Searches for cLFV at Current and Future Colliders

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SCIENTIA
MANU ET MENTE
UNSW
SYDNEY

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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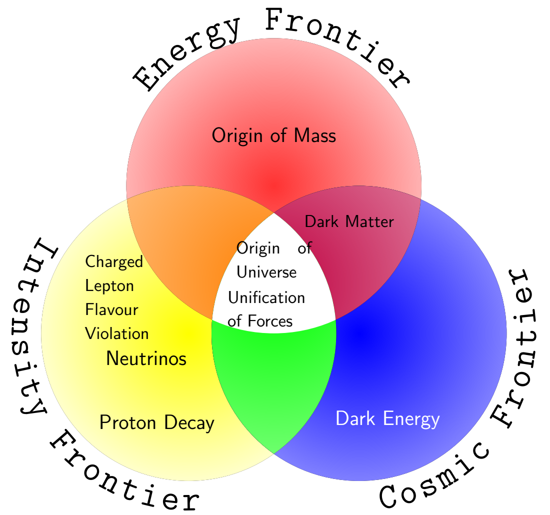

Can high-energy colliders compete with the intensity frontier?

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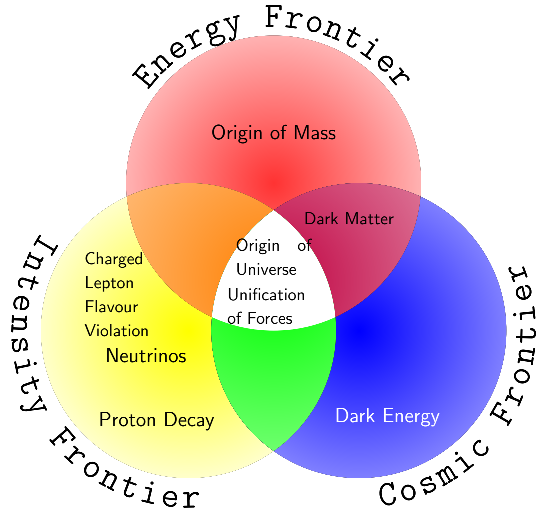


Can high-energy colliders compete with the intensity frontier?

Overview

Z boson decays

Higgs boson decay

Top-quark decay

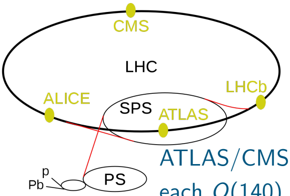
Heavy resonance decay

Scattering at the LHC

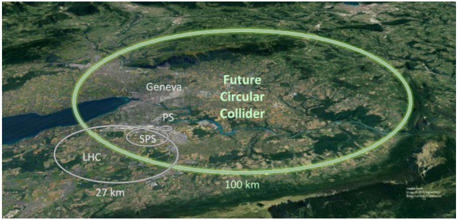
Scattering at future lepton colliders

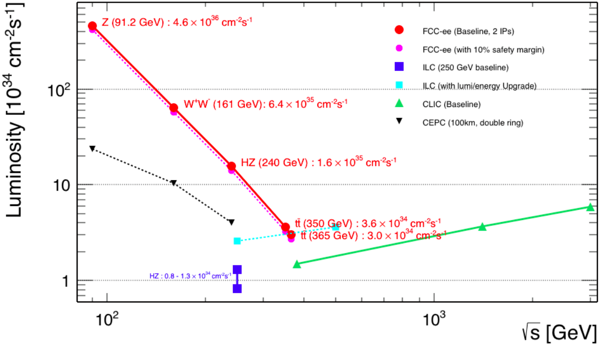
Conclusions

Colliders



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





Ellis 1810.11263

e.g. CEPC quotes

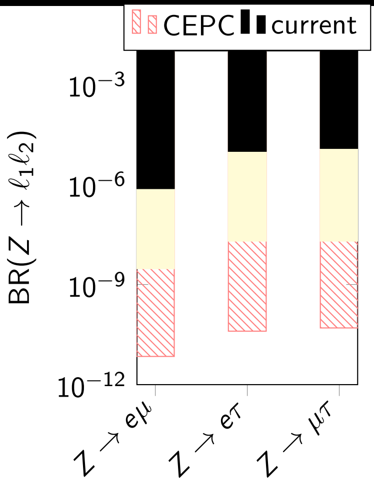
CEPC 1811.10545

10^6 Higgs bosons

10^{12} Z bosons

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

Z boson decays



$Z \to e\mu$: 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 $\mu\tau$

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

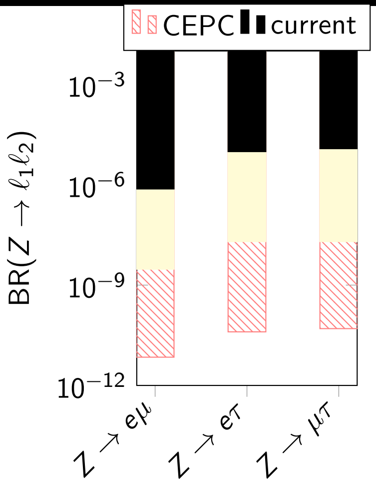
today typically less stringent as low-energy precision experiments

but will be more interesting with new Z boson factory

or if there is a signal to disentangle physics

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

cLFV Z boson decays



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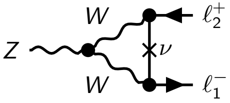

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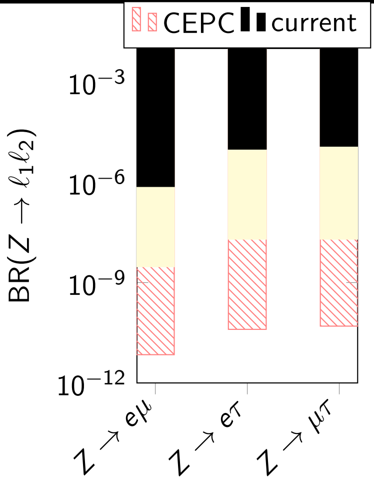

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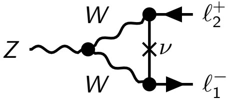

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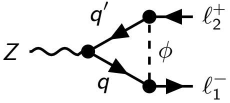

