LHC vs. Precision Experiments

A Comparison of LFV D6 Operators QQLL

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The University of Sydney

based on

Yi Cai, MS JHEP 02 (2016) 176 [1510.02486]

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

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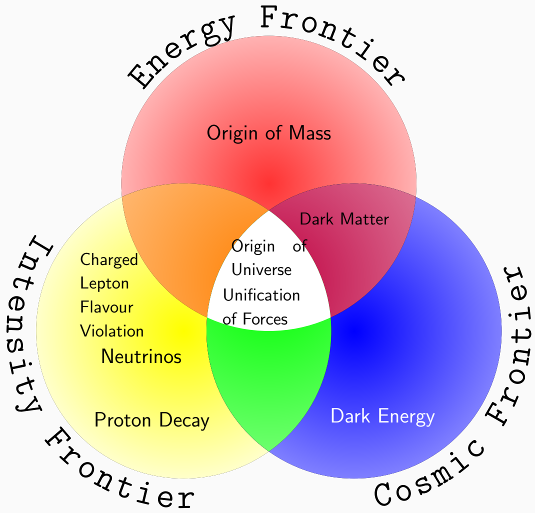
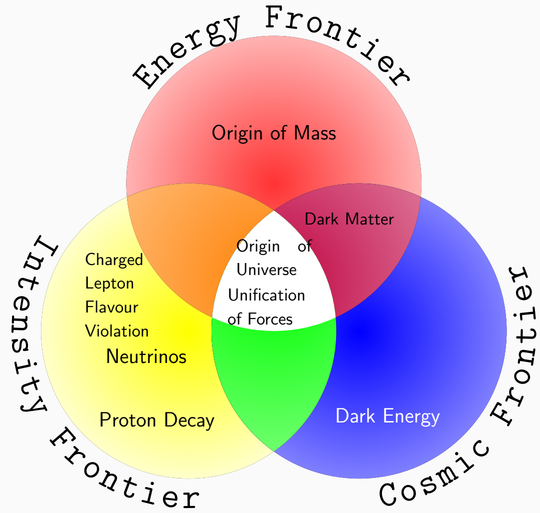

Energy Frontier
Intensity Frontier
Cosmic Frontier
Origin of Mass
Dark Matter
Origin of Universe
Unification of Forces
Charged Lepton Flavour Violation
Neutrinos
Proton Decay
Dark Energy

Motivation



Can the LHC compete with precision experiments?

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

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

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

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

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

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

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

We do not consider top quark because of different phenomenology.

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Thus the most general four fermion coefficients are

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

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

In general there is quark flavour violation.

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Effective four fermion Lagrangian

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

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

$\Rightarrow$ No tree-level FCNC processes.

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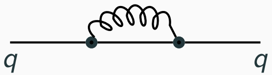
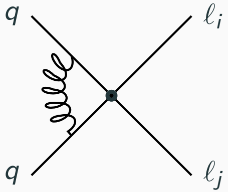
Renormalization Group Corrections

- Main effect are QCD corrections





- Following the standard discussion at NLO

Buchalla,Buras, Lautenbacher hep-ph/9512380

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

with coefficients

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

- Wilson coefficients become larger at smaller scales.

⇒ Increases reach of precision experiments

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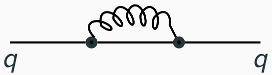

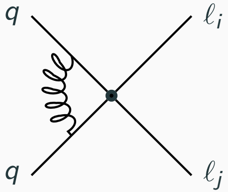

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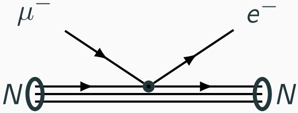
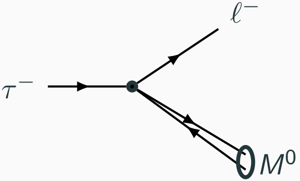
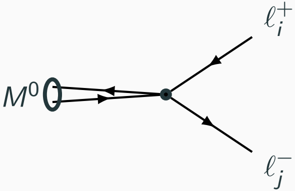
Precision Experiments



