Charged lepton flavour violation at colliders

Michael A. Schmidt

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3rd FCC Physics and Experiments Workshop

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

UNSW SYDNEY

Motivation

The Standard Model is very successful. . .

. . . but incomplete

In particular neutrinos are massive

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

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$\rightarrow$ need way to discriminate models

Lepton flavour is not conserved ($\leftarrow \nu$ oscillations)

- 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
- LFV processes a good probe to discriminate m_ν models
- could be completely unrelated to neutrino mass, e.g. SUSY

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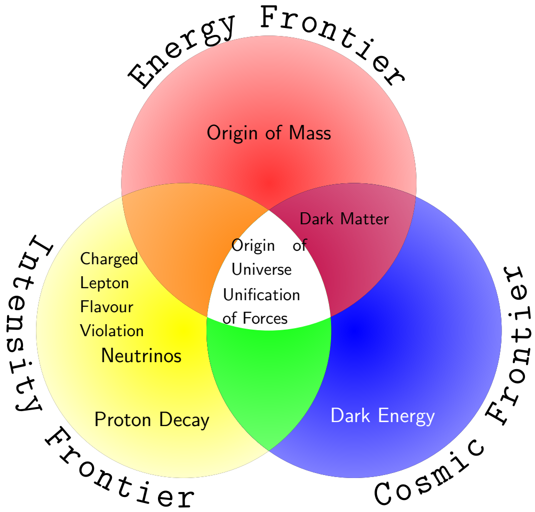

Can high-energy colliders compete with the intensity frontier?

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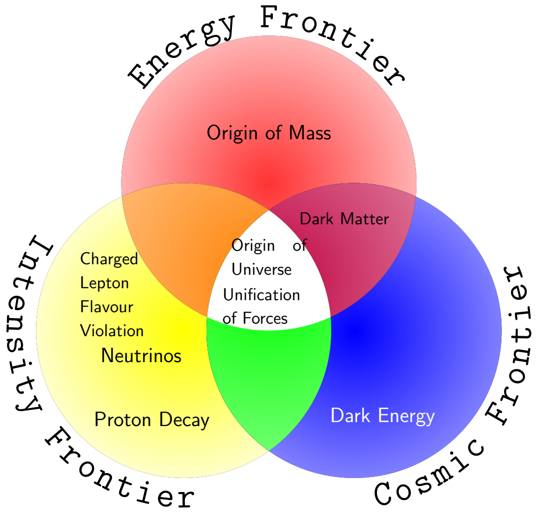


Can high-energy colliders compete with the intensity frontier?

cLFV at colliders

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

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

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

Conclusions

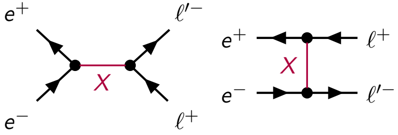
Future lepton colliders: $e^+e^- \to \ell\ell'$

cLFV scattering processes at a future lepton collider

Consider simplified models with bileptons X

Off-shell production:

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



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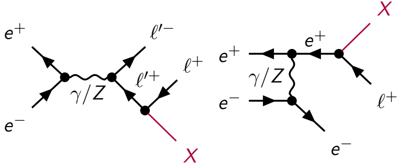

- ✓ 2-body final state
- ✗ depends on product of couplings

- ✗ phase space suppression
- ✓ depends on single LFV coupling

Bileptons - seven simplified models [Li,MS 1809.07924 1907.06963]

$\Delta L = 0$

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

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

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

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

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

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

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

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

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

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

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

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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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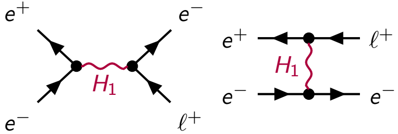


Basic cuts: $p_T > 10$ GeV and $|\eta| < 2.5$

Four collider configurations:

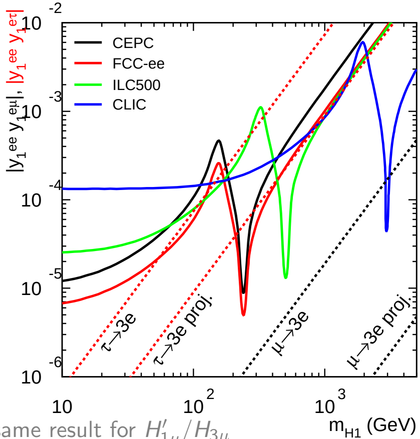
CEPC: 5 ab^{-1} at 240 GeV

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

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

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

LFV trilepton decays, $\ell^- \to \ell_1^- \ell_2^+ \ell_3^-$

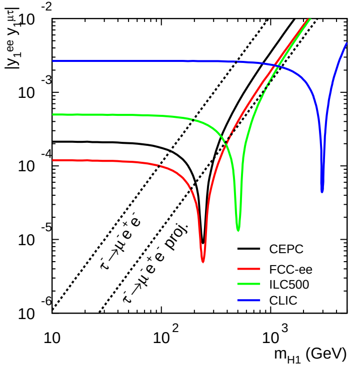


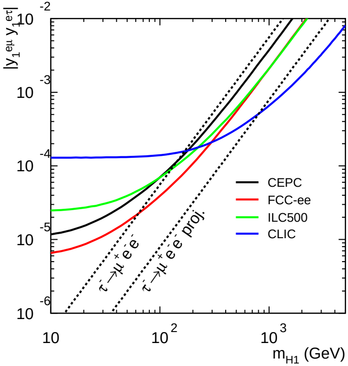
same result for $H'_{1\mu}/H_{3\mu}$

τ efficiency not included in figure

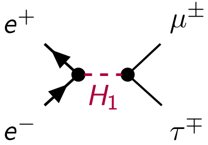
60% τ eff. $\Rightarrow$ 77% sensitivity reduction for 1 τ

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





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



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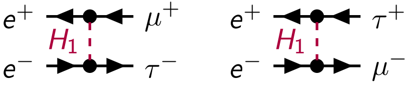
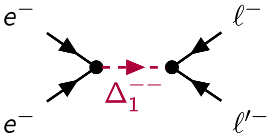
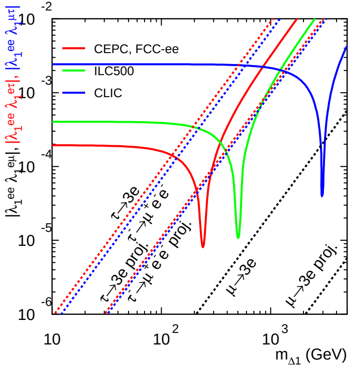


Same-sign lepton collider - Δ_1: $e^- e^- \to \ell^- \ell'^-$ [Li,MS 1809.07924]



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



same centre of mass energies

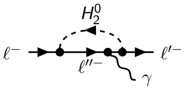
smaller integrated luminosity
$\mathcal{L} = 500\,\mathrm{fb}^{-1}$

Future lepton colliders:

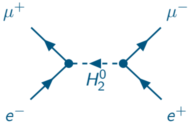
$e^+e^- \to \ell\ell' + X$

Other observables [Li,MS 1907.06963]

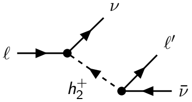
- anomalous magnetic moments, a_ℓ



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

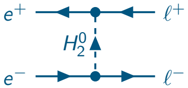


- lepton flavour universality, $\ell \to \ell' \nu \bar{\nu}$



- shift of G_F: $\sin^2\theta_W$, m_W, CKM unitarity

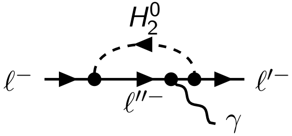
- non-standard interactions, e.g. KARMEN: ν oscillation at $L = 0$: $\bar{\nu}_\mu \to \bar{\nu}_e$