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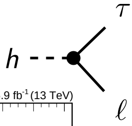
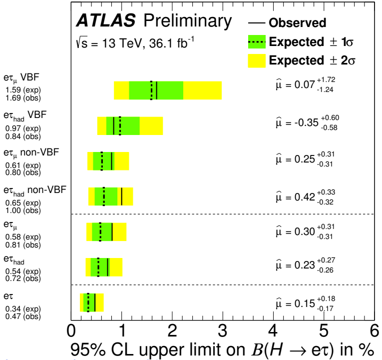
Higgs boson decay

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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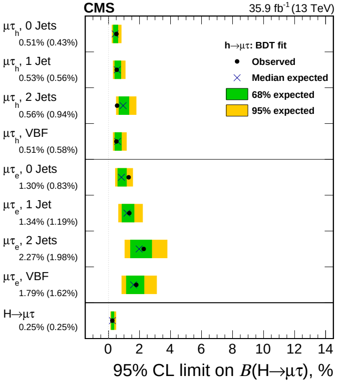
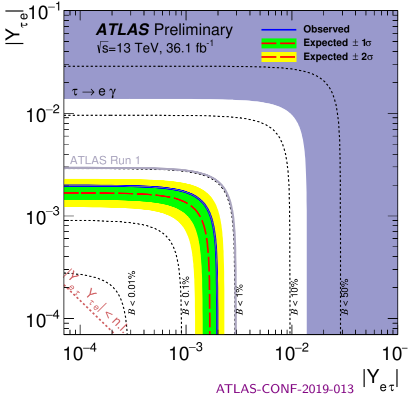


$BR(h \to \mu\tau) < 0.25\%$

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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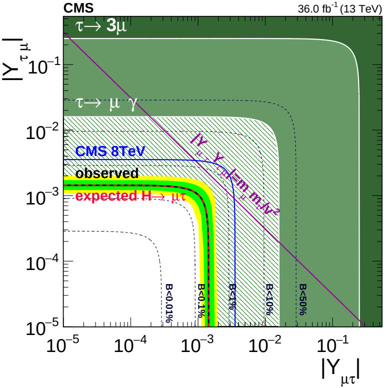
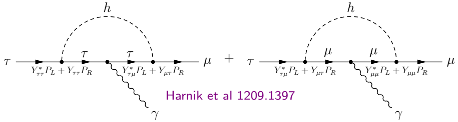
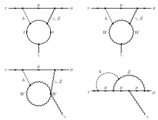


CMS 1712.07173



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

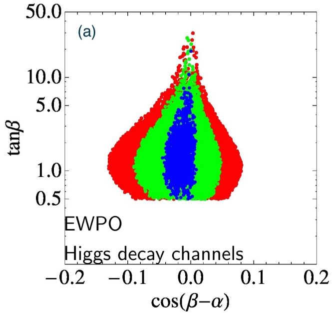
$$\Phi_i = (v_i + \phi_i)/\sqrt{2} \qquad \frac{v_2}{v_1} = t_\beta$$

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

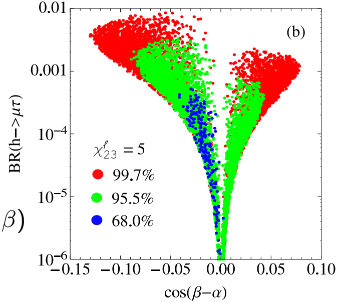
$$Y_{ij} = -\frac{s_\alpha}{c_\beta}\frac{m_i}{v}\delta_{ij} + \frac{\cos(\beta-\alpha)}{c_\beta}\frac{\sqrt{m_i m_j}}{v}\chi^\ell_{ij}$$

Not suppressed by $v^2/\Lambda^2 \to$ large contribution

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

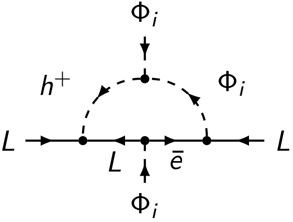


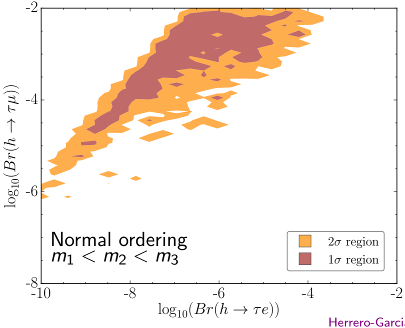
Benbrik, Chen, Nomura 1511.08544

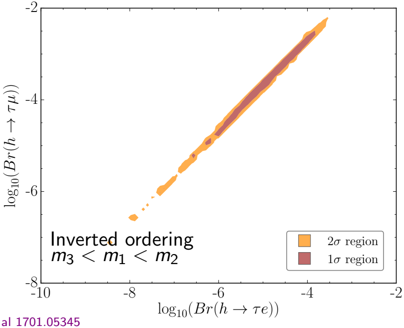


Example: Zee model

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



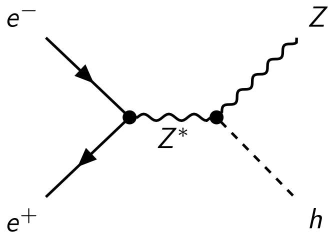


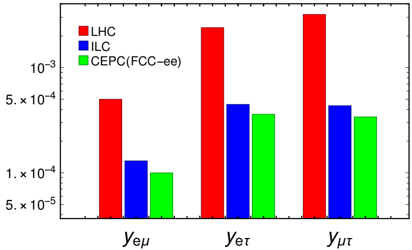


Herrero-Garcia et al 1701.05345

[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, $\mathcal{L} = 2$ ab^{-1}
CEPC $\sqrt{s} = 240$ GeV, $\mathcal{L} = 5$ ab^{-1}

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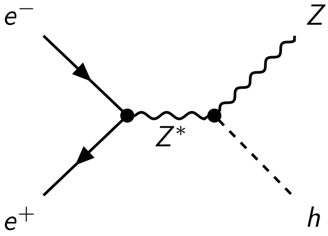