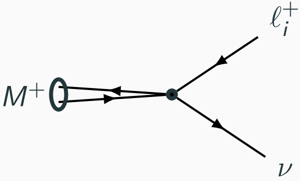
$\mu - e$ conversion in nuclei



$\tau \to \ell M^0$



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

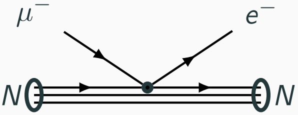


$M^+ \to \ell_i^+ \nu$

$\mu - e$ Conversion

- Agnostic about mediation mechanism
- Following discussion in

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



Dimensionless $\mu - e$ conversion rate

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

with muon conversion rate

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

$\mathcal{F}$ 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

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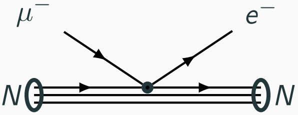

	^{48}Ti	^{197}Au	^{208}Pb
$R_{\mu e}^{\max}$	4.3×10^{-11}	7.0×10^{-13}	4.6×10^{-11}
$\bar{u}u$	1100 [870]	2100 [1700]	760 [610]
$\bar{d}d$	1100 [930]	2200 [1900]	780 [680]
$\bar{s}s$	480 [-]	950 [-]	340 [-]
$\bar{c}c$	150 [-]	290 [-]	110 [-]
$\bar{b}b$	84 [-]	170 [-]	61 [-]

Direct nuclear mediation [Meson mediation]

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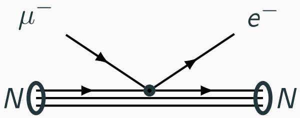

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Direct nuclear mediation [Meson mediation]

Strongest limit for first generation quarks,
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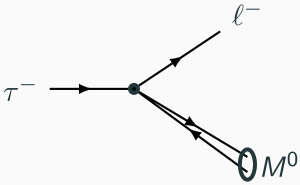
LFV Semileptonic τ Decays

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



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

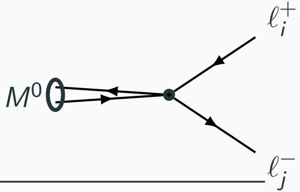
decay	$\mathrm{Br}_i^{\max}$	cutoff scale Λ [TeV]		
		$\Xi^u_{ij,uu}$	$\Xi^d_{ij,dd}$	$\Xi^d_{ij,ss}$
$\tau^- \to e^-\pi^0$	8.0×10^{-8}	10	10	-
$\tau^- \to e^-\eta$	9.2×10^{-8}	34	34	7.9
$\tau^- \to e^-\eta'$	1.6×10^{-7}	42	42	12
$\tau^- \to e^- K^0_S$	2.6×10^{-8}	-	$7.8\sqrt{\lambda}$	$7.8\sqrt{\lambda}$
$\tau^- \to e^-(f_0(980) \to \pi^+\pi^-)$	3.2×10^{-8}	$13\sqrt{\sin\varphi_m}$	$13\sqrt{\sin\varphi_m}$	$16\sqrt{\cos\varphi_m}$
$\tau^- \to \mu^-\pi^0$	1.1×10^{-7}	$9.0-9.6$	$9.0-9.6$	-
$\tau^- \to \mu^-\eta$	6.5×10^{-8}	$36-38$	$36-38$	$8.4-8.9$
$\tau^- \to \mu^-\eta'$	1.3×10^{-7}	$42-46$	$42-46$	$12-13$
$\tau^- \to \mu^- K^0_S$	2.3×10^{-8}	-	$(7.8-8.3)\sqrt{\lambda}$	$(7.8-8.3)\sqrt{\lambda}$
$\tau^- \to \mu^-(f_0(980) \to \pi^+\pi^-)$	3.4×10^{-8}	$(12-14)\sqrt{\sin\varphi_m}$	$(12-14)\sqrt{\sin\varphi_m}$	$(15-16)\sqrt{\cos\varphi_m}$

Leptonic Neutral Meson Decays $M^0 \to \ell_i^+ \ell_j^-$

Quark FCNC parameterised by λ

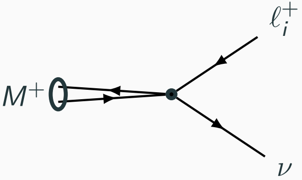
$$\Xi^u_{ij,kl} = \lambda \Xi^u_{ij,ll} V_{kl} \qquad \Xi^d_{ij,kl} = \lambda \Xi^d_{ij,kk} V_{kl}$$