- LEP/LHC searches

- neutrino trident prod'n: $\nu_\mu N \to \nu_\mu N \ell^+ \ell^-$

Anomalous magnetic moment [Li,MS 1907.06963]



$$\Delta a_\mu = (2.74 \pm 0.73) \times 10^{-9} \quad \to \quad > 3\sigma$$
$$\Delta a_e = (-0.88 \pm 0.36) \times 10^{-12} \quad \to \quad > 2\sigma$$

- definite signs $\quad H_{1\mu}^{(\prime 0)}, \Delta_1, \Delta_3 : \quad \Delta a_\ell \geq 0$

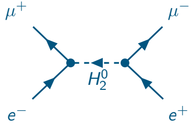
  $\Delta_{2\mu} : \quad \Delta a_\ell \leq 0$

  $H_{3\mu}$ and H_2 can have either sign

- generally suppressed by lepton masses: $\Delta a_\ell \sim O(1) \frac{y^2}{12\pi^2} \frac{m_\ell^2}{m_X^2}$
  with exception of H_2:

$$\Delta a_\ell(H_2) = -\frac{(y_2^\dagger y_2 + y_2 y_2^\dagger)^{\ell\ell}}{96\pi^2} \left(\frac{m_\ell^2}{m_{h_2}^2} + \frac{m_\ell^2}{m_{a_2}^2} \right) + \frac{(y_2^\dagger y_2)^{\ell\ell}}{96\pi^2} \frac{m_\ell^2}{m_{H_2^+}^2}$$
$$+ \sum_k \mathrm{Re}[y_2^{k\ell} y_2^{\ell k}] \frac{m_k m_\ell}{16\pi^2} \left(\frac{\ln\left(\frac{m_k^2}{m_{h_2}^2}\right) + \frac{3}{2}}{m_{h_2}^2} - \frac{\ln\left(\frac{m_k^2}{m_{a_2}^2}\right) + \frac{3}{2}}{m_{a_2}^2} \right)$$

Muonium-antimuonium oscillation [Li,MS 1907.06963]



$P(B = 0.1\,T) \leq 8.3 \times 10^{-11}$ Willmann et al hep-ex/9807011

factor > 100 improvement possible Bernstein, Schöning (2019)

- in QM muonium $M = (\mu^+ e^-)$ described by
  $H = H_0 + H_{hf} + H_{Zeeman} \to |\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$ states mix
- bileptons induce muonium-antimuonium mixing $H_{M\bar{M}}$

$$H_{M\bar{M}} \sim \frac{1}{\pi a_B^3} \begin{pmatrix} 1 & & & \\ & * & * & \\ & * & * & \\ & & & 1 \end{pmatrix}$$

using basis of energy eigen-states of (anti)muonium $|\lambda_1\rangle \equiv |\uparrow\uparrow\rangle$, $|\lambda_{2,3}\rangle$, $|\lambda_4\rangle \equiv |\downarrow\downarrow\rangle$

- reevaluated under assumption of $H_{M\bar{M}} \ll H$
- magnetic fields suppress conversion probability by
  0.36 ($H_{1\mu}^{(\prime)0}$, $H_{3\mu}$, $\Delta_{1,3}$),
  0.79 (Δ_2, $H_2 : m_{h_2} = m_{a_2}$), and 0.5 ($H_2 : m_{h_2} \ll m_{a_2}$)

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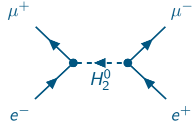

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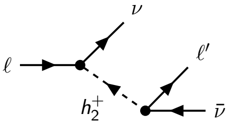
Lepton flavour universality [Li,MS 1907.06963]



$$\mathcal{L} = -2\sqrt{2}G_F[\bar{\nu}_i\gamma_\mu P_L\nu_j][\bar{\ell}_k\gamma^\mu(g_{LL}^{ijkl}P_L+g_{LR}^{ijkl}P_R\ell)]$$

Consider LFU ratios

$$R_{\mu e} = \frac{\Gamma(\tau \to \nu_\tau \mu \bar{\nu}_\mu)}{\Gamma(\tau \to \nu_\tau e \bar{\nu}_e)} \qquad \frac{R_{\mu e}^{\rm exp}}{R_{\mu e}^{\rm SM}} = 1.0034 \pm 0.0032$$

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$H_{1\mu}$, $H_{3\mu}$ and Δ_3: Contribution to $g_{LL,NP}$ $\rightarrow$ interference with SM
H_2, Δ_2: Contribution to $g_{LR,NP}$ $\rightarrow$ no interference

$$g_{LL,NP}^{ijkl} = -\frac{y_1^{ij}y_1^{kl}}{2\sqrt{2}G_F m_{H_1^0}^2} - \frac{y_3^{kj}y_3^{il}}{\sqrt{2}G_F m_{H_3^+}^2} - \frac{\lambda_3^{jl}\lambda_3^{ik*}}{2\sqrt{2}G_F m_{\Delta_3^+}^2} \qquad g_{LR,NP}^{ijkl} = \frac{y_2^{il}y_2^{jk*}}{4\sqrt{2}G_F m_{H_2^+}^2} - \frac{\lambda_2^{il}\lambda_2^{jk*}}{2\sqrt{2}G_F m_{\Delta_2^+}^2}$$

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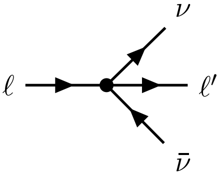

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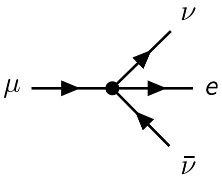
New contributions to muon decay and $G_{F,\mu}$ [Li,MS 1907.06963]



$$G_F = G_{F,\mu}(1 + \delta G_F)$$

$$\delta G_F = -\mathrm{Re}(g^{\mu ee\mu}_{LL,NP}) - \frac{1}{2}\sum_{\alpha,\beta}(|g^{\alpha\beta e\mu}_{LL,NP}|^2 + |g^{\alpha\beta e\mu}_{LR,NP}|^2)$$

A shift in the Fermi constant measured in muon decays induces shifts in

- Weinberg angle $\frac{\delta s_W^2}{s_W^2} = \frac{c_W^2}{s_W^2 - c_W^2}\delta G_F$
- W boson mass $\frac{\delta m_W^2}{m_W^2} = \frac{s_W^2}{s_W^2 - c_W^2}\delta G_F$
- CKM unitarity $|V_{ud}^{\mathrm{exp}}|^2 + |V_{us}^{\mathrm{exp}}|^2 + |V_{ub}^{\mathrm{exp}}|^2 = 1 + 2\delta G_F$
  Caveat: analysis based on PDG 2018, does not include the recent determination of V_{ud} and V_{us}

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

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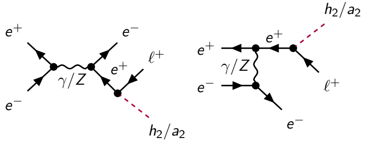

Cuts: $p_T > 10$ GeV and $|\eta| < 2.5$
100% h/a reconstruction efficiency

Five collider configurations:
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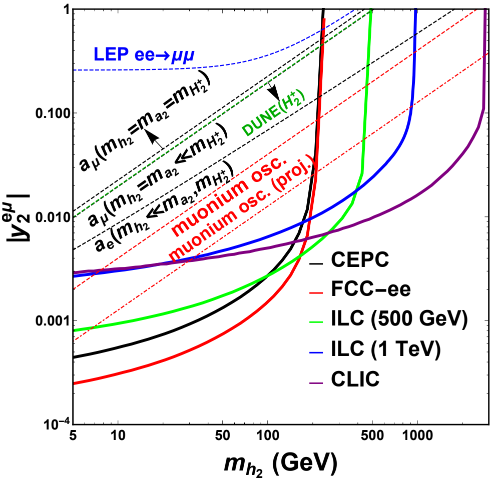
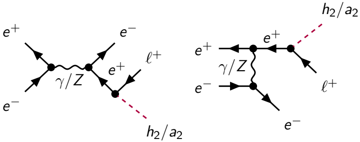
ILC (1TeV): 1 ab^{-1} at 1 TeV
CLIC: 5 ab^{-1} at 3 TeV



