LHC vs. Precision Experiments

A Comparison of LFV D6 and D8 Operators

Yi Cai

May 31, 2017

Blois

w/ M. Schmidt[G. Valencia] JHEP 02 (2016) 176 [1706.xxxxx]

THE UNIVERSITY OF MELBOURNE

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

Motivation

The Standard Model is very successful...

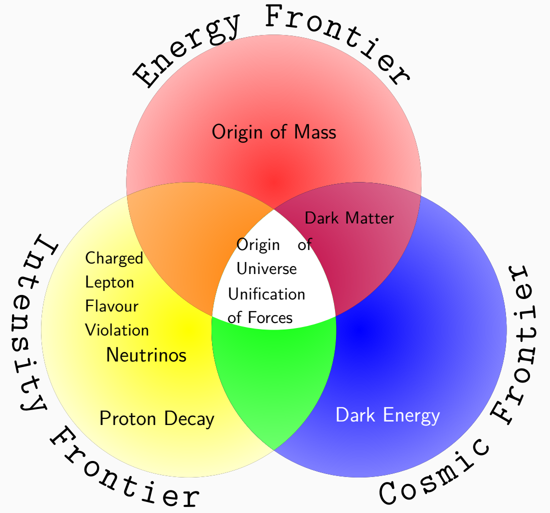
...but incomplete

In particular neutrinos are massive

Lepton flavour is not conserved

$\rightarrow$ Flavour changing processes are a sensitive probe

Motivation



Can the LHC compete with precision experiments?

Dimension-6 Operators in SM EFT

D6 Operators with 2 Quarks and 2 Leptons

Buchmüller, Wyler NPB268(1986)621; Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

Scalar

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

Vector

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

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

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

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

Tensor

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

D6 Operators with 2 Quarks and 2 Leptons

Buchmüller, Wyler NPB268(1986)621; Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

Scalar with same-flavour quark

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

Vector e.g. Carpentier, Davidson 1008.0280; Petrov,Zhuridov 1308.6561

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

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

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

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

Tensor

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

D6 Scalar Operators

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

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

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

Effective four fermion Lagrangian

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

We do not consider top quark because of different phenomenology.

D6 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

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

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.

D6 Scalar Operators

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

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

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

Effective four fermion Lagrangian

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

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

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

$\Rightarrow$ No tree-level FCNC processes.

We do not consider top quark because of different phenomenology.

D6 Scalar Operators

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

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

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

Effective four fermion Lagrangian

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

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

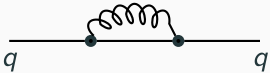
$$\begin{aligned} \Xi^{Nd}_{ij,kl} &= \delta_{kl}\Xi^d_{ij,kk} & \qquad \Xi^{Cd}_{ij,kl} &= U^*_{ii'} V^*_{kl} \Xi^d_{i'j,kk} \\ \Xi^{Nu}_{ij,kl} &= -\delta_{kl}\Xi^u_{ij,kk} & \qquad \Xi^{Cu}_{ij,kl} &= U^*_{ii'} V^*_{kl} \Xi^u_{i'j,ll} \end{aligned}$$

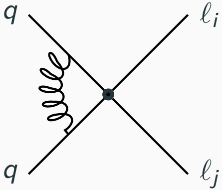
$\Rightarrow$ No tree-level FCNC processes.

We do not consider top quark because of different phenomenology.

Renormalization Group Corrections for D6 Ops

- Main effect are QCD corrections





- Following the standard discussion at NLO

Buchalla,Buras, Lautenbacher hep-ph/9512380

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

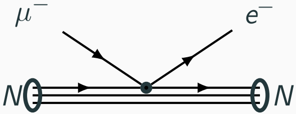
with coefficients

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

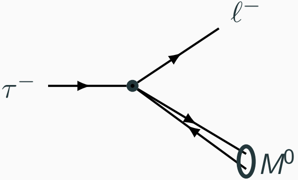
- Wilson coefficients become larger at smaller scales.