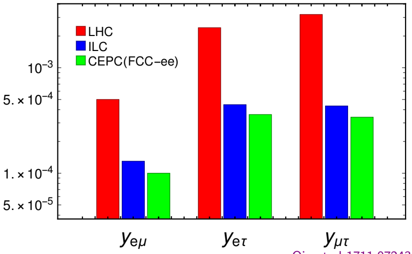

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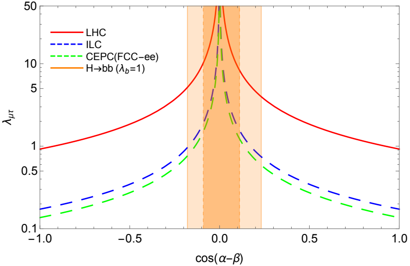

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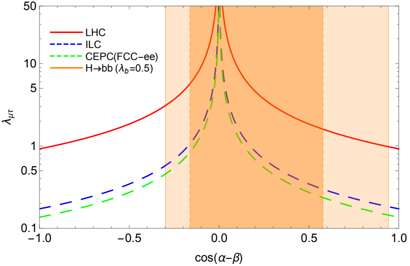

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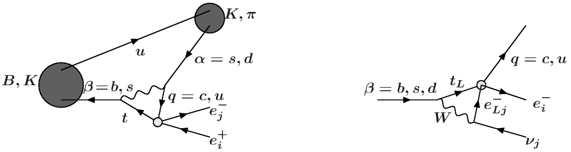
Top-quark decay

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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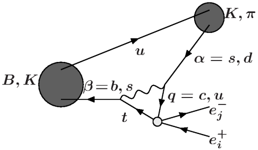
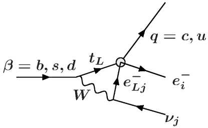
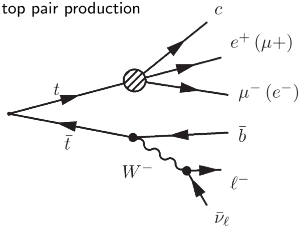




Davidson et al 1507.07163

top pair production



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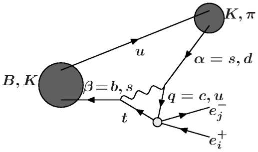

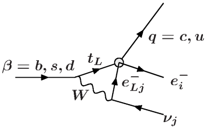

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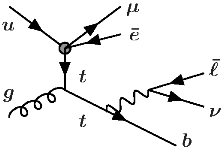
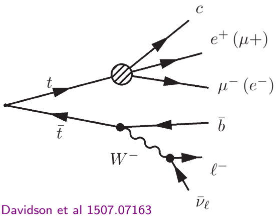
single top quark production (more diag's)



cLFV top quark decay: top-quark pair production

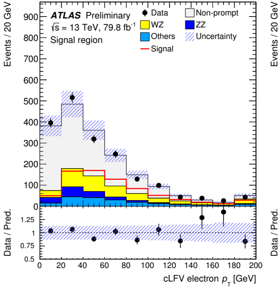


Davidson et al 1507.07163

cross section

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

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



ATLAS-CONF-2018-044

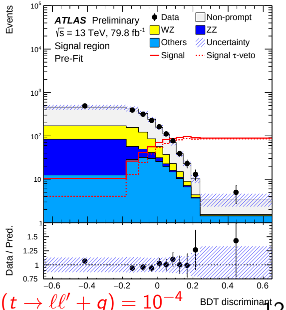
Main backgrounds:

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

Multi-variate analysis w/ 13 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 $t \to \tau + X$

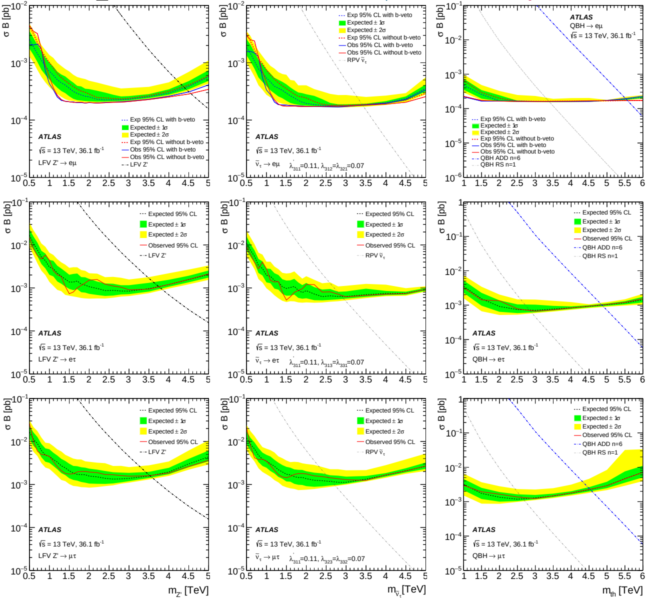
$BR(t \to \ell\ell' + q) = 10^{-4}$

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

Heavy resonance decay

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

	Z'	RPV SUSY $\tilde{\nu}_\tau$	QBH
$e\mu$			
$e\tau$			
$\mu\tau$			



Z'

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

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

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

QBH

ADD (universal ED)

RS (warped ED)

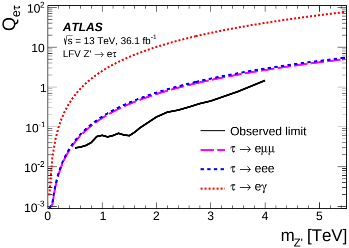
n number of ED

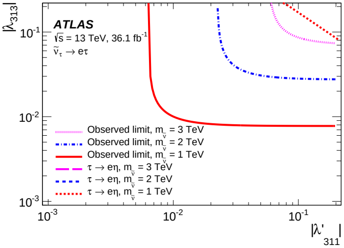
ATLAS 1807.06573

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

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

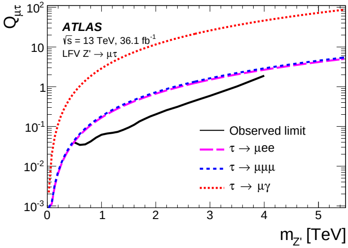
$e\tau$

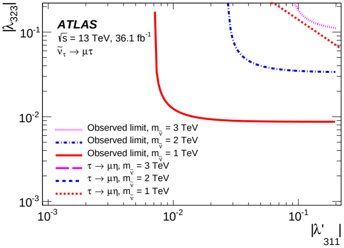




ATLAS 1807.06573

$\mu\tau$





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

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

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

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

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with same-flavour quark

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D8 Operators with 2 Gluons and 2 Leptons

