Leptoquarks: A Tale of Four Searches at the ATLAS Detector

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BNL Seminar
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On Behalf of the ATLAS Collaboration
To Boldly Search...

• The Standard Model and Beyond
  – A Brief Introduction to Leptoquarks
• The LHC and the ATLAS detector
• Reconstruction and Identification
• Leptoquark Analysis
• Results and Conclusion
The Standard Model

• Quantum Field Theory
  – particles are fields
  – gauge invariance
  – SU(3)xSU_L(2)xU_Y(1) yields 12 gauge bosons

• Forces act on particles
  – fermions - quarks/leptons

• Families have identical gauge interactions

• Differ by mass and flavor quantum number

http://www.ipp.phys.ethz.ch/aboutus/?file=institut
A Brief Introduction to Leptoquarks

• SM provides no communication/symmetry between quarks/leptons
• Leptoquarks: Another Boson
  – baryon and lepton number, couple triplet color charge
  – obey SM group symmetries
  – spin-0 scalar/spin-1 vector
    • 2 couplings: $\ell(\nu)$-q
    • 4 couplings: 2 with $\lambda_G$ and $\kappa_G$
  – Produced singly or in pairs
• Theories predict LQs
  – lepton/quark substructure, Grand Unified Theories (GUTs), technicolor
Production Cross Sections

- Focus: scalar LQ pair production
- Use NLO $\sigma$ for scalar signal
- Early LHC data sensitive to mass range beyond other accelerators

HERA and the Tevatron

- Excitement from HERA
  - 1997: H1 and ZEUS observed excess at $e^+\text{jet}$ mass of 200 GeV
- HERA results
  - later ruled out anomaly
- Tevatron results
  - $\beta$ is branching fraction to charged leptons
The LHC and the ATLAS Detector
The Large Hadron Collider

- 27 km long collider ring 100 m underground
- $\sqrt{s} = 7$ TeV
- $\mathcal{L}_{\text{inst}} = 2.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- 200 bunches with $1.15 \times 10^{11}$ p/bunch
ATLAS coordinate system

\[ \eta = -\ln\left(\tan\frac{\theta_{cm}}{2}\right) \]

- \(d_0\)- min distance between particle trajectory and the event primary vertex in xy-plane
- \(z_0\)- parallel to beam direction

pseudorapidity

to LHC center
Momentum resolution dependent on $\eta$ and $p_T$
($\sim 5 \times 10^{-4} \frac{p_T}{\text{GeV}} \pm 0.01$)

Pixel detector:
- size-50x400 $\mu$m$^2$
- res-14x115 $\mu$m$^2$

Semiconductor Tracker:
- size-6.36x6.40 cm$^2$
- accurate to 17mm/layer

Transition Radiation Tracker:
- size-4mm dia
- precision of 0.17 mm

• Impact parameter resolution ($d_0$) $\sim 10\mu$m ($r\phi$), $\sim 70\mu$m ($z$)
• Secondary vertex resolution
  $\sim 50\mu$m ($r\phi$), $\sim 70\mu$m ($z$)
• Primary (main) vertex resolution
  $\sim 11\mu$m ($r\phi$), $\sim 45\mu$m ($z$)
Calorimeters

Scintillating Tile: (Iron absorber), $|\eta|<1.8$, 11 $\lambda_0$

LAr Had End-caps: (copper plates) $1.5<|\eta|<3.2$

LAr EM End-caps: $1.375<|\eta|<3.2$, >26 $X_0$

Rel. energy res: ~10$/\sqrt{E/\text{GeV}}$%+

LAr EM Barrel: (lead plates) $|\eta|<1.475$, >24 $X_0$

LAr forward: (copper/tungsten) $3.1<|\eta|<4.9$

Rel. energy res: ~60$/\sqrt{E/\text{GeV}}$%+0.03
Magnet System

Central Solenoid:
2T field

Toroids:
3-each with 8 coils
Barrel: 3.9 T, End-caps: 4.1 T
Muon System

Layout based on deflection of tracks by toroids

Momentum resolution (~2%)
Triggers
Reconstruction and Identification

• Leptons
  – electrons
  – muons
• Jets
• Missing Energy
Leptons

Electrons
- Energy clusