LHC vs. Precision Experiments

A Comparison of LFV D6 Operators QQLL

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The University of Sydney

based on

Yi Cai, MS   JHEP02(2016)176

THE UNIVERSITY OF SYDNEY

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

Motivation

- Standard Model very successful

Motivation

- Standard Model very successful
- but incomplete

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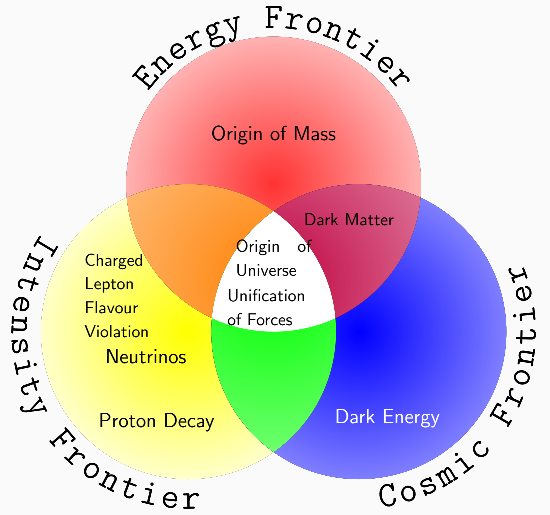
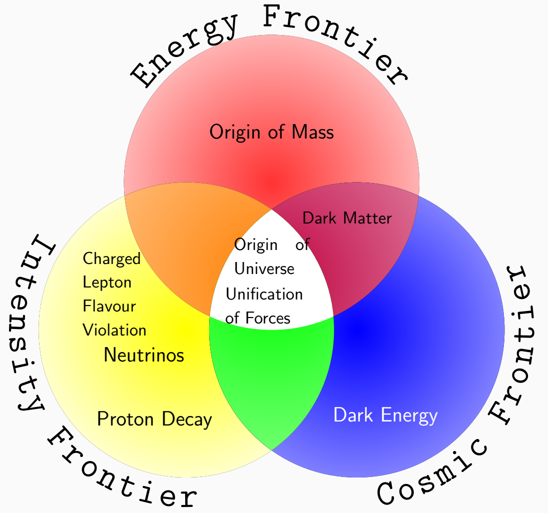
- Standard Model very successful
- but incomplete
- Flavour changing processes are a sensitive probe

Motivation



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

Motivation



Can the LHC compete with precision experiments?

Operators

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

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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 Carpentier, Davidson 1008.0280; Petrov,Zhuridov 1308.6561

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

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

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

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Tensor

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

Scalar Operators

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

Wilson coefficients $\Xi^{u,d}$ in Lagrangian [unbroken phase]

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

Effective four fermion Lagrangian [broken phase]

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

Thus the most general four fermion coefficients are

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

$\Rightarrow$ In general there is quark flavour violation.

We do not consider top-quark, because phenomenology is different.

Scalar Operators

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

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

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

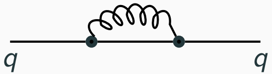
$$\Xi^{Nu}_{ij,kl} = -\delta_{kl}\Xi^u_{ij,kk} \qquad \Xi^{Cu}_{ij,kl} = U^*_{ii'} V^*_{kl} \Xi^u_{i'j,ll}$$

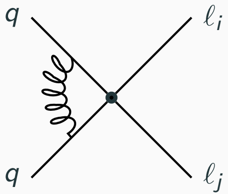
$\Rightarrow$ No new flavour changing neutral current processes (FCNCs).

We do not consider top-quark, because phenomenology is different.

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

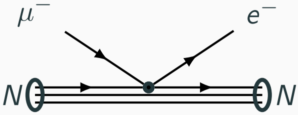
$$\beta_0 = 11 - 2n_F/3 \quad \text{and} \quad \gamma_0 = 6C_2(3) = 8$$

- Wilson coefficients become larger at smaller scales.

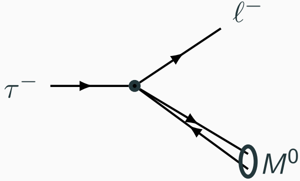
⇒ Increases reach of precision experiments

Precision Experiments

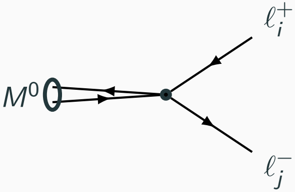
Precision Experiments



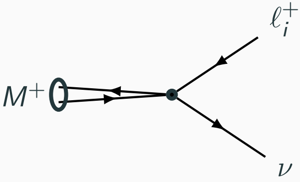
$\mu - e$ conversion in nuclei



$\tau \to eM^0$



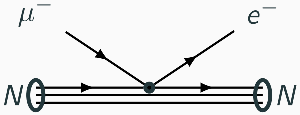
$M^0 \to \ell_i^+ \ell_j^-$



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

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in Gonzalez et al. 1303.0596