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



decay	$\mathrm{Br}_i^{\mathrm{max}}$	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 $M^+ \to \ell_i^+ \nu$



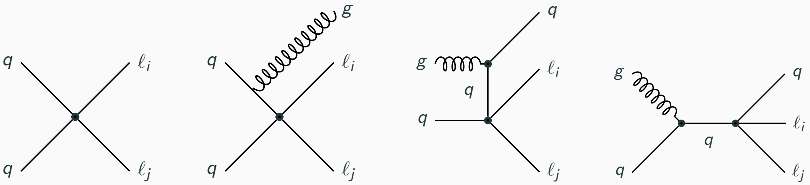
- $R_M = \frac{\mathrm{Br}(M^+ \to e^+ \nu)}{\mathrm{Br}(M^+ \to \mu^+ \nu)}$
- Theoretical error for R_π (R_K) about 5%
- Improvement by factor 20 (2) possible
- (✓) indicates constraints
- Second index of Λ corresponds to charged lepton

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

Large Hadron Collider

LFV at the Large Hadron Collider (LHC)

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

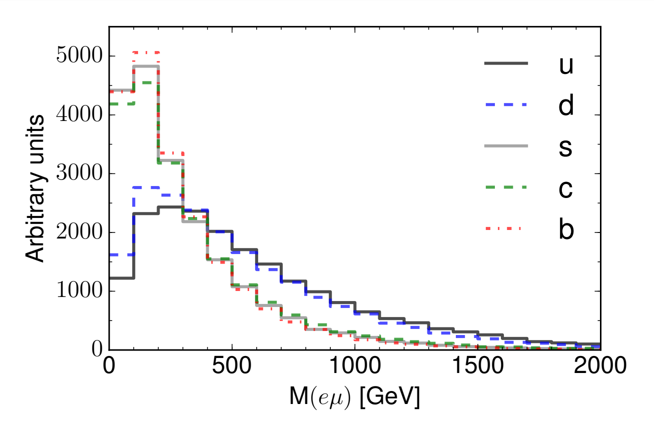


Signal: opposite-sign different flavour pair of leptons

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 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

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

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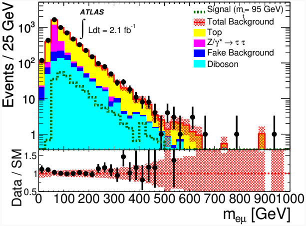
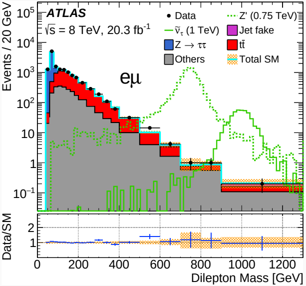
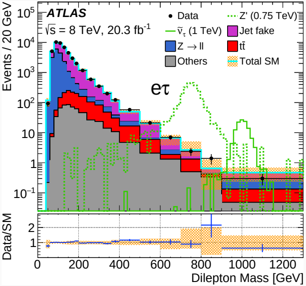
ATLAS Searches



ATLAS 7TeV 1205.0725





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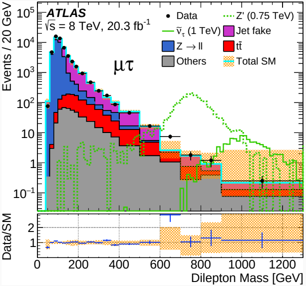
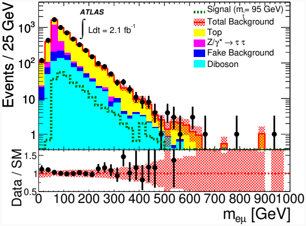


ATLAS 8TeV 1503.04430

SM Background



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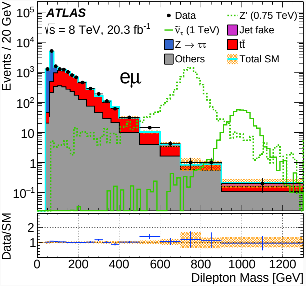