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

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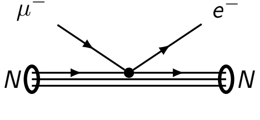
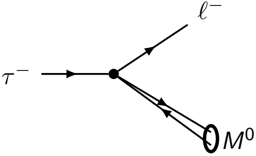
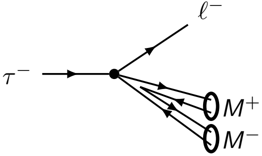
Precision Experiments [Cai, MS 1510.02486]



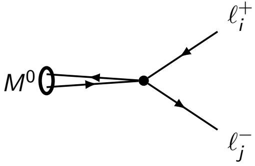
$\mu - e$ conversion in nuclei



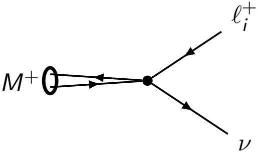
$\tau \to \ell M^0$



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



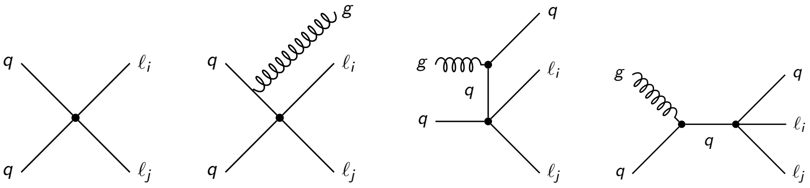
$M^0 \to \ell_i^+ \ell_j^-$



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

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

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



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

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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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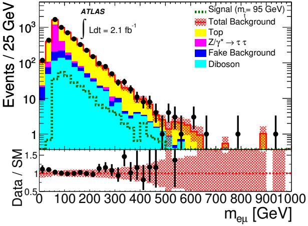

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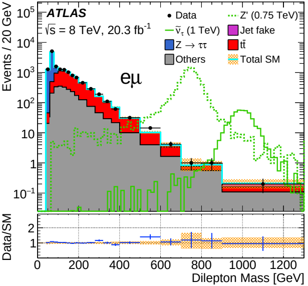

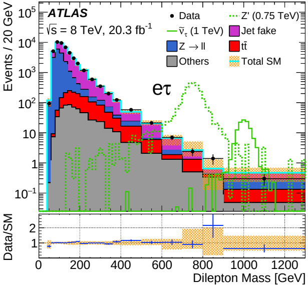

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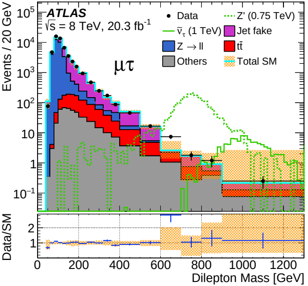

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cLFV at hadron colliders: quarks

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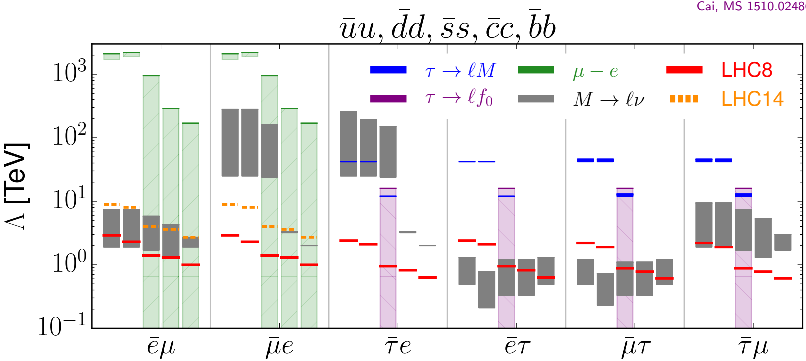

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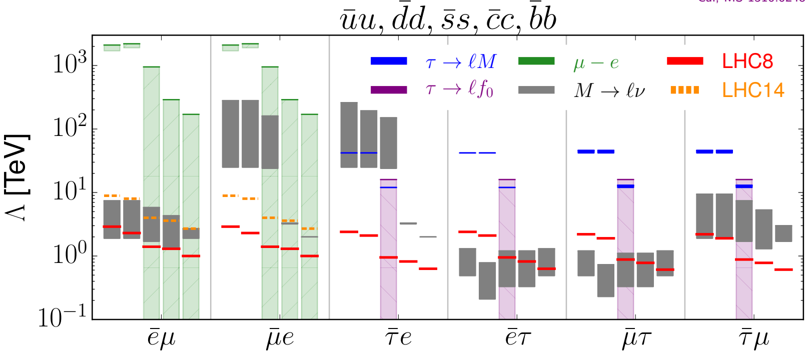

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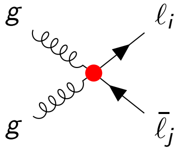

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newer ATLAS search: 13 TeV, 36.1 fb^{-1} 1807.06573

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

$\Rightarrow$ Violation of perturbative unitarity

Solutions:

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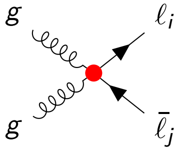

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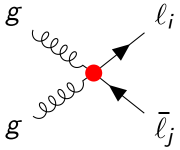

