



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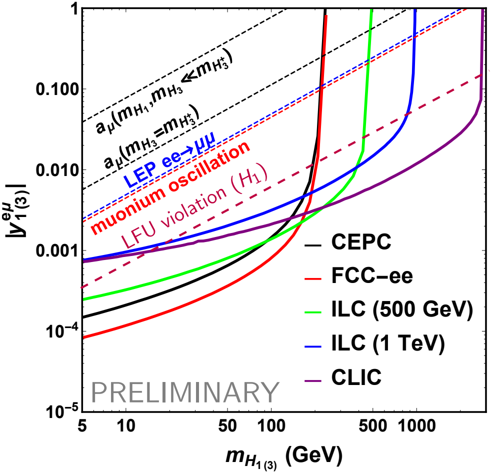


τ efficiency not included in figure

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

Conclusions

Conclusions

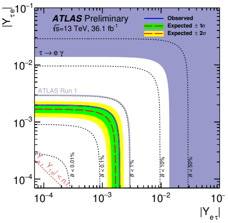
colliders complementary way to search for charged LFV

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

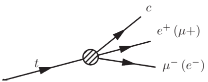
$\tau \leftrightarrow \ell$ flavour complementary sensitivity at colliders

colliders test more Lorentz structures

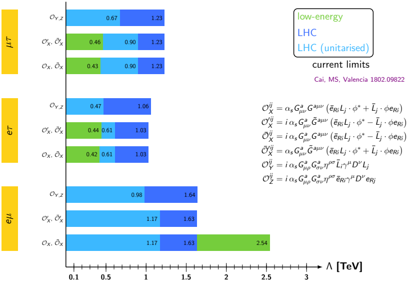
best for operators which are difficult to constrain at low energy



cLFV Higgs decay



cLFV top decay



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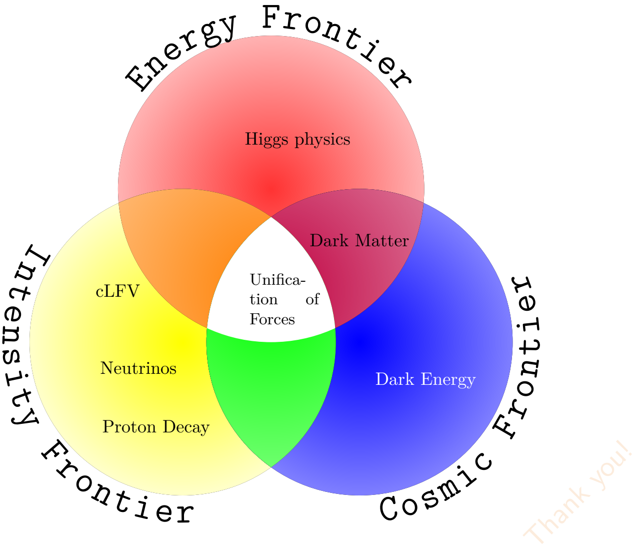
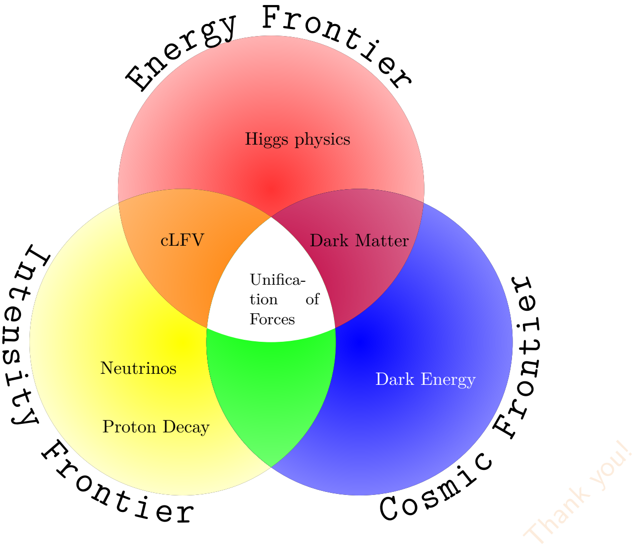
$$\mathcal{O}_Y^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j$$
$$\mathcal{O}_Z^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