ATLAS 8TeV 1503.04430

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

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

$\Rightarrow$ 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

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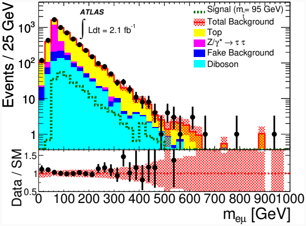

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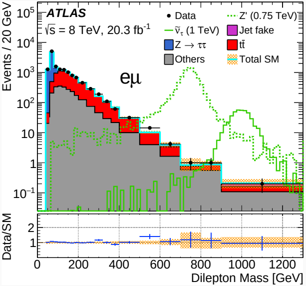

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Selection Criteria

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

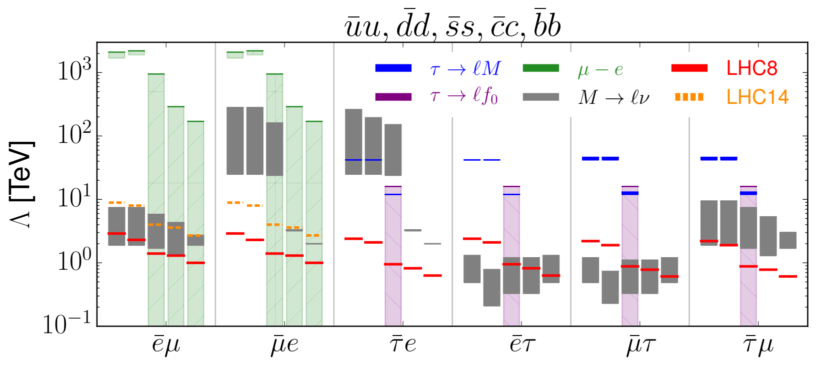
Limits from LHC on Cutoff Scale in TeV

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

Conclusions and Outlook

Conclusions



Precision experiments win for light quarks

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

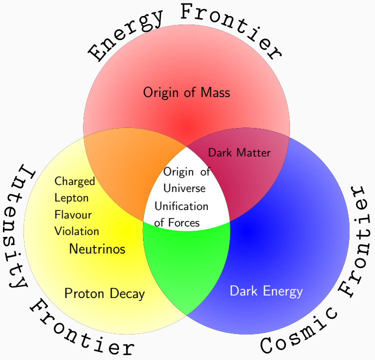
$\Lambda \gtrsim 600 - 800$ GeV

Outlook

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

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

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



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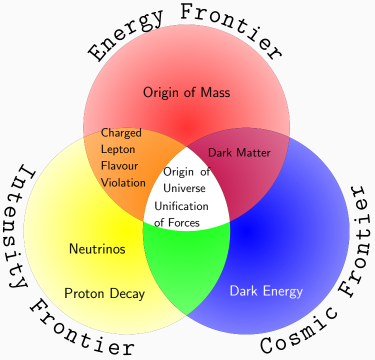

LHC and Effective Field Theory: a word of caution

- Scattering amplitudes grow indefinitely in EFTs

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

$\Rightarrow$ Violation of perturbative unitarity

Monojet searches: Shoemaker, Vecchi 1112.5457; Endo, Yamamoto 1403.6610; Yamamoto 1409.5775; El-Hedri, Shepherd, Walker 1412.5660

$\Rightarrow$ Solutions...

- Simplified models 1507.00966
- Truncation Busoni, De Simone, Morgante, Riotto 1307.2253, +Gramling 1402.1275, +Jacques 1405.3101

$$\frac{1}{Q_{tr}^2 - M^2} = -\frac{1}{M^2}\left[1 + \frac{Q_{tr}^2}{M^2} + \dots\right]$$

Discard events with $Q_{tr} > M \equiv \Lambda/\sqrt{g_q g_\chi}$

- Impose unitarity of S-matrix ... e.g. Bell, Busoni, Kobakhidze, Long, MS 1606.02722