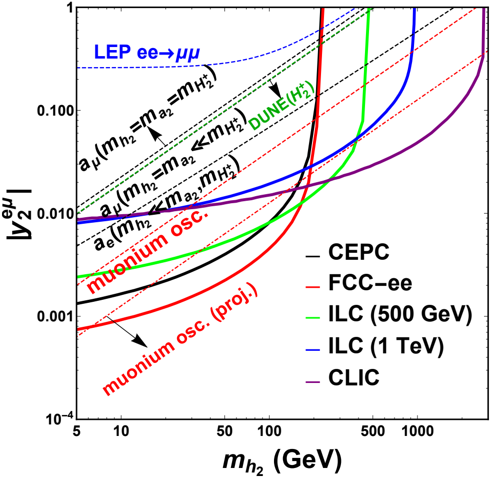
On-shell production H_2: $e^+e^- \to e^\pm\mu^\mp + h_2/a_2$ [Li,MS 1907.06963]

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

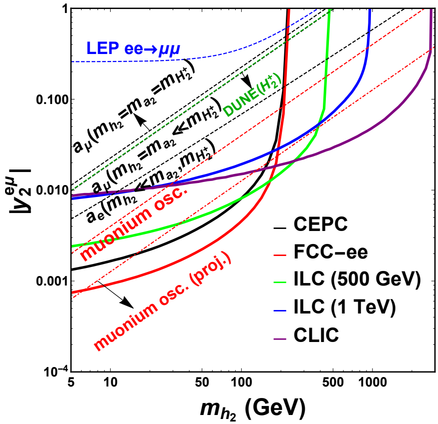


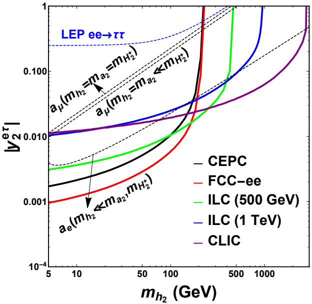
Cuts: $p_T > 10$ GeV and $|\eta| < 2.5$
10% h/a reconstruction efficiency

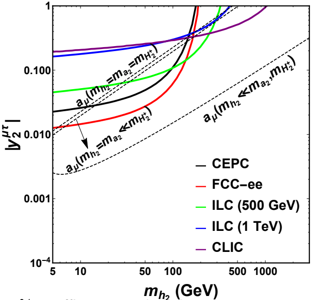
Five collider configurations:
CEPC: 5 ab^{-1} at 240 GeV
FCC-ee: 16 ab^{-1} at 240 GeV
ILC (500 GeV): 4 ab^{-1} at 500 GeV
ILC (1TeV): 1 ab^{-1} at 1 TeV
CLIC: 5 ab^{-1} at 3 TeV

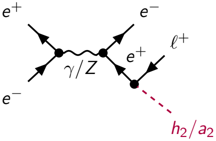


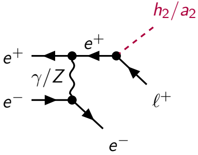
On-shell production H_2: $e^+e^- \to \ell^\pm \ell'^\mp + H_2$ [Li,MS 1907.06963]





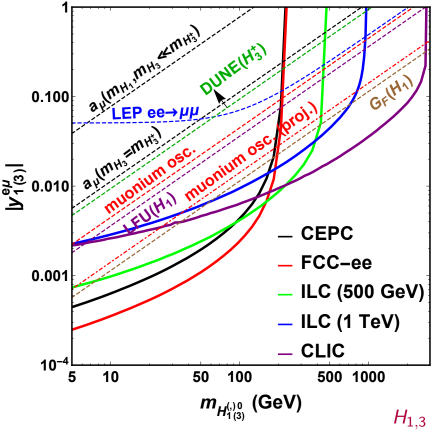


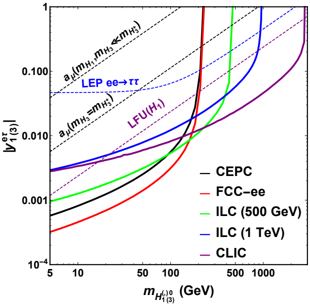


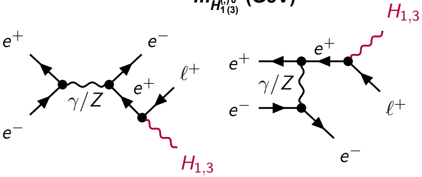


60% τ efficiency included

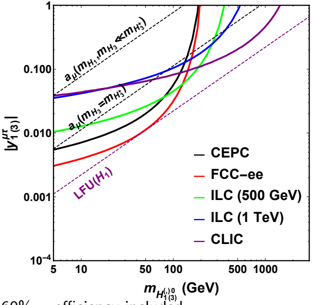
On-shell production $H_{1,3\mu}$: $e^+e^- \to \ell^\pm \ell'^\mp + H_{1,3}$ [Li,MS 1907.06963]





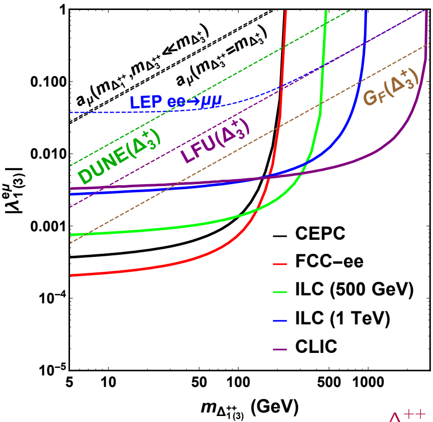


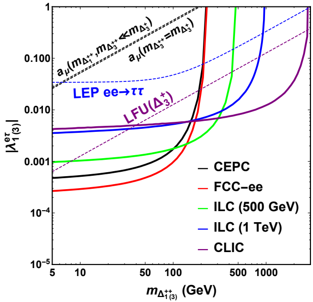
$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{L}_i \gamma^\mu P_L L_j + y_3^{ij} \bar{L}_i \gamma^\mu \vec{\sigma} \cdot H_{3\mu} P_L L_j$$

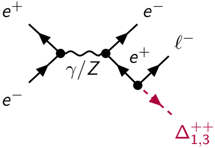


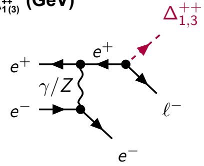
60% τ efficiency included

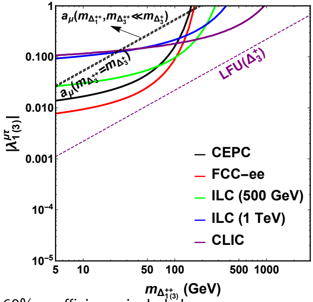
On-shell production $\Delta_{1,3}$: $e^+e^- \to \ell^\pm\ell'^\mp + \Delta_{1,3}$ [Li,MS 1907.06963]







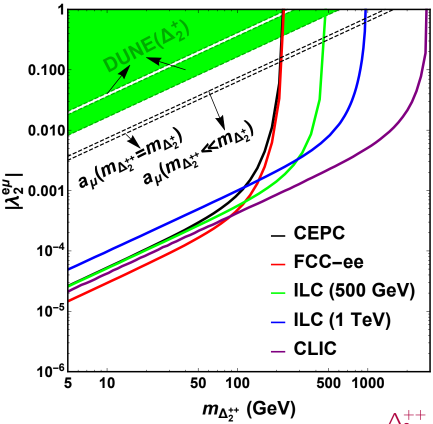


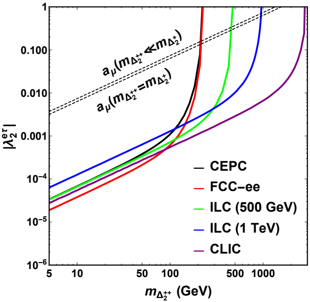


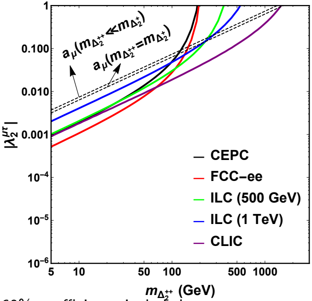
$$\mathcal{L} = \lambda_1^{ij}\Delta_1^{++}\ell_i^T C P_R \ell_j + \frac{\lambda_3^{ij}}{\sqrt{2}} L_i^T C i\sigma_2\vec{\sigma}\cdot\vec{\Delta}_3 P_L L_j + h.c.$$