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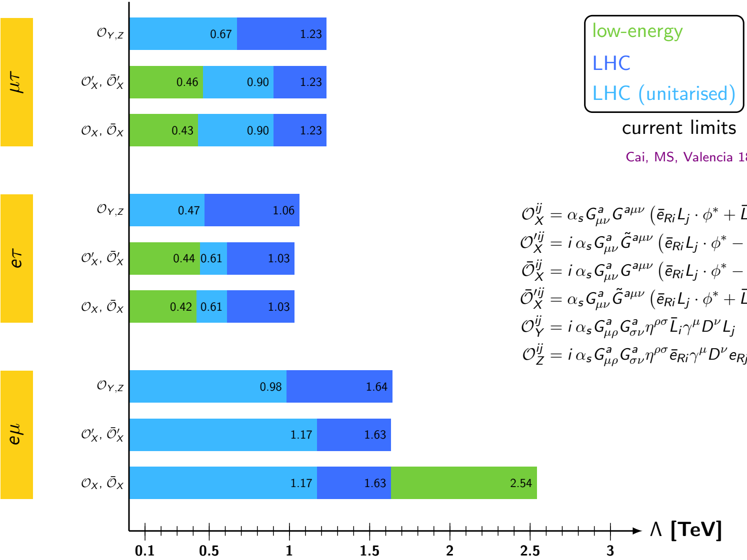

current limits

Cai, MS, Valencia 1802.09822

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

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

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

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

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

$\Delta L = 2$

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

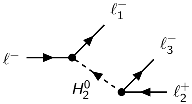
$$\mathcal{L} = \lambda_2^{ij} \Delta_{2\mu\alpha} L_{i\beta}^T \gamma^\mu P_R \ell_j \epsilon_{\alpha\beta} + h.c.$$

assumption: real and symmetric Yukawa coupling matrices

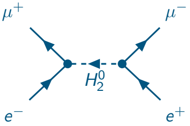
related work: Dev, Mohapatra, Zhang 1711.08430, also 1712.03642, 1803.11167

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

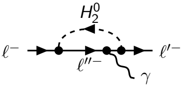
- LFV trilepton decays, $\ell \to \ell_1 \overline{\ell}_2 \overline{\ell}_3$



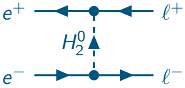
- Muonium antimuonium conversion, $\mu^+ e^- \to \mu^- e^+$



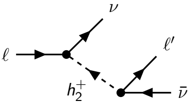
- anomalous magnetic (and electric) dipole moments, a_ℓ



- 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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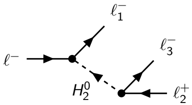

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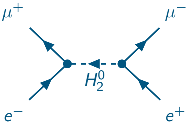

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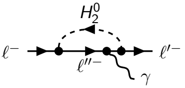

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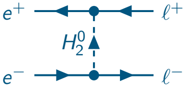

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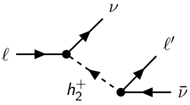

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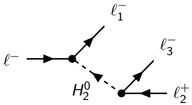

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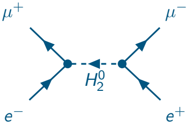

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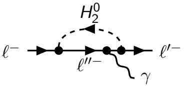

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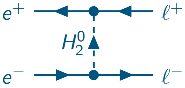

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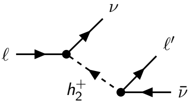

Future sensitivity improvements at e.g. Belle 2, Mu3E, . . .

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

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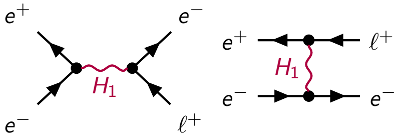
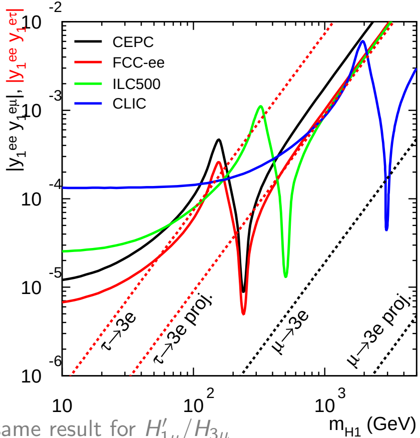


Basic cuts: $p_T > 10$ GeV and $|\eta| < 2.5$

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

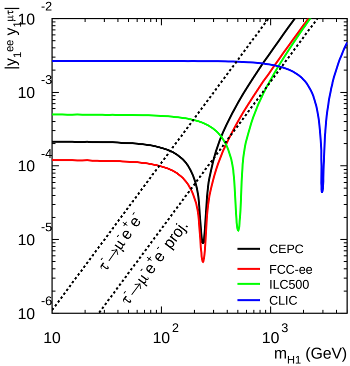


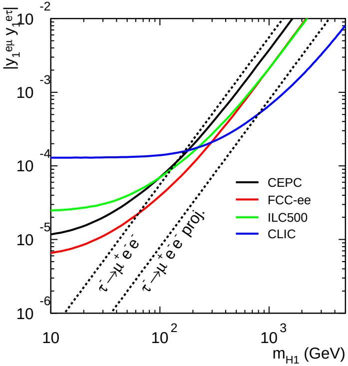
same result for $H'_{1\mu}/H_{3\mu}$

τ efficiency not included in figure

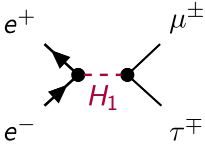
60% τ eff. $\Rightarrow$ 77% sensitivity reduction for 1 τ

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





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



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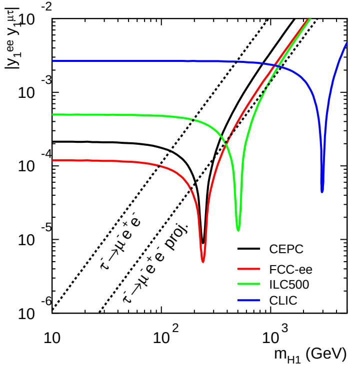
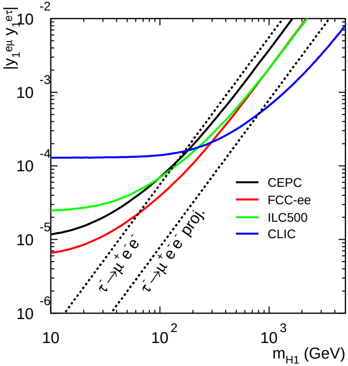
$H_{1\mu}$: $e^+e^- \to \mu^\pm\tau^\mp$ [Li,MS 1809.07924]





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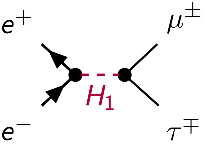