cLFV scattering with initial state gluons

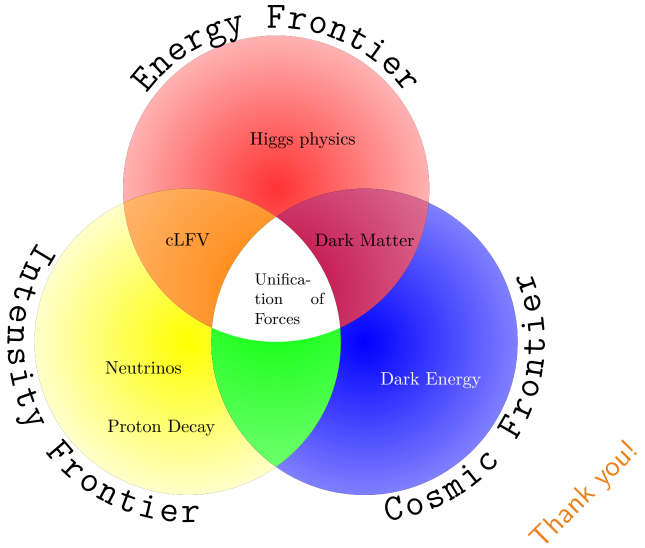
Conclusions cont.



Conclusions cont.



Conclusions cont.



Backup slides

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

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

We do not consider top quark because of different phenomenology.

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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.

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

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

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$\Rightarrow$ No tree-level FCNC processes.

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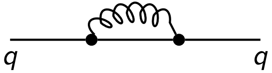
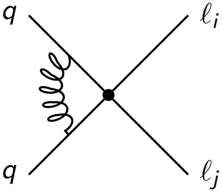
Renormalization Group Corrections

- 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.

⇒ Increases reach of precision experiments

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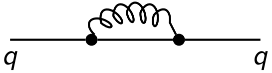

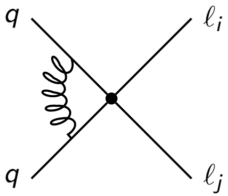

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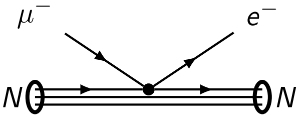
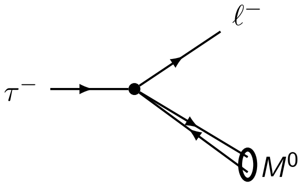
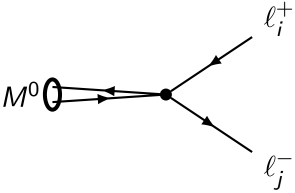
Precision Experiments



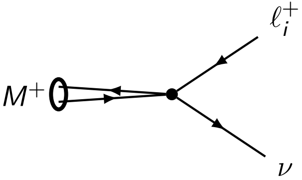
$\mu - e$ conversion in nuclei



$\tau \to \ell M^0$



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

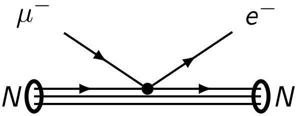


$M^+ \to \ell_i^+ \nu$

$\mu - e$ 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.

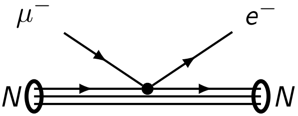
Strongest limit for first generation quarks,

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]

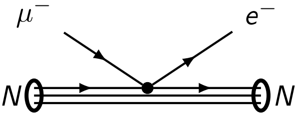
Strongest limit for first generation quarks,

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}
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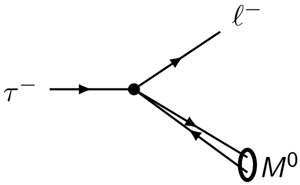
Direct nuclear mediation [Meson mediation]

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



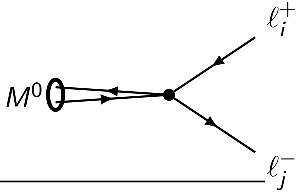
$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

decay	$\mathrm{Br}_i^{\max}$	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

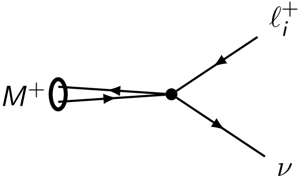
$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$



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}	-	$0.18\sqrt{\lambda}$	-	-	$0.12\sqrt{\lambda}$