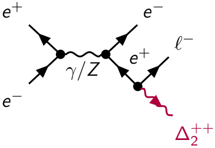
60% τ efficiency included

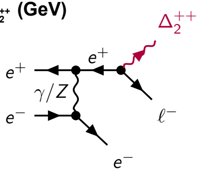
On-shell production $\Delta_{2\mu}$: $e^+e^- \to \ell^\pm \ell'^\mp + \Delta_2$ [Li,MS 1907.06963]











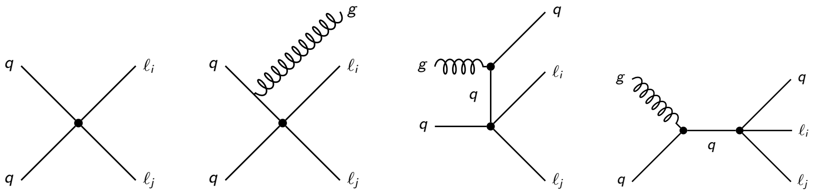
$$\mathcal{L} = \lambda_2^{ij} \Delta_{2\mu\alpha} L_{i\beta}^T C \gamma^\mu P_R \ell_j \epsilon_{\alpha\beta} + h.c.$$

60% τ efficiency included

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

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

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

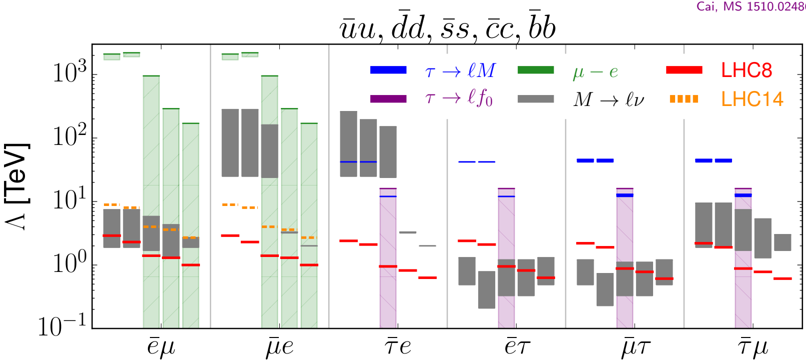


Signal: opposite-sign different flavour pair of leptons → existing searches:

- 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, 2.1 fb^{-1}, exclusive:
  LFV in $e\mu$ continuum in $\not R$ SUSY ATLAS 1205.0725
- ATLAS 8 TeV, 20.3 fb^{-1}, inclusive:
  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

cLFV at hadron colliders: quarks

Cai, MS 1510.02486



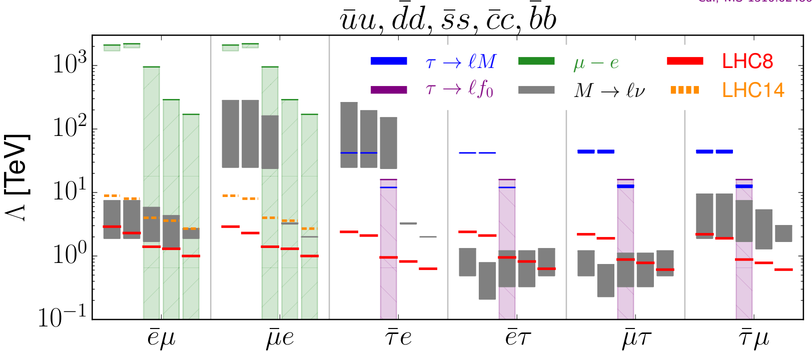
ATLAS 8TeV 1503.04430; ATLAS 14 TeV, 300 fb^{-1} projection

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

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

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

Cai, MS 1510.02486



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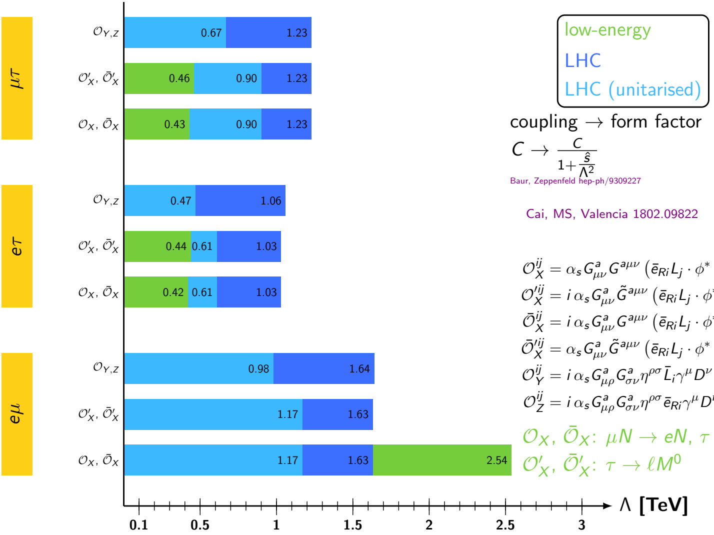
cLFV at hadron colliders: gluons



coupling → form factor

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

Baur, Zeppenfeld hep-ph/9309227

Cai, MS, Valencia 1802.09822

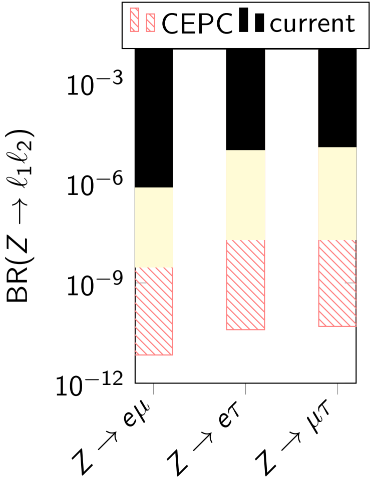
$$\mathcal{O}^{ij}_X = \alpha_s G^a_{\mu\nu} G^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* + \bar{L}_j \cdot \phi e_{Ri}\right)$$
$$\mathcal{O}'^{ij}_X = i\, \alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* - \bar{L}_j \cdot \phi e_{Ri}\right)$$
$$\bar{\mathcal{O}}^{ij}_X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

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

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

LHC searches: ATLAS 13 TeV, 3.2 fb^{-1} ($e\mu$, $e\tau$, $\mu\tau$) 1607.08079, CMS 13 TeV, 35.9 fb^{-1} ($e\mu$) 1802.01122

Searches for cLFV in decays of Z and Higgs boson

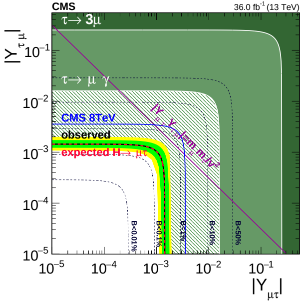


$Z \to e\mu$: ATLAS 1408.5774, CMS EXO-13-005

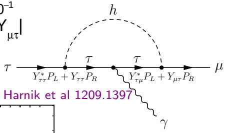
$Z \to \ell\tau$: DELPHI ($\mu\tau$), OPAL ($e\tau$)

similar sensitivity as LFV τ decays

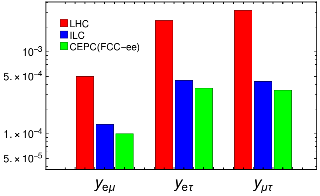
$\to$ complementary probe



CMS 1712.07173



Harnik et al 1209.1397



Qin et al 1711.07243

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

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

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

Conclusions

Conclusions

colliders provide complementary way to search for charged LFV

Off-shell production/EFT

- $\mu \leftrightarrow e$ flavour: stringent limits from low-energy precision exp.
- $\tau \leftrightarrow \ell$ flavour complementary sensitivity at colliders