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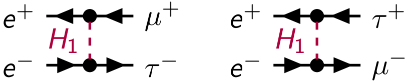
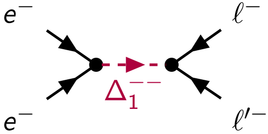
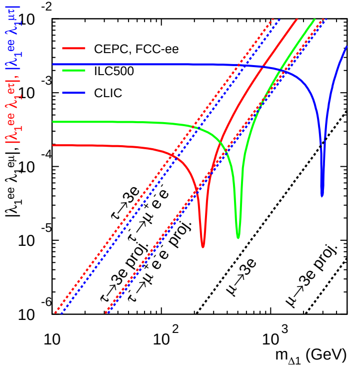


Same-sign lepton collider - Δ_1: $e^- e^- \to \ell^- \ell'^-$ [Li,MS 1809.07924]



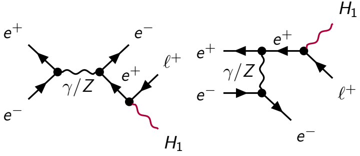
relevant couplings
$|\lambda_1^{ee}\lambda_1^{e\ell}|$ and $|\lambda_1^{ee}\lambda_1^{\mu\tau}|$



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]

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



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

Five collider configurations:

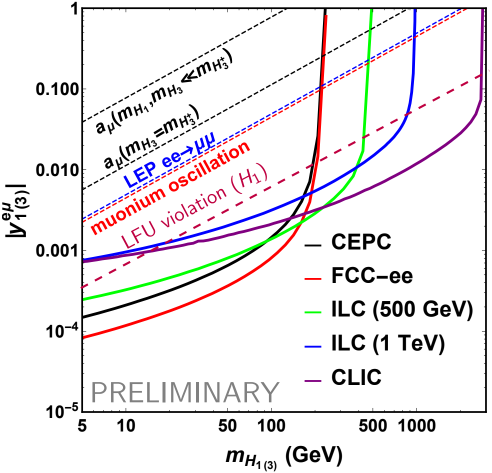
CEPC: 5 ab^{-1} at 240 GeV

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

Conclusions

Conclusions

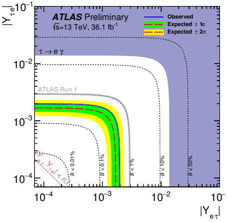
colliders complementary way to search for charged LFV

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

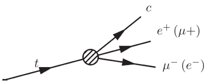
$\tau \leftrightarrow \ell$ flavour complementary sensitivity at colliders

colliders test more Lorentz structures

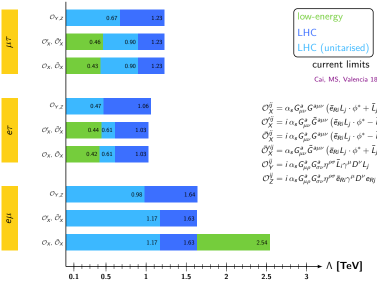
best for operators which are difficult to constrain at low energy



cLFV Higgs decay



cLFV top decay



Cai, MS, Valencia 1802.09822

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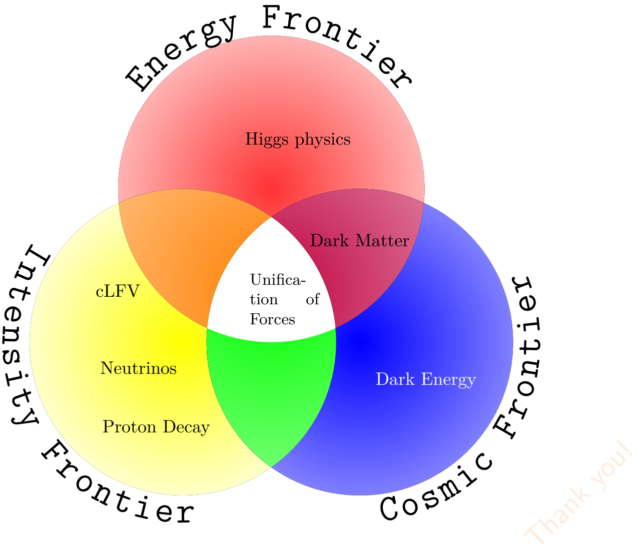
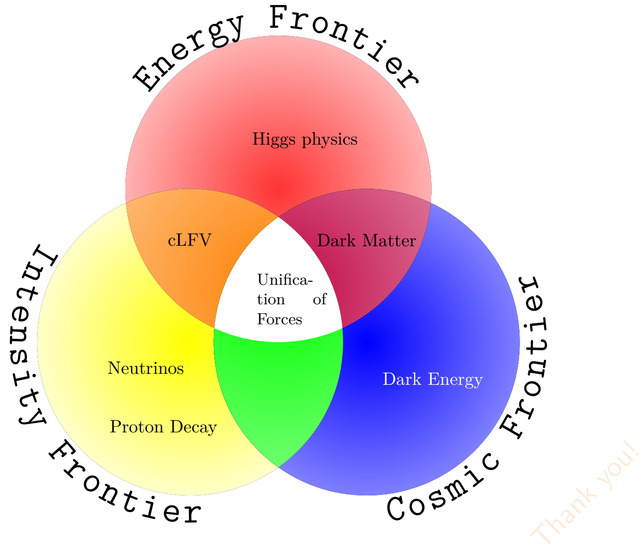
$$\mathcal{O}_Y^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j$$
$$\mathcal{O}_Z^{ij} = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

cLFV scattering with initial state gluons

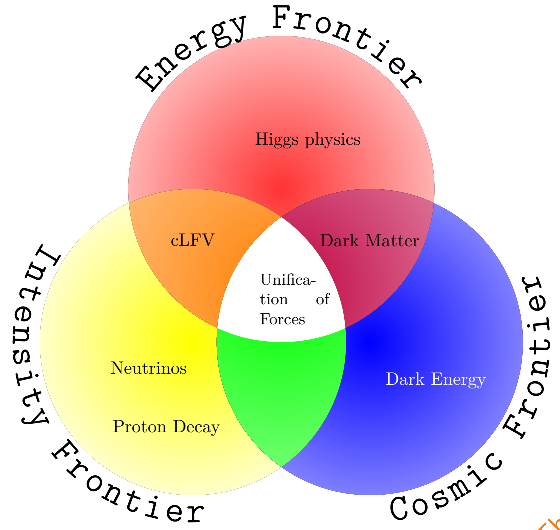
Conclusions cont.