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Unitarity of S-matrix

Scattering processes described by S matrix

$$S = \mathbb{I} + 2i\,T$$

It is unitary

$$S^\dagger S = \mathbb{I}$$

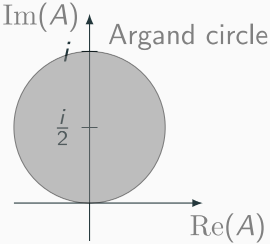
In terms of T-matrix, unitarity implies the optical theorem

$$T - T^\dagger = 2i\,T^\dagger T$$

For an eigenvalue A of T

$$|1 + 2iA|^2 = 1$$

$$\Rightarrow \left| A - \frac{i}{2} \right| = \frac{1}{2}$$



Unitarity and the K-Matrix

- Perturbative Expansion of S-matrix not unitary at fixed order

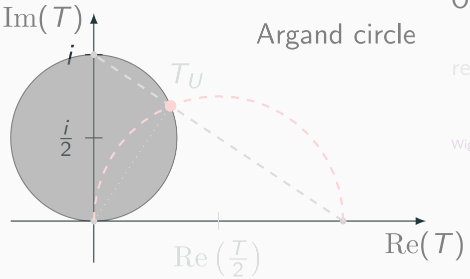
$$S = \mathbb{I} + 2i\,T \qquad\qquad T = T_1 + T_2 + T_3 + \dots$$

- Expansion of K-matrix unitary order by order

$$S = \frac{\mathbb{I} + i\,K}{\mathbb{I} - i\,K} \qquad\qquad K = K_1 + K_2 + K_3 + \dots$$

S is Cayley transform of K: K hermitean $\Leftrightarrow$ S unitary

Heitler 1941; Schwinger 1948



Optical theorem

$$T - T^\dagger = 2i\;T^\dagger T$$

rewrite to

$$\left(T^{-1} + i\,\mathbb{I}\right)^\dagger = T^{-1} + i\,\mathbb{I} \equiv K^{-1}$$

Wigner 1946; Wigner, Eisenbud 1947; Gupta 1950

$$\Rightarrow T_U = \frac{1}{\phantom{K^{-1}} - i\,\mathbb{I}}$$

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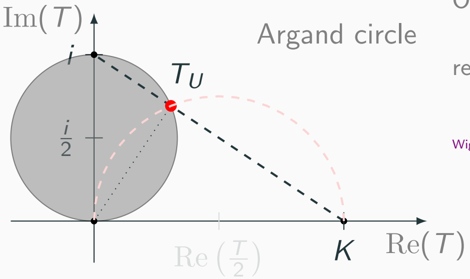

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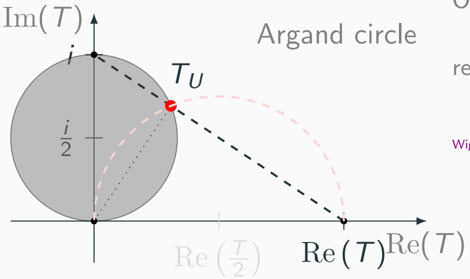

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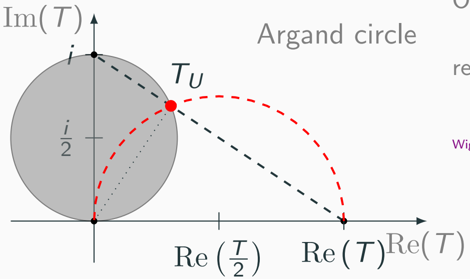

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K-Matrix Formalism

$$T_U = \frac{1}{\mathrm{Re}\,(T^{-1}) - i\,\mathbb{I}}$$

Wigner 1946; Wigner, Eisenbud 1947; Gupta 1950; Kilian et. al 1408.6207

- Well-known for WW-scattering e.g. Alboteanu et. al 0806.4145; Kilian et. al 1408.6207 and hadronic physics e.g. Chung et. al 1995
- Other unitarisation methods: e.g. Inverse Amplitude, N/D, ...
- K-matrix formalism is minimal: no new resonances introduced by unitarisation

! Does not describe resonances of true high energy theory

→ Resonances can be added by hand, if necessary

- Scattering amplitudes well behaved at high energies

→ Allows to derive meaningful limits on EFT models from LHC collisions with high centre of mass energies