$\Rightarrow$ Increases reach of precision experiments

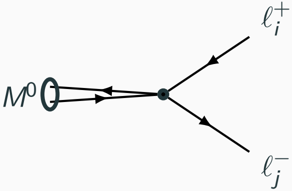
Precision Experiments for D6 Ops



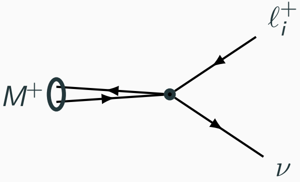
$\mu - e$ conversion in nuclei



$\tau \to \ell M^0$



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

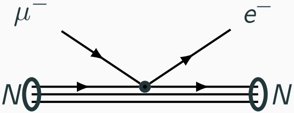


$M^+ \to \ell_i^+ \nu$

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in

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



Dimensionless $\mu - e$ conversion rate

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

with muon conversion rate

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

$\mathcal{F}$ depends on mediation mechanism

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

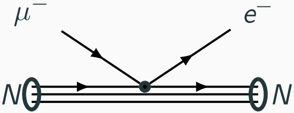
Strongest limit for first generation quarks,

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

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in

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



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

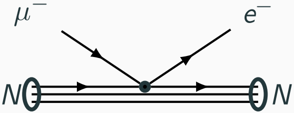
Direct nuclear mediation [Meson mediation]

Strongest limit for first generation quarks,
but non-negligible for other quarks if pure direct nuclear mediation

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in

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



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

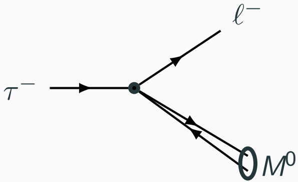
Direct nuclear mediation [Meson mediation]

Strongest limit for first generation quarks,
but non-negligible for other quarks if pure direct nuclear mediation

LFV Semileptonic τ Decays

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

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



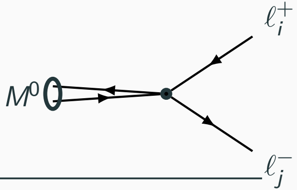
decay	$\mathrm{Br}_i^{\max}$	cutoff scale Λ [TeV]		
		$\Xi^u_{ij,uu}$	$\Xi^d_{ij,dd}$	$\Xi^d_{ij,ss}$
$\tau^- \to e^-\pi^0$	8.0×10^{-8}	10	10	-
$\tau^- \to e^-\eta$	9.2×10^{-8}	34	34	7.9
$\tau^- \to e^-\eta'$	1.6×10^{-7}	42	42	12
$\tau^- \to e^-K^0_S$	2.6×10^{-8}	-	$7.8\sqrt{\lambda}$	$7.8\sqrt{\lambda}$
$\tau^- \to e^-(f_0(980) \to \pi^+\pi^-)$	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

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

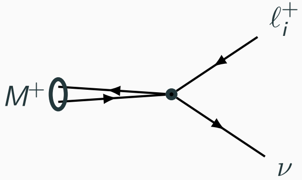
For $\lambda = 0$ only constraints from $\pi^0, \eta^{(\prime)}$ decays



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

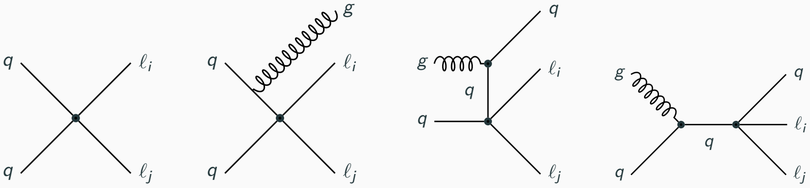
- $R_M = \frac{\mathrm{Br}(M^+ \to e^+ \nu)}{\mathrm{Br}(M^+ \to \mu^+ \nu)}$
- Theoretical error for R_π (R_K) about 5%
- Improvement by factor 20 (2) possible
- $\boxed{\checkmark}$ indicates constraints
- Second index of Λ corresponds to charged lepton