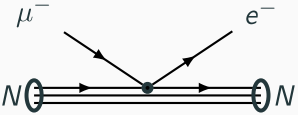


	^{48}Ti	^{197}Au	^{208}Pb
$R_{\mu e}^{\max}$	4.3×10^{-11}	7.0×10^{-13}	4.6×10^{-11}
$\bar{u}u$	1100 [870]	2100 [1700]	760 [610]
$\bar{d}d$	1100 [930]	2200 [1900]	780 [680]
$\bar{s}s$	480 [-]	950 [-]	340 [-]
$\bar{c}c$	150 [-]	290 [-]	110 [-]
$\bar{b}b$	84 [-]	170 [-]	61 [-]

Direct nuclear mediation [Meson mediation]

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in Gonzalez et al. 1303.0596



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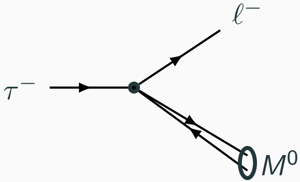
Direct nuclear mediation [Meson mediation]

$\Rightarrow$ Strongest limit for first generation quarks,
and non-negligible for other quarks if pure direct nuclear mediation

LFV τ Decays

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

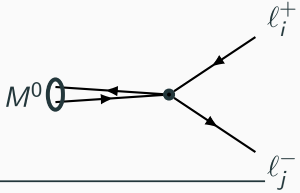


$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \quad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

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

- Assumption: no quark FCNC processes
- What if assumption does not hold?

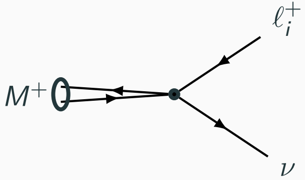


$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

decay	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 corresponds to charged lepton

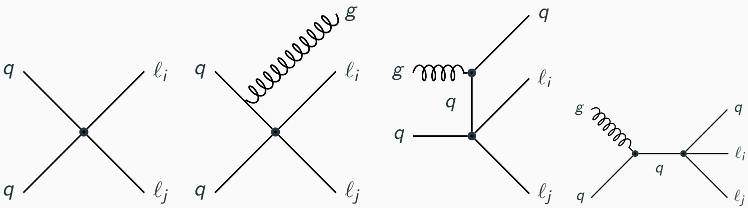


decay	constraint	cutoff scale Λ [TeV]		Wilson coefficients				
		$\Lambda_{\mu e, e\mu, e\tau}$	$\Lambda_{\tau e, \tau\mu, \mu\tau}$	$\Xi^u_{ij,uu}$	$\Xi^d_{ij,dd}$	$\Xi^d_{ij,ss}$	$\Xi^u_{ij,cc}$	$\Xi^d_{ij,bb}$
R_π	$R_\pi^{exp} \pm 5\%$	$25 - 280$	$25 - 260$	**✓**	**✓**	-	-	-
R_K	$R_K^{exp} \pm 5\%$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

Large Hadron Collider

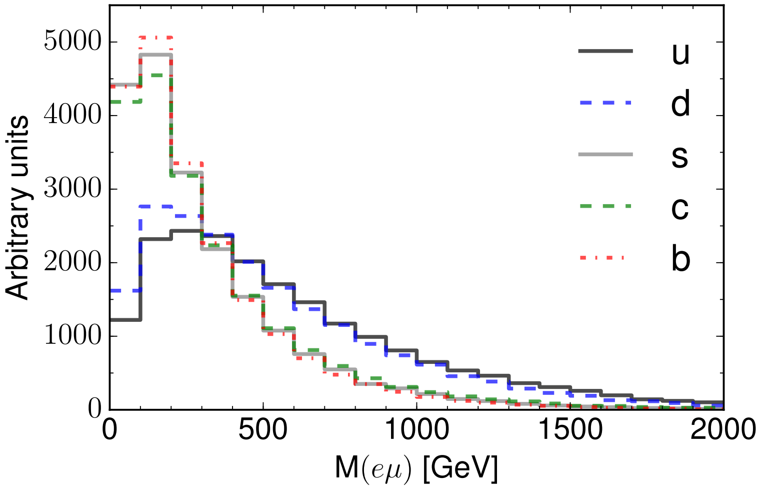
LFV at the Large Hadron Collider (LHC)

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



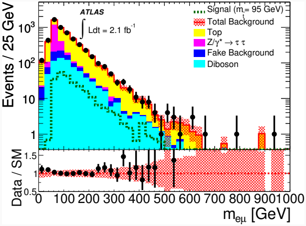
- Signal: opposite-sign different flavour pair of leptons and possibly jets
- ATLAS 7 TeV: LFV in $e\mu$ continuum [$\tilde{t}$ and $\not{R}$]ATLAS 1205.0725
- ATLAS 8 TeV: LFV heavy neutral particle decay ATLAS 1503.04430
- Projection to 14 TeV with 300 fb^{-1}
- Study invariant mass distribution of $e\mu$ pair