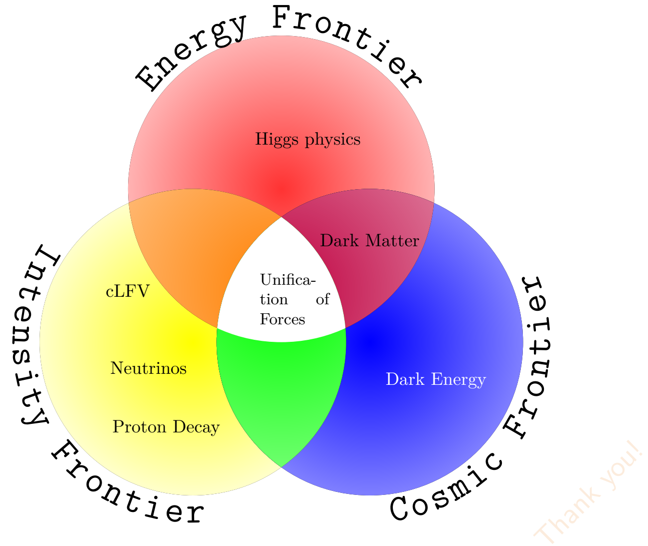
On-shell production

- possibly no constraints from LFV decays
- $\mu \leftrightarrow \tau$ flavour: constraints from LFU $[H_1, \Delta_3]$ and a_μ $[H_2]$
- $e \leftrightarrow \ell$ flavour complementary sensitivity at colliders

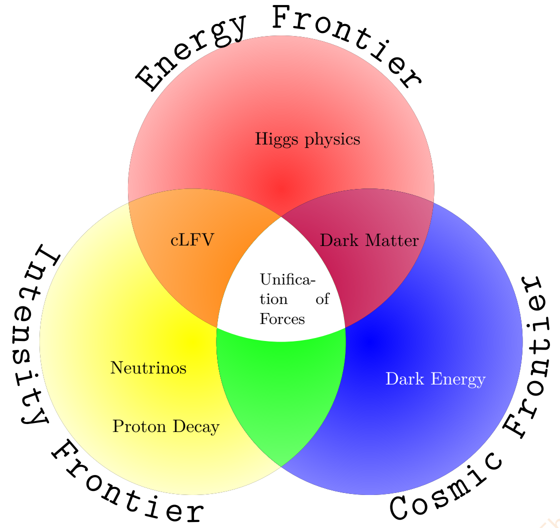
EFT

- colliders test more Lorentz structures
- best for operators which are difficult to constrain at low energy

Conclusions cont.

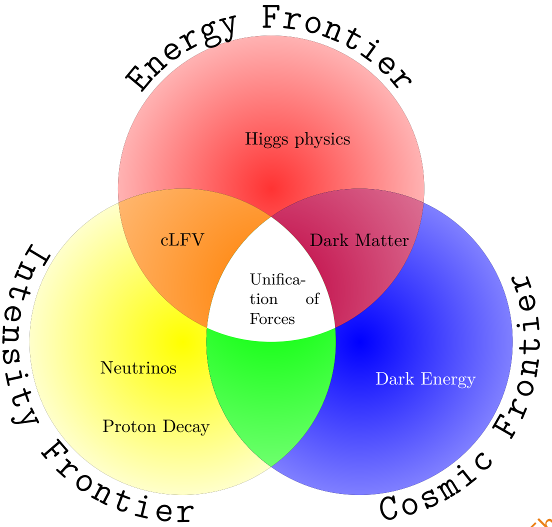


Conclusions cont.



Thank you!

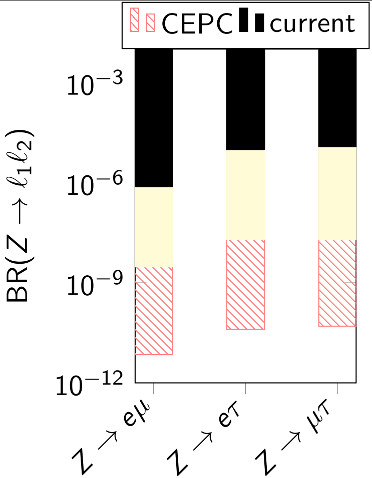
Conclusions cont.



Thank you!

Backup slides

cLFV 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

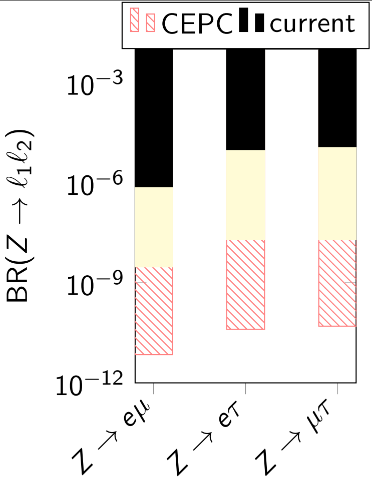
e.g. due to a leptoquark

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

cLFV Z boson decays



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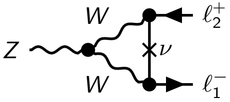

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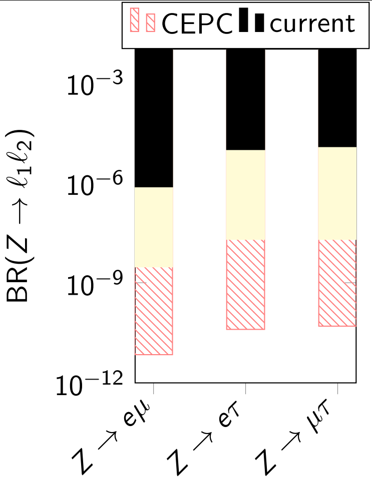
cLFV Z boson decays



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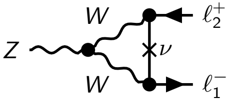

$\propto \frac{G_F m_\nu^2}{16\pi^2} \simeq 10^{-28}$

Observation clear sign of new physics

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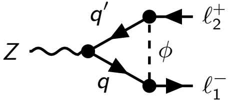


today typically less stringent as low-energy precision experiments

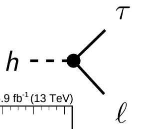
but will be more interesting with new Z boson factory

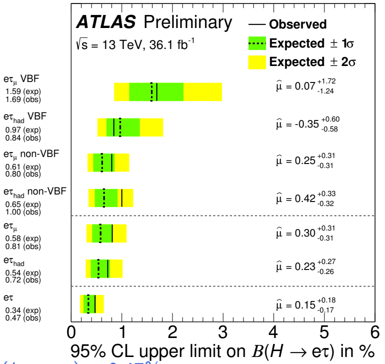
or if there is a signal to disentangle physics

cLFV Higgs decay

Dimension-6 SMEFT operators Grzadkowski et al 1008.4884

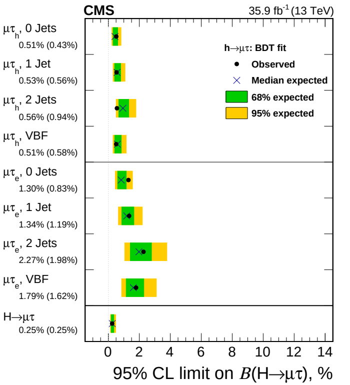
$$\mathcal{L} = \left[Y_{ij} + \frac{c_{ij}}{\Lambda^2} \left(H^\dagger H\right) \right] \bar{L}_i P_R \ell_j H + h.c. \rightarrow \left[\frac{m_{ij}}{v} + \frac{c_{ij}}{\sqrt{2}} \frac{v^2}{\Lambda^2} \right] h \bar{\ell}_i P_R \ell_j + h.c.$$