Simple Example Bell, Busoni, Kobakhidze, Long, MS 1606.02722

- Effective operator from coloured scalar t-channel mediator

$$\mathcal{L}_1 = \frac{1}{\Lambda_{q\chi}^2} \bar{q}\gamma_\mu P_R q \bar{\chi}\gamma^\mu P_L \chi$$

- For $s \gg m_\chi^2, m_q^2$, the T-matrix in basis of $(|q_R\bar{q}_L\rangle, |\chi_L\bar{\chi}_R\rangle)$

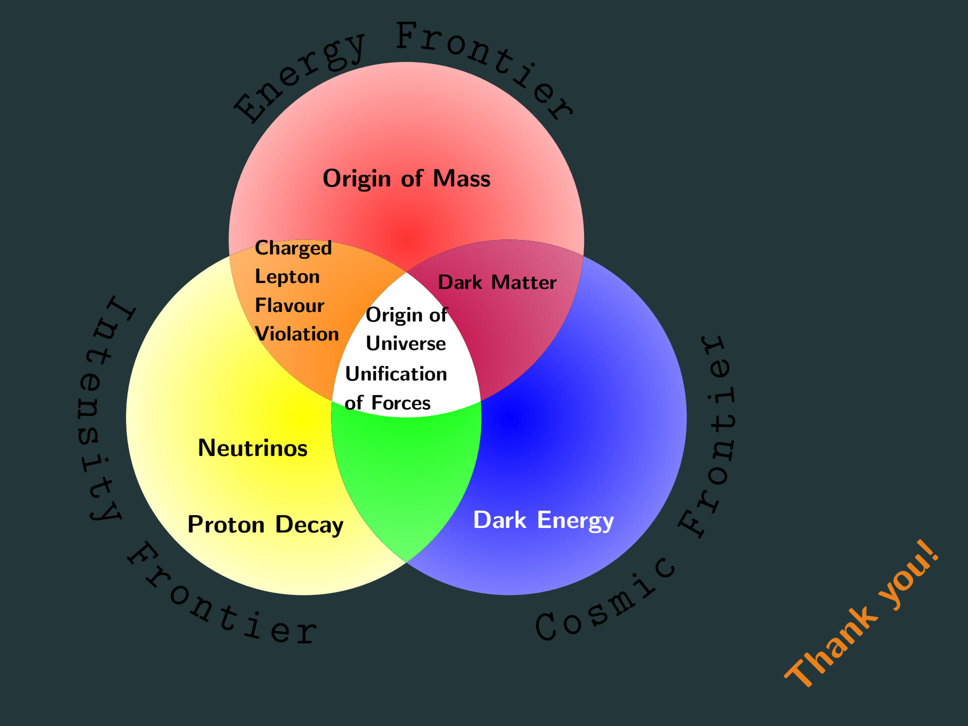
$$T = \begin{pmatrix} q_R\bar{q}_L \to q_R\bar{q}_L & \chi_L\bar{\chi}_R \to q_R\bar{q}_L \\ q_R\bar{q}_L \to \chi_L\bar{\chi}_R & \chi_L\bar{\chi}_R \to \chi_L\bar{\chi}_R \end{pmatrix} = -\frac{1}{16\pi^2}\frac{s}{\Lambda_{q\chi}^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \sin^2\frac{\theta}{2}$$

- Partial wave decomposition: only $J = 1$

$$T^1 = -\frac{1}{12\pi}\frac{s}{\Lambda_{q\chi}^2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

- Unitarised T-matrix $T_U^J \equiv \frac{1}{\mathrm{Re}\left[(T^J)^{-1}\right] - i\,\mathbb{I}}$

$$T_U^1 = \frac{1}{s^2 + 144\pi^2\Lambda_{q\chi}^4} \begin{pmatrix} i s^2 & -12\pi s\Lambda_{q\chi}^2 \\ -12\pi s\Lambda_{q\chi}^2 & i s^2 \end{pmatrix} \xrightarrow{s\to\infty} i\,\mathbb{I}$$


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

Backup Slides

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 $\Delta B = 10\% B$.