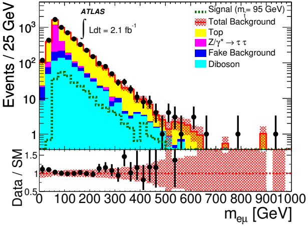
Leptonic Charged Meson Decays $M^+ \to \ell_i^+ \nu$



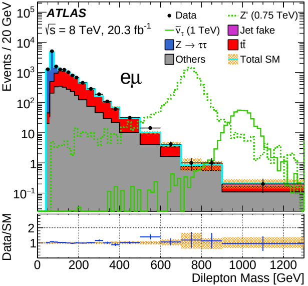
- $R_M = \frac{\mathrm{Br}(M^+ \to e^+\nu)}{\mathrm{Br}(M^+ \to \mu^+\nu)}$
- Theoretical error for R_π (R_K) about 5%
- Improvement by factor 20 (2) possible
- (✓) indicates constraints
- Second index of Λ corresponds to charged lepton

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, $Z/\gamma^* \to \tau\tau$

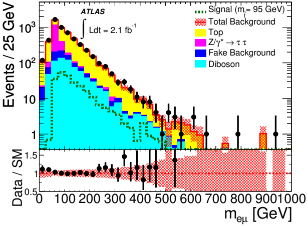
  also W/Z plus jets, WZ/ZZ, single top and $W/Z+\gamma$

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

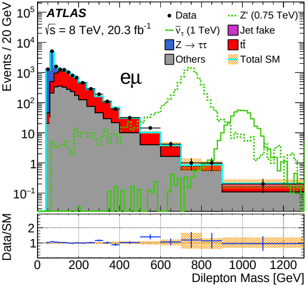
- Modelling of main background agrees with ATLAS
- Fake background estimated from data

⇒ Use background from ATLAS publications

SM Background



ATLAS 7TeV 1205.0725



ATLAS 8TeV 1503.04430

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

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$\Rightarrow$ 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

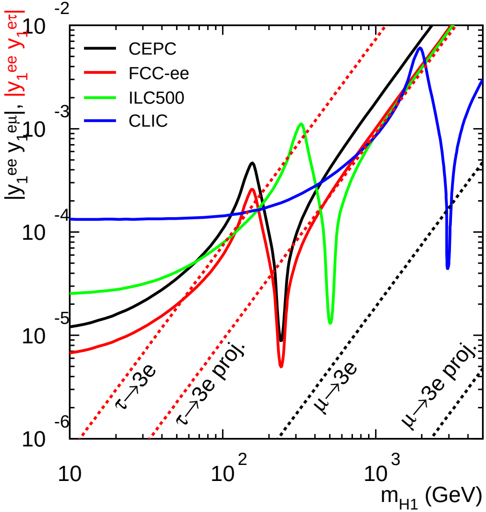
$\bar{q}q$ \ $\bar{\ell}_i\ell_j$	$\bar{e}\mu$			$\bar{e}\tau$	$\bar{\mu}\tau$
	7 TeV	8 TeV	14 TeV	8 TeV	8 TeV
$\bar{u}u$	2.6	2.9	8.9	2.4	2.2
$\bar{d}d$	2.3	2.3	8.0	2.1	1.9
$\bar{s}s$	1.1	1.4	4.0	0.95	0.88
$\bar{c}c$	0.97	1.3	3.6	0.82	0.78
$\bar{b}b$	0.74	1.0	2.7	0.63	0.61

- 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

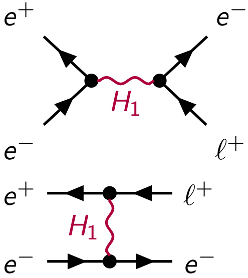
cLFV D8 operator with 2 gluons and 2 leptons