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

ATLAS-CONF-2019-013

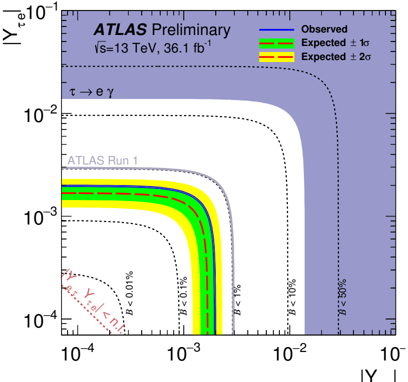


$BR(h \to \mu\tau) < 0.25\%$

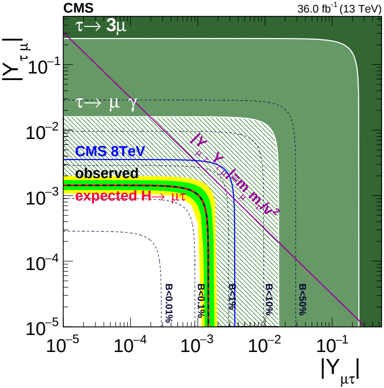
CMS 1712.07173

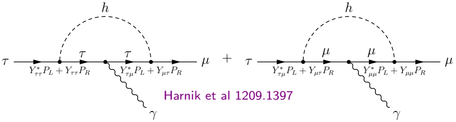
cLFV Higgs decay cont.

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

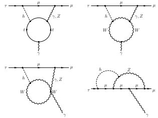


ATLAS-CONF-2019-013





Harnik et al 1209.1397



CMS 1712.07173

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

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

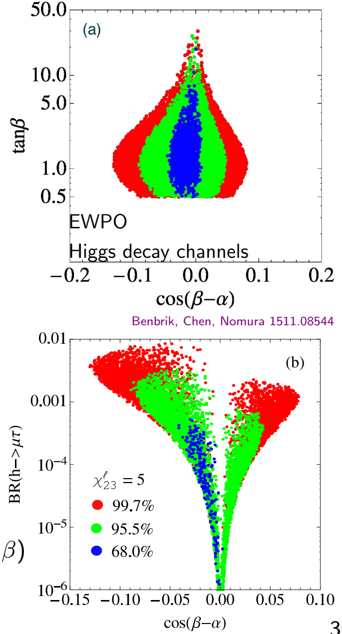
SM Higgs: $h = -s_\alpha \phi_1 + c_\alpha \phi_2$

with Yukawa couplings

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

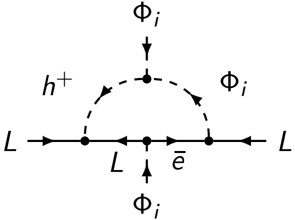
Not suppressed by $v^2/\Lambda^2 \to$ large contribution

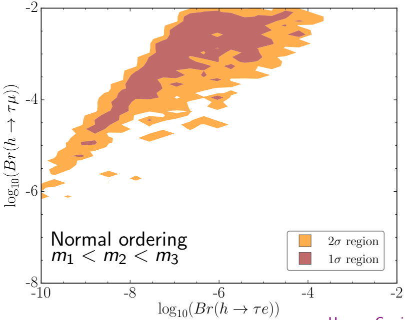
$$BR(h \to \mu\tau) \propto \left(|\chi^\ell_{23}|^2 + |\chi^\ell_{32}|^2\right)\cos^2(\beta-\alpha)(1+\tan^2\beta)$$

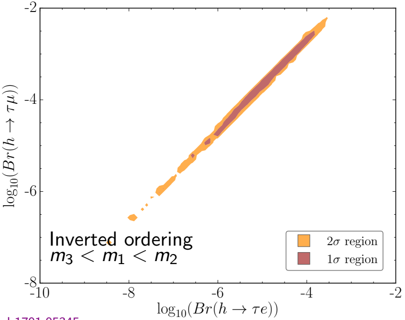


Example: Zee model

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



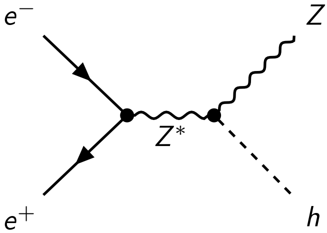


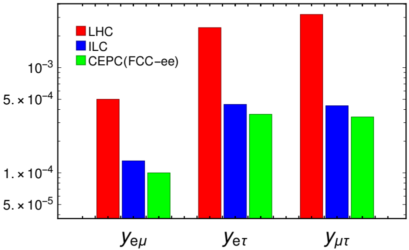


Herrero-Garcia et al 1701.05345

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

Future lepton collider

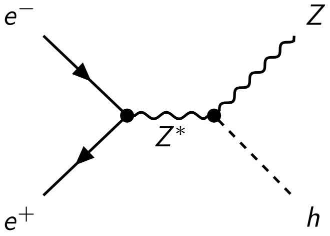


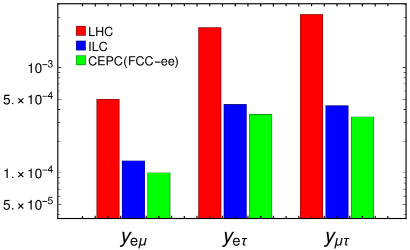


Qin et al 1711.07243

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, $\mathcal{L} = 5\ \text{ab}^{-1}$

Future lepton collider





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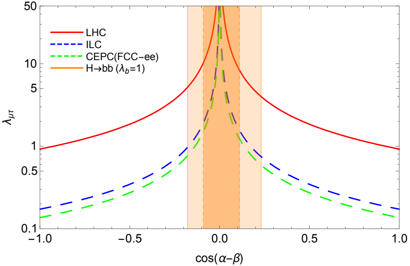
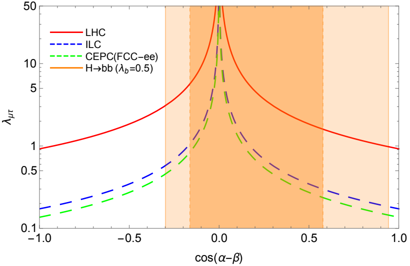


Qin et al 1711.07243



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.

We do not consider top quark because of different phenomenology.

Scalar Operators

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

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

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

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

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

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

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

⇒ No tree-level FCNC processes.

We do not consider top quark because of different phenomenology.

Scalar Operators

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

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

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

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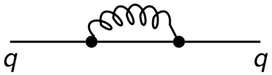
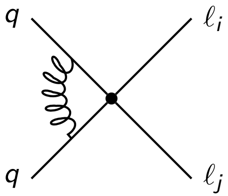
$$\begin{aligned}\Xi^{Nd}_{ij,kl} &= \delta_{kl}\Xi^d_{ij,kk} & \Xi^{Cd}_{ij,kl} &= U^*_{ii'}\, V^*_{kl}\, \Xi^d_{i'j,kk} \\ \Xi^{Nu}_{ij,kl} &= -\delta_{kl}\Xi^u_{ij,kk} & \Xi^{Cu}_{ij,kl} &= U^*_{ii'}\, V^*_{kl}\, \Xi^u_{i'j,ll}\end{aligned}$$

$\Rightarrow$ No tree-level FCNC processes.

We do not consider top quark because of different phenomenology.

- 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

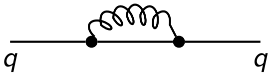
$$\beta_0 = 11 - 2n_F/3 \quad \text{and} \quad \gamma_0 = 6C_2(3) = 8$$

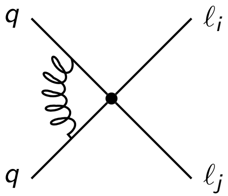
- Wilson coefficients become larger at smaller scales.