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	$R_\pi^{exp} \pm 5\%$	$25 - 280$	$25 - 260$	$\boxed{\checkmark}$	$\boxed{\checkmark}$	-	-	-
R_K	$R_K^{exp} \pm 5\%$	$24 - 160$	$24 - 150$	$\checkmark$	-	$\boxed{\checkmark}$	-	-
$\mathrm{Br}(D^+ \to e^+ \nu)$	$< 8.8 \times 10^{-6}$	$2.8 - 2.9$	2.9	-	$\checkmark$	-	$\checkmark$	-
$\mathrm{Br}(D_s^+ \to e^+ \nu)$	$< 8.3 \times 10^{-5}$	$3.2 - 3.3$	$3.2 - 3.3$	-	-	$\checkmark$	$\boxed{\checkmark}$	-
$\mathrm{Br}(B^+ \to e^+ \nu)$	$< 9.8 \times 10^{-7}$	2.0	2.0	$\checkmark$	-	-	-	$\boxed{\checkmark}$
$\mathrm{Br}(\pi^+ \to \mu^+ \nu)$	$\mathrm{Br}^{exp} \pm 5\%$	$1.9 - 7.4$	$1.9 - 9.4$	$\boxed{\checkmark}$	$\boxed{\checkmark}$	-	-	-
$\mathrm{Br}(K^+ \to \mu^+ \nu)$	$\mathrm{Br}^{exp} \pm 5\%$	$1.7 - 5.8$	$1.7 - 7.4$	$\checkmark$	-	$\boxed{\checkmark}$	-	-
$\mathrm{Br}(D^+ \to \mu^+ \nu)$	$(3.82 \pm 0.33) \times 10^{-4}$	$1.1 - 2.7$	$1.1 - 3.4$	-	$\checkmark$	-	$\checkmark$	-
$\mathrm{Br}(D_s^+ \to \mu^+ \nu)$	$(5.56 \pm 0.25) \times 10^{-3}$	$1.3 - 4.3$	$1.3 - 5.3$	-	-	$\checkmark$	$\boxed{\checkmark}$	-
$\mathrm{Br}(B^+ \to \mu^+ \nu)$	$< 1.0 \times 10^{-6}$	$1.9 - 2.7$	$1.7 - 3.0$	$\checkmark$	-	-	-	$\boxed{\checkmark}$
$\mathrm{Br}(D^+ \to \tau^+ \nu)$	$< 1.2 \times 10^{-3}$	$0.21 - 0.78$	$0.23 - 0.73$	-	$\boxed{\checkmark}$	-	$\checkmark$	-
$\mathrm{Br}(D_s^+ \to \tau^+ \nu)$	$(5.54 \pm 0.24) \times 10^{-2}$	$0.33 - 1.2$	$0.33 - 1.1$	-	-	$\boxed{\checkmark}$	$\boxed{\checkmark}$	-
$\mathrm{Br}(B^+ \to \tau^+ \nu)$	$(1.14 \pm 0.27) \times 10^{-4}$	$0.49 - 1.3$	$0.49 - 1.2$	$\boxed{\checkmark}$	-	-	-	$\boxed{\checkmark}$

LHC

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

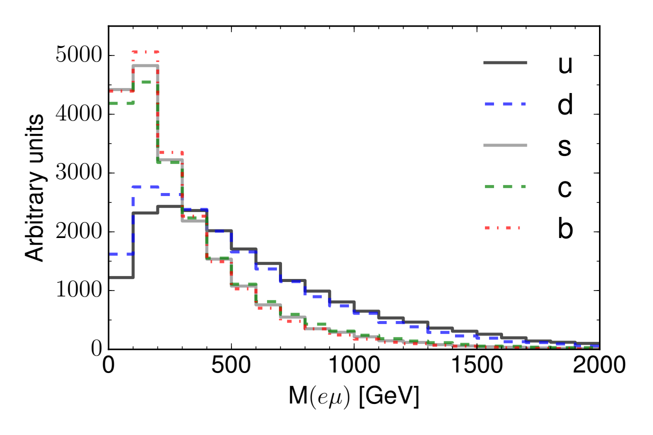


Signal: opposite-sign different flavour pair of leptons

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: LFV heavy neutral particle decay ATLAS 1607.08079

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

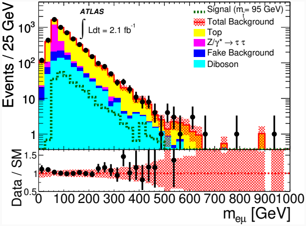
This Study

Recast limits of most sensitive previous searches

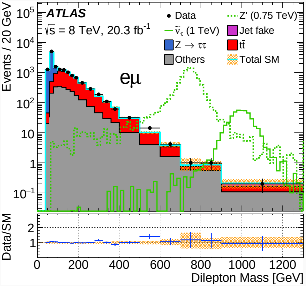
ATLAS 1503.04430	ATLAS 1205.0725
8 TeV	7 TeV
$20.3\ \mathrm{fb}^{-1}$	$2.1\ \mathrm{fb}^{-1}$
$e\mu$, $e\tau$, $\mu\tau$	$e\mu$
inclusive	exclusive
including arbitrary number of jets	separated by number of jets

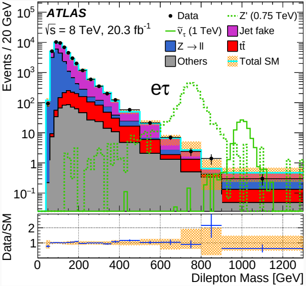
- Assuming $300\ \mathrm{fb}^{-1}$
- Follow searching strategy of exclusive 7 TeV search