Conclusions cont.



Conclusions cont.



Thank you!

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

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

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

In general there is quark flavour violation.

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Scalar Operators

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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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Scalar Operators

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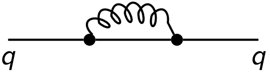
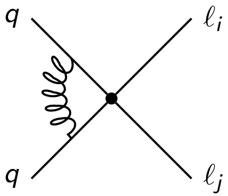
Renormalization Group Corrections

- 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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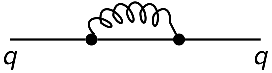

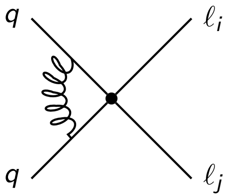

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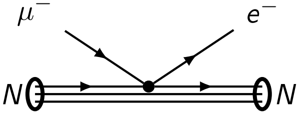
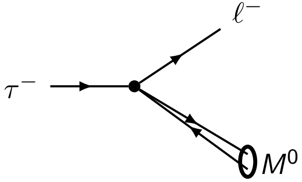
⇒ Increases reach of precision experiments

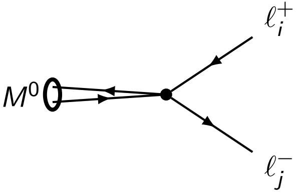
Precision Experiments



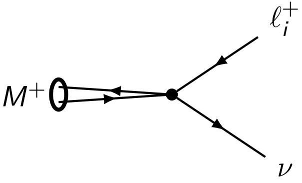
$\mu - e$ conversion in nuclei



$\tau \to \ell M^0$

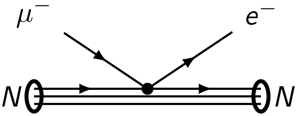


$M^0 \to \ell_i^+ \ell_j^-$



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

$\mu - e$ 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.

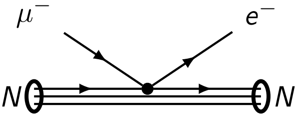
Strongest limit for first generation quarks,

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

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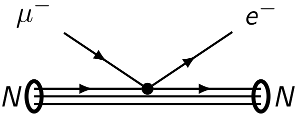
- Agnostic about mediation mechanism
- Following discussion in

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



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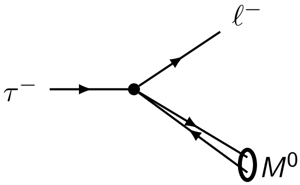
Direct nuclear mediation [Meson mediation]

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

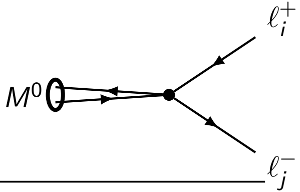


$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \quad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

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



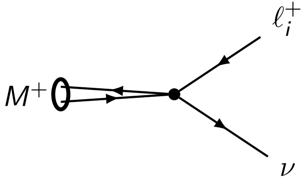
$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

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

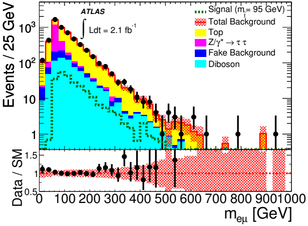
Leptonic Charged Meson Decays $M^+ \to \ell_i^+ \nu$

- $R_M = \frac{\mathrm{Br}(M^+ \to e^+ \nu)}{\mathrm{Br}(M^+ \to \mu^+ \nu)}$
- 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

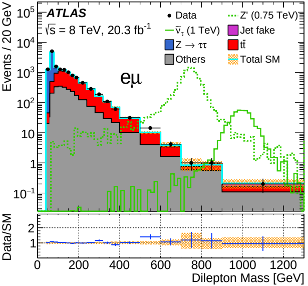


decay	constraint	cutoff scale Λ [TeV]		Wilson coefficients				
		$\Lambda_{\mu e, e\mu, e\tau}$	$\Lambda_{\tau e, \tau\mu, \mu\tau}$	$\Xi^u_{ij,uu}$	$\Xi^d_{ij,dd}$	$\Xi^d_{ij,ss}$	$\Xi^u_{ij,cc}$	$\Xi^d_{ij,bb}$
R_π	$R_\pi^{exp} \pm 5\%$	$25 - 280$	$25 - 260$	**✓**	**✓**	-	-	-
R_K	$R_K^{exp} \pm 5\%$	$24 - 160$	$24 - 150$	✓	-	**✓**	-	-
$\mathrm{Br}(D^+ \to e^+\nu)$	$< 8.8 \times 10^{-6}$	$2.8 - 2.9$	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, $Z/\gamma^* \to \tau\tau$

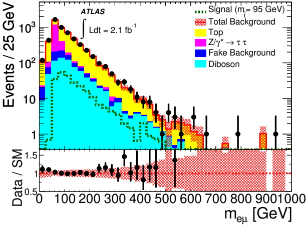
  also W/Z plus jets, WZ/ZZ, single top and $W/Z + \gamma$

$\Rightarrow$ 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



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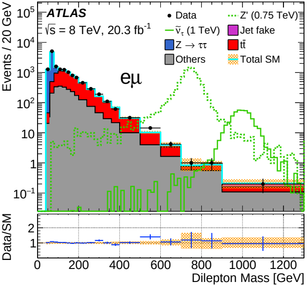

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- Modelling of main background agrees with ATLAS
- Fake background estimated from data

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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