⇒ Increases reach of precision experiments

Renormalization Group Corrections

- Main effect are QCD corrections





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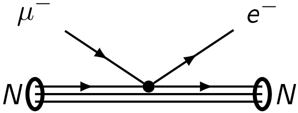
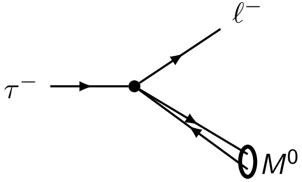
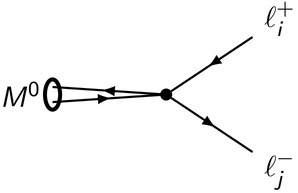


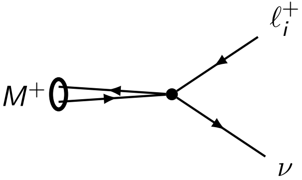
$\mu - e$ conversion in nuclei



$\tau \to \ell M^0$



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

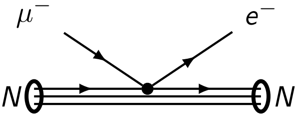


$M^+ \to \ell_i^+ \nu$

$\mu - e$ 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

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

$\mathcal{F}$ depends on mediation mechanism

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

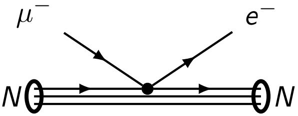
Strongest limit for first generation quarks,

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

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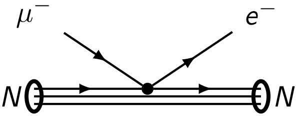
- Following discussion in

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



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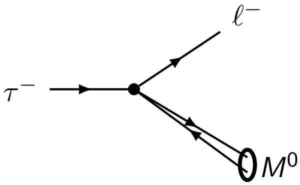
Direct nuclear mediation [Meson mediation]

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



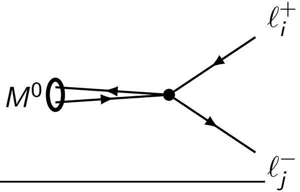
$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

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

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

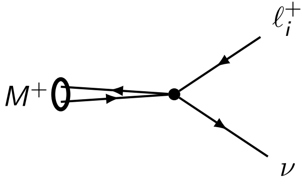


For $\lambda = 0$ only constraints from $\pi^0, \eta^{(\prime)}$ decays

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

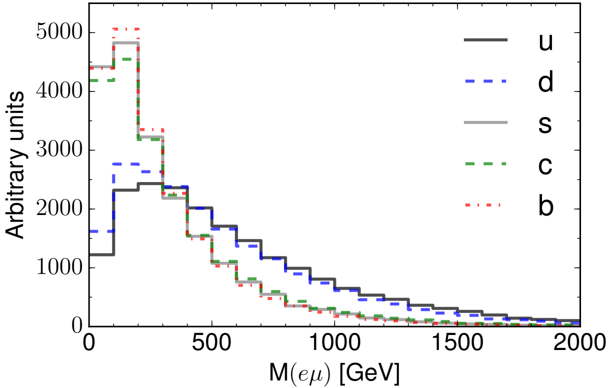
Leptonic Charged Meson Decays $M^+ \to \ell_i^+ \nu$

- $R_M = \frac{\mathrm{Br}(M^+ \to e^+ \nu)}{\mathrm{Br}(M^+ \to \mu^+ \nu)}$
- 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	✓	-	-	-	(✓)
$\mathrm{Br}(\pi^+ \to \mu^+ \nu)$	$\mathrm{Br}^{exp} \pm 5\%$	$1.9 - 7.4$	$1.9 - 9.4$	(✓)	(✓)	-	-	-
$\mathrm{Br}(K^+ \to \mu^+ \nu)$	$\mathrm{Br}^{exp} \pm 5\%$	$1.7 - 5.8$	$1.7 - 7.4$	✓	-	(✓)	-	-
$\mathrm{Br}(D^+ \to \mu^+ \nu)$	$(3.82 \pm 0.33) \times 10^{-4}$	$1.1 - 2.7$	$1.1 - 3.4$	-	✓	-	✓	-
$\mathrm{Br}(D_s^+ \to \mu^+ \nu)$	$(5.56 \pm 0.25) \times 10^{-3}$	$1.3 - 4.3$	$1.3 - 5.3$	-	-	✓	(✓)	-
$\mathrm{Br}(B^+ \to \mu^+ \nu)$	$< 1.0 \times 10^{-6}$	$1.9 - 2.7$	$1.7 - 3.0$	✓	-	-	-	(✓)
$\mathrm{Br}(D^+ \to \tau^+ \nu)$	$< 1.2 \times 10^{-3}$	$0.21 - 0.78$	$0.23 - 0.73$	-	(✓)	-	✓	-
$\mathrm{Br}(D_s^+ \to \tau^+ \nu)$	$(5.54 \pm 0.24) \times 10^{-2}$	$0.33 - 1.2$	$0.33 - 1.1$	-	-	(✓)	(✓)	-
$\mathrm{Br}(B^+ \to \tau^+ \nu)$	$(1.14 \pm 0.27) \times 10^{-4}$	$0.49 - 1.3$	$0.49 - 1.2$	(✓)	-	-	-	(✓)

Invariant Mass Distribution of $e\mu$ Pair for Different Quarks



Production cross section normalised to same value for each quark.

- Sea quarks s, c, b peaked at low invariant mass
- Valence quarks u, d shifted towards larger invariant mass

Interesting ATLAS searches [Cai, MS 1510.02486]

Recast limits of most sensitive previous searches

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

Projection to 14 TeV

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

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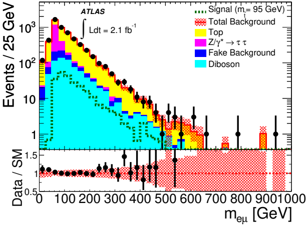
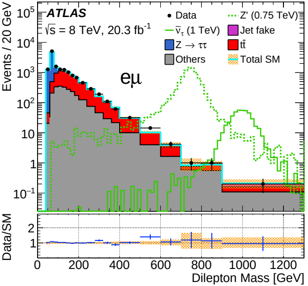
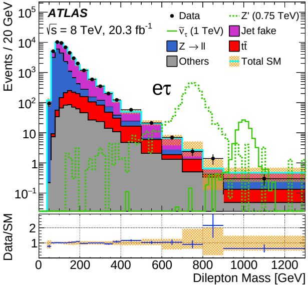


ATLAS 7TeV 1205.0725





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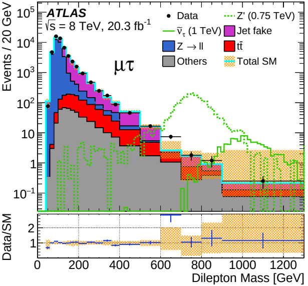

ATLAS 8TeV 1503.04430

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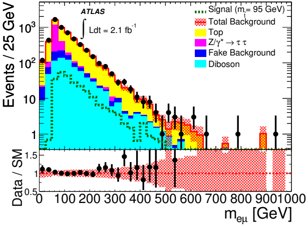

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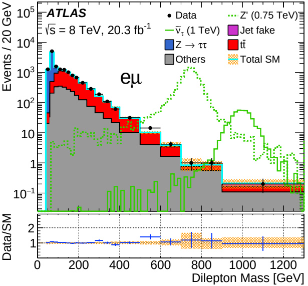


ATLAS 8TeV 1503.04430

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

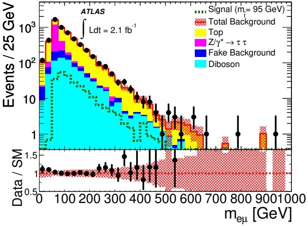
  also W/Z plus jets, WZ/ZZ, single top and $W/Z+\gamma$

⇒ 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



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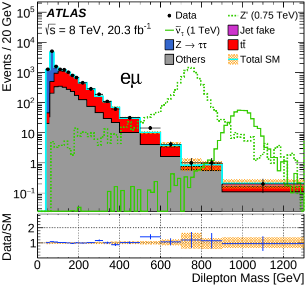