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

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



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

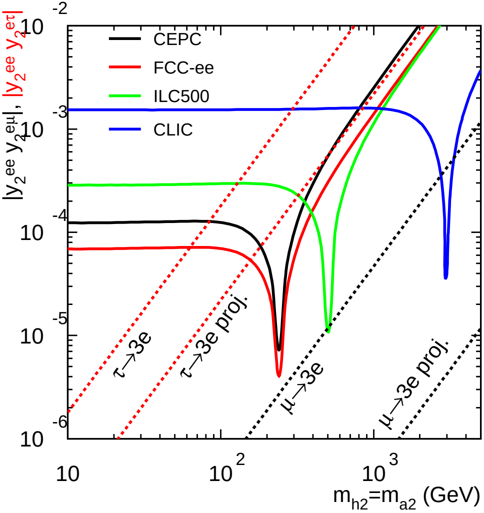


same result for right-handed $H'_{1\mu}$

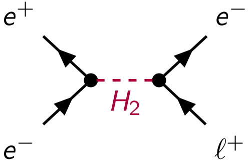
τ efficiency not included in figure

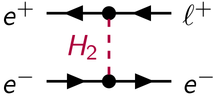
60% τ eff. $\Rightarrow$ 77% (60%) sensitivity reduction for 1 (2) τ leptons

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

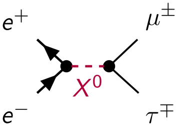


$$\mathcal{L} = y_2^{ij} H_2^0 \bar{\ell}_i P_R \ell_j + h.c.$$



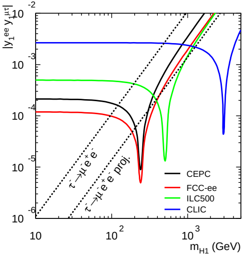


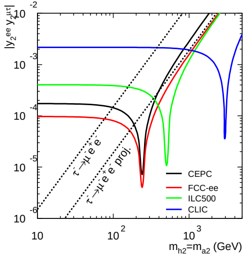
$H_{1\mu}, H_2$: $e^+e^- \to \mu^\pm\tau^\mp$

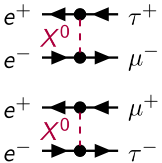


rel. couplings

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

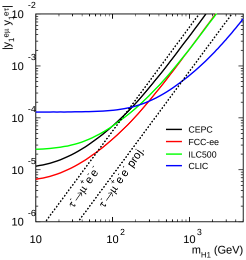


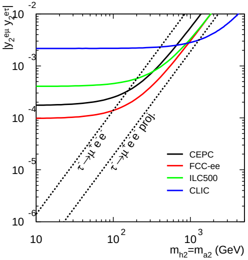




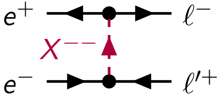
rel. couplings

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

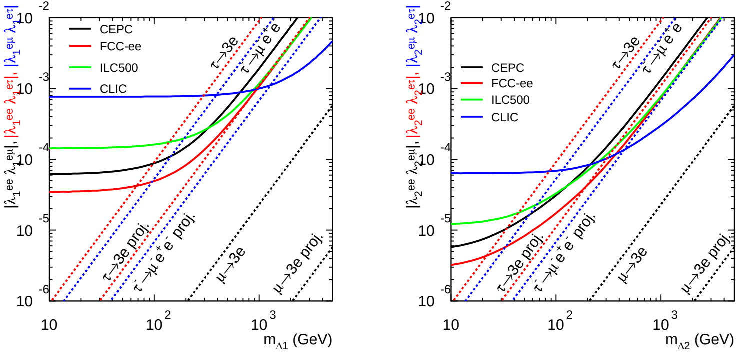




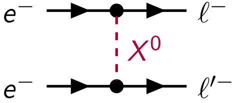
Δ_1, $\Delta_{2\mu}$: $e^+e^- \to \ell^+\ell'^-$



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

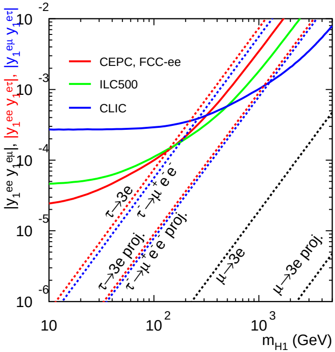


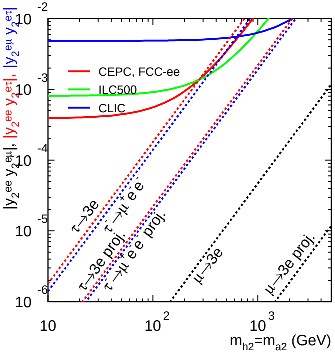
$H_{1\mu}$, H_2: $e^- e^- \to \ell^- \ell'^-$



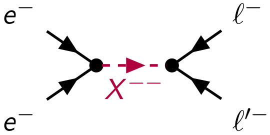
relevant couplings

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