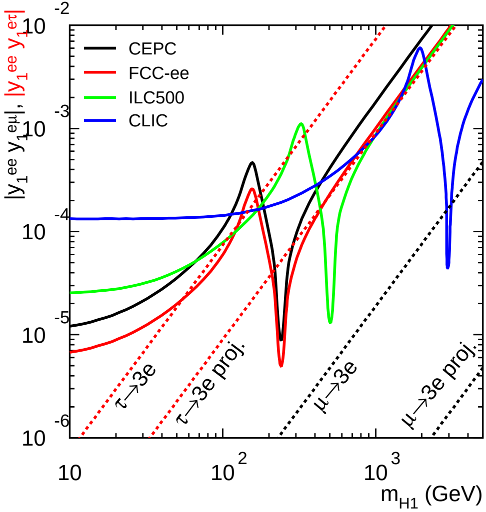
$\bar{q}q$ \ $\bar{\ell}_i\ell_j$	$\bar{e}\mu$ 7 TeV	$\bar{e}\mu$ 8 TeV	$\bar{e}\mu$ 14 TeV	$\bar{e}\tau$ 8 TeV	$\bar{\mu}\tau$ 8 TeV
$\bar{u}u$	2.6	2.9	8.9	2.4	2.2
$\bar{d}d$	2.3	2.3	8.0	2.1	1.9
$\bar{s}s$	1.1	1.4	4.0	0.95	0.88
$\bar{c}c$	0.97	1.3	3.6	0.82	0.78
$\bar{b}b$	0.74	1.0	2.7	0.63	0.61

- 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

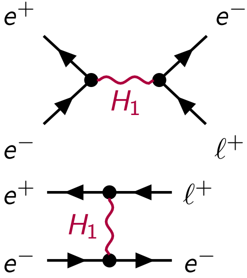
cLFV D8 operator with 2 gluons and 2 leptons

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

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



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

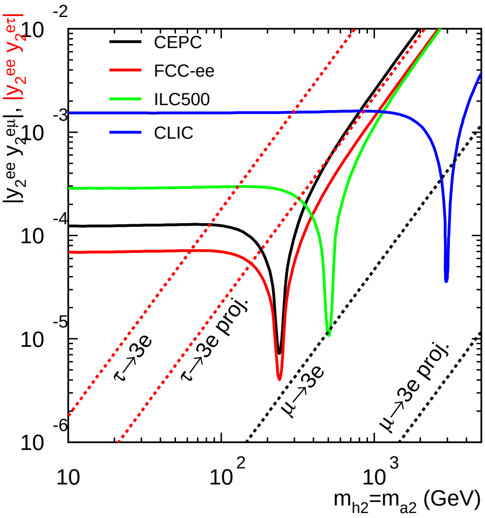


same result for right-handed $H'_{1\mu}$

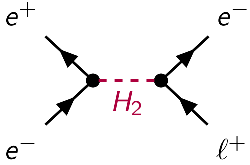
τ efficiency not included in figure

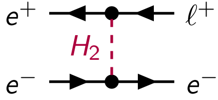
60% τ eff. $\Rightarrow$ 77% (60%) sensitivity reduction for 1 (2) τ leptons

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

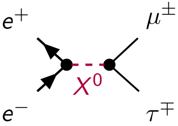


$$\mathcal{L} = y_2^{ij} H_2^0 \bar{\ell}_i P_R \ell_j + h.c.$$



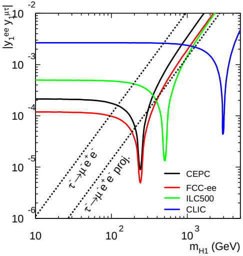


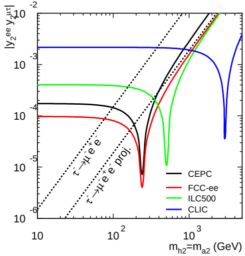
$H_{1\mu}, H_2$: $e^+e^- \to \mu^\pm\tau^\mp$

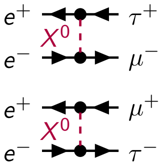


rel. couplings

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

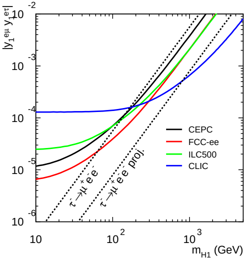


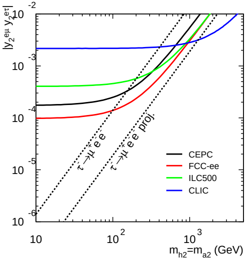




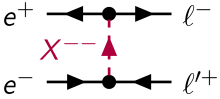
rel. couplings

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



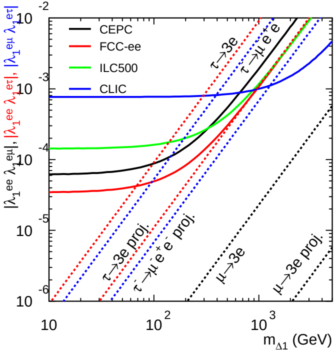


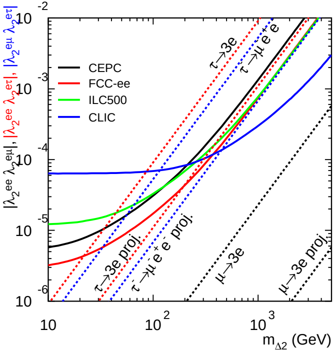
Δ_1, $\Delta_{2\mu}$: $e^+e^- \to \ell^+\ell'^-$



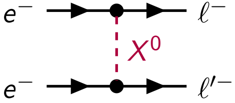
relevant couplings

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



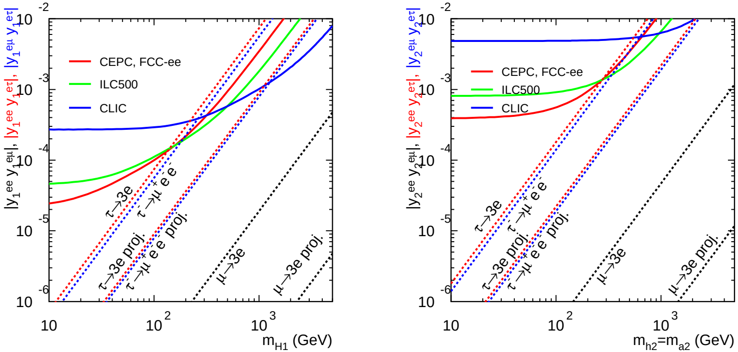


$H_{1\mu}$, H_2: $e^- e^- \to \ell^- \ell'^-$

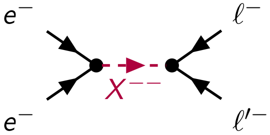


relevant couplings

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