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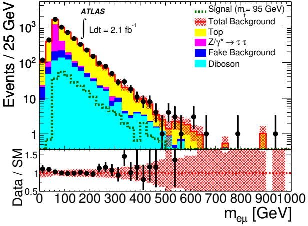

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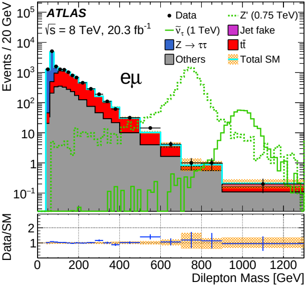

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Selection Criteria

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

$\bar{q}q$ \ $\bar{\ell}_i\ell_j$	$\bar{e}\mu$			$\bar{e}\tau$	$\bar{\mu}\tau$
	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

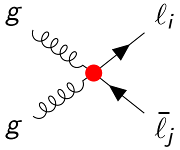
- 8 TeV analysis gives only a slight improvement compared to 7 TeV despite 10 times more data because of large background
- $e\tau$ and $\mu\tau$ limits weaker than $e\mu$ because of low τ-tagging rate and higher fake background
- 14 TeV projection: same search strategy as 7 TeV exclusive search

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

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

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



Signal:

opposite-sign different flavour pair of leptons

Most sensitive searches

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13 TeV	13 TeV
3.2 fb^{-1}	35.9 fb^{-1}
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newer ATLAS search: 13 TeV, 36.1 fb^{-1} 1807.06573

EFT scattering amplitudes

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

$\Rightarrow$ Violation of perturbative unitarity

Solutions:

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

  Wigner 1964; Wigner, Eisenbud 1947; Gupta 1950

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

  Baur, Zeppenfeld hep-ph/9309227

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

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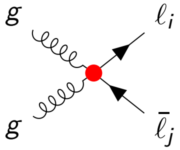

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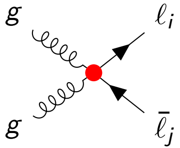

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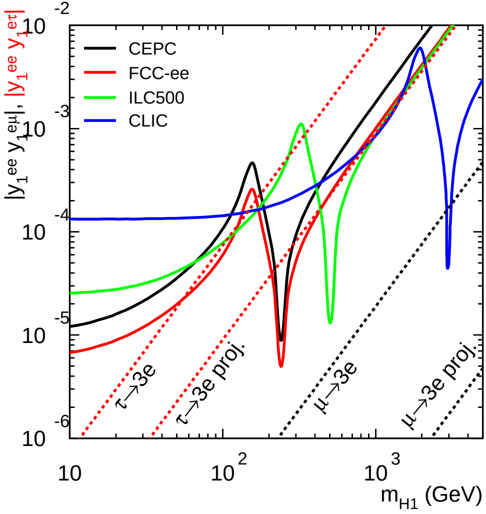
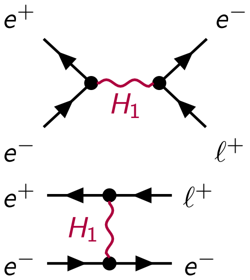
$H_{1\mu}$: $e^+e^- \to e^\pm\mu^\mp(e^\pm\tau^\mp)$



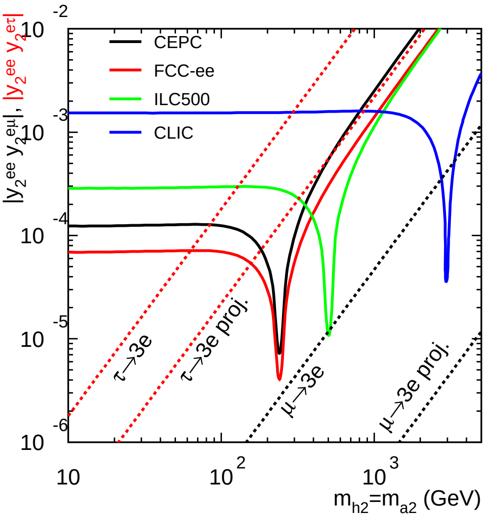
$$\mathcal{L} = y_1^{ij} H_{1\mu} \bar{\ell}_i \gamma^\mu P_L \ell_j$$



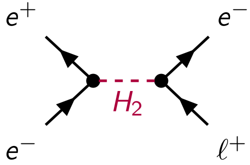
same result for right-handed $H'_{1\mu}$

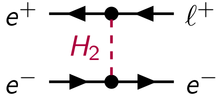
τ efficiency not included in figure
60% τ eff. $\Rightarrow$ 77% (60%) sensitivity reduction for 1 (2) τ leptons

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

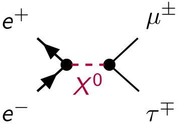


$$\mathcal{L} = y_2^{ij} H_2^0 \bar{\ell}_i P_R \ell_j + h.c.$$



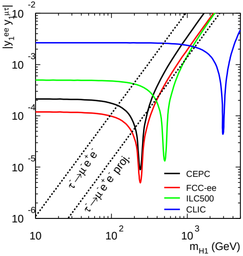


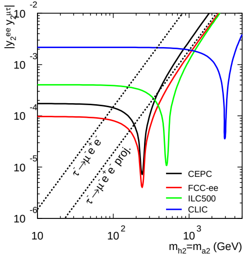
$H_{1\mu}, H_2$: $e^+e^- \to \mu^\pm\tau^\mp$

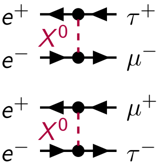


rel. couplings

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







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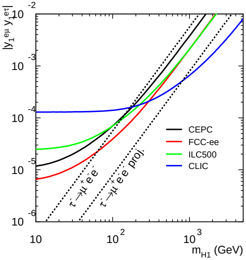
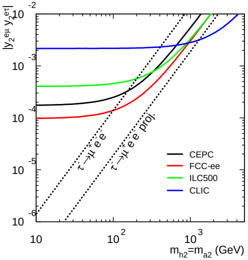
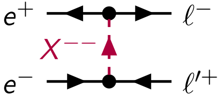




Δ_1, $\Delta_{2\mu}$: $e^+e^- \to \ell^+\ell'^-$



relevant couplings
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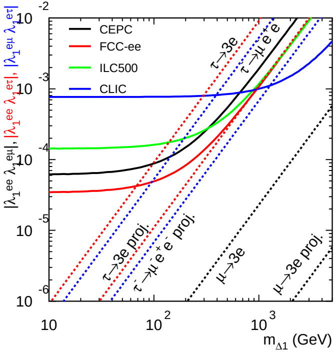

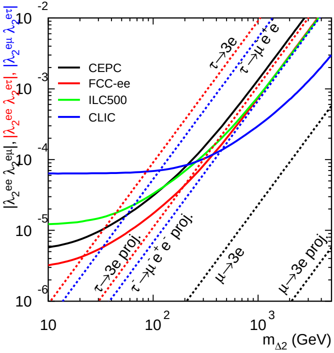

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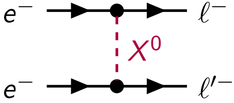

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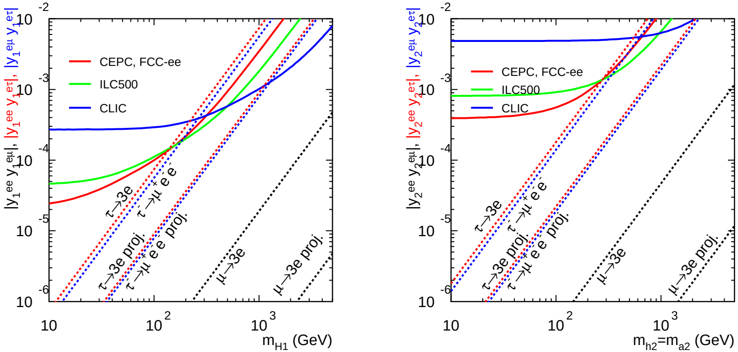

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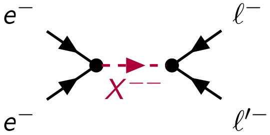

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