ATLAS Searches

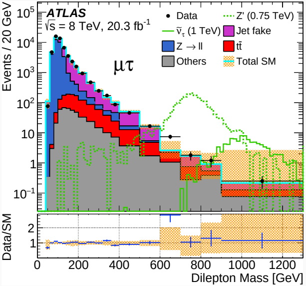


ATLAS 7TeV 1205.0725





ATLAS 8TeV 1503.04430



ATLAS 8TeV 1503.04430

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

Dimension 8 Operators

D8 Operators

- Operators with two gluons and two leptons

  Henning *et. al.* 1512.03433

$$
\begin{aligned}
\mathcal{L}_{8d} \sim & x_{ij}\left(G^a_{\mu\nu}G^{a\mu\nu}\bar{e}_i L_j \phi^* + h.c.\right) + x'_{ij}\left(i\tilde{G}^a_{\mu\nu}G^{a\mu\nu}\bar{e}_i L_j \phi^* + h.c.\right) \\
& + \bar{x}_{ij}\left(G^a_{\mu\nu}G^{a\mu\nu}\bar{e}_i L_j \phi^* - h.c.\right) + \bar{x}'_{ij}\left(i\tilde{G}^a_{\mu\nu}G^{a\mu\nu}\bar{e}_i L_j \phi^* - h.c.\right) \\
& + y_{ij}G^a_{\mu\rho}G^a_{\sigma\nu}\eta^{\rho\sigma}L^\dagger_i \bar{\sigma}^\mu D^\nu L_i + z_{ij}G^a_{\mu\rho}G^a_{\sigma\nu}\eta^{\rho\sigma}\bar{e}^\dagger_i \bar{\sigma}^\mu D^\nu \bar{e}_i
\end{aligned}
$$

- Possible UV Completions
  - *s*-channel exchange of a spin 0 particle
  - *s*-channel exchange of a spin 2 particle

Precision Experiments for D8 Ops

- μ-e conversion
  - weaker constraints on operators with derivatives
  - $G\tilde{G}$ leads to incoherent contribution

$$\mathrm{Ti}: \quad \Lambda > 3.1\mathrm{TeV} \qquad\qquad \mathrm{Au}: \quad \Lambda > 3.7\mathrm{TeV}$$

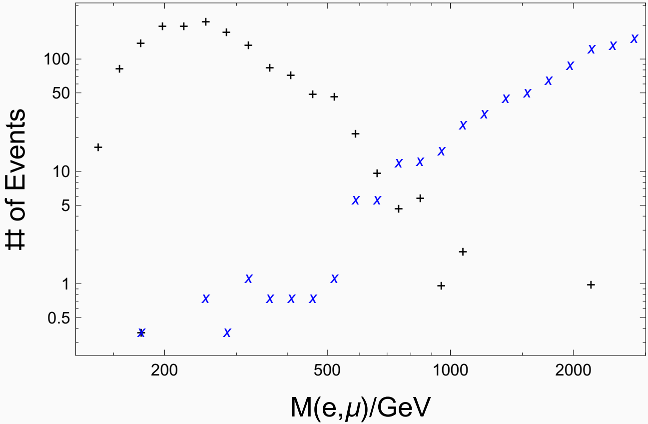
- τ decay
  - on GG

$$Br(\tau \to \mu\pi^+\pi^-) < 2.1 \times 10^{-8} \qquad \Lambda > 430\mathrm{GeV}$$
$$Br(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-8} \qquad \Lambda > 420\mathrm{GeV}$$

  - on $G\tilde{G}$

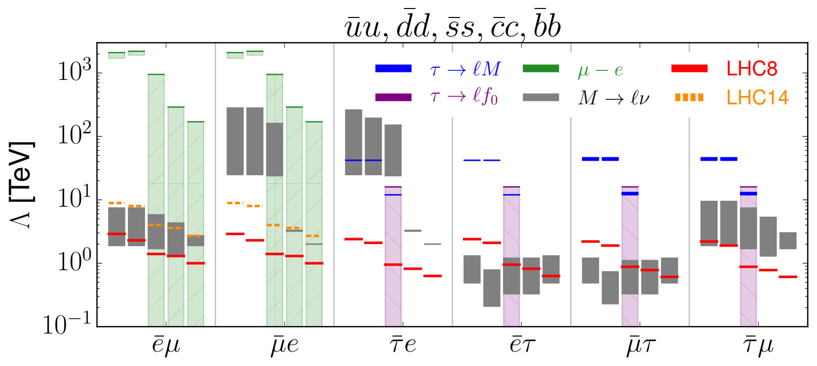
$$Br(\tau \to \mu\eta') < 1.3 \times 10^{-7} \qquad \Lambda > 330\mathrm{GeV}$$
$$Br(\tau \to e\eta') < 1.6 \times 10^{-7} \qquad \Lambda > 320\mathrm{GeV}$$