Comparison for Different Quarks

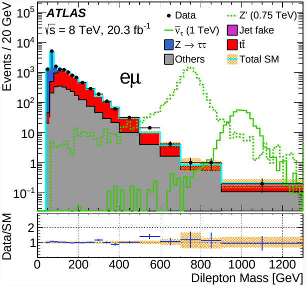


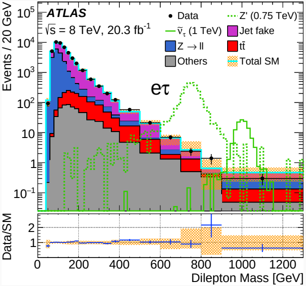
Production cross section normalised to same value for each quark.

ATLAS Searches

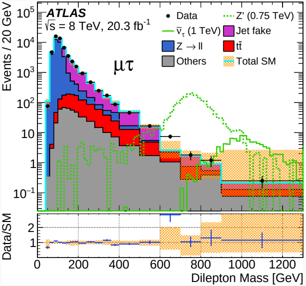


ATLAS 7TeV 1205.0725



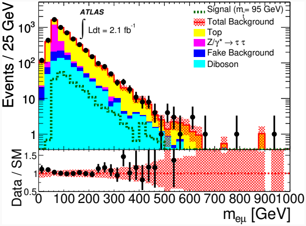


ATLAS 8TeV 1503.04430

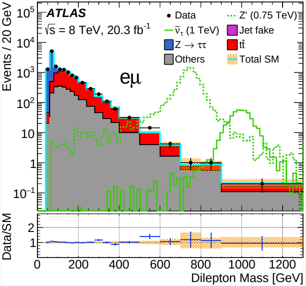


ATLAS 8TeV 1503.04430

Backgrounds



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

- Limit setting: Maximum likelihood estimator for 7 and 8 TeV and estimate significance for 14 TeV.

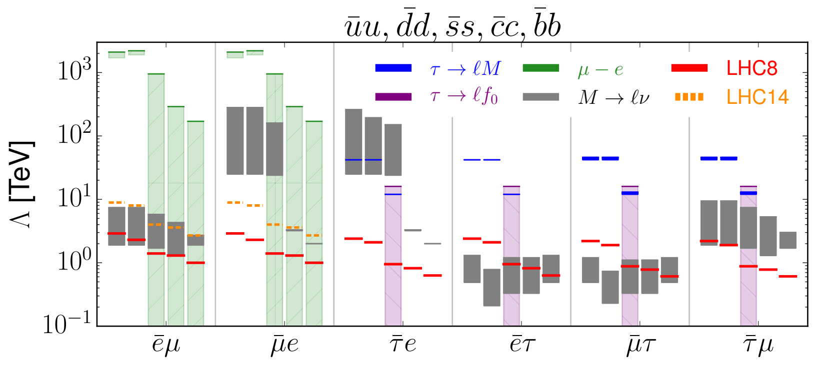
Limits from LHC on Cutoff Scale in TeV

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

Conclusions

Conclusions



Precision experiments win for light quarks

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

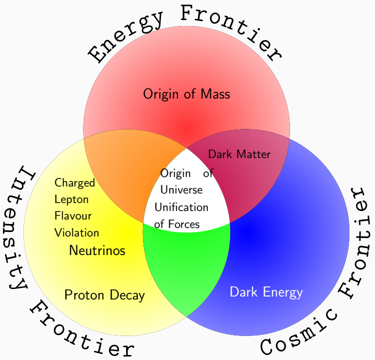
$\Lambda > 600 - 800$ GeV

Outlook

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

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

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



Outlook

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

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

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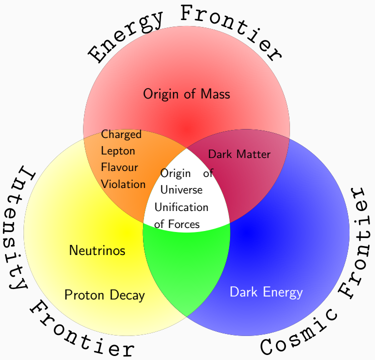

Thank you!

Backup Slides

Selection Criteria 7 and 8 TeV

Same selection critera as in ATLAS analysis.

- oppositely charged leptons
- Electrons:
  - $E_T > 25$ GeV
  - tight identification criteria
  - $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
- 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

Selection Criteria 14 TeV

Cuts follow 7 TeV inclusive analysis.

In addition

- $p_T(\ell) > 300$ GeV
- $E_T^{miss} < 20$ GeV

Limit setting

7 and 8 TeV

- 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

- 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 $\Delta B = 10\% B$.