LHC for D8 Ops(Preliminary)



- ATLAS 3.2 fb^{-1} analysis 1607.08079
- signal shown for cross section $\sigma = 1$ pb
- cut $M(e, \mu) > 1$ TeV, limit set at $\Lambda > 2.3$ TeV

Conclusions



Precision experiments win for light quarks

LHC competitive for heavy quarks and right-handed τ-leptons

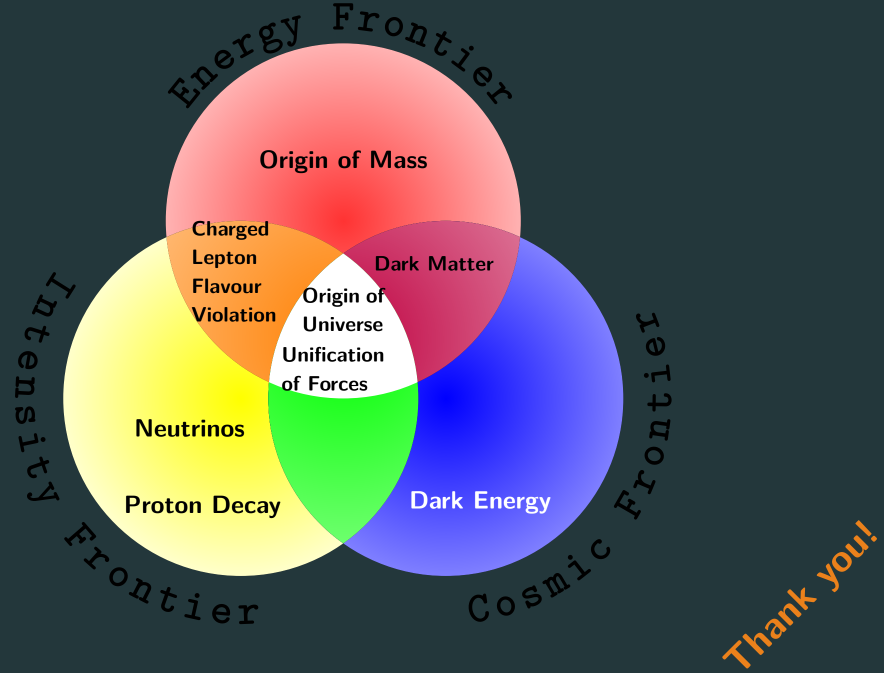
$\gtrsim$ 600 – 800 GeV

Outlook

- LHC more competitive for vector operators with right-handed quark currents

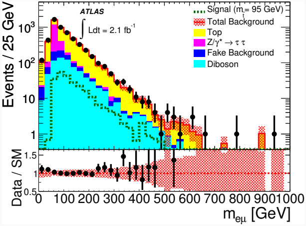
$$\mathcal{Q}_{eu} = (\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ed} = (\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)$$
$$\mathcal{Q}_{lu} = (\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}_{ld} = (\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$$

- D8 operators with two gluons and two leptons have better limits at the LHC with more data

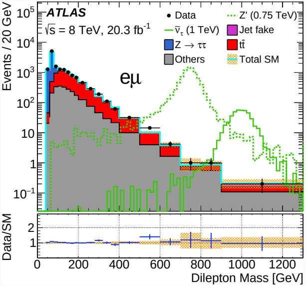

Energy Frontier
Intensity Frontier
Cosmic Frontier
Origin of Mass
Charged Lepton Flavour Violation
Dark Matter
Origin of Universe
Unification of Forces
Neutrinos
Proton Decay
Dark Energy
Thank you!

Backup Slides

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

Limit setting

7 and 8 TeV

- Use maximum likelihood estimator for 7 and 8 TeV

$$\mathcal{L}_i(\mu, \tilde{\theta}_i | n_i) = \mathcal{P}(n_i | \mu s_i + b_i)\mathcal{G}(\tilde{\theta}_i, 0, 1)$$

$\mathcal{P}$ is Poisson function and $\mathcal{G}$ Gaussian function, nuisance parameters $\tilde{\theta}_i$

- SM background and observed events taken from ATLAS publications
- Total likelihood function is product

$$\mathcal{L} = \prod_i \mathcal{L}_i$$

14 TeV

- Estimate reach for 14 TeV using

$$\text{Significance} = \frac{S}{\sqrt{S + (\Delta S)^2 + (\Delta B)^2}}$$

with $\Delta S = 10\% S$ and $\Delta B = 10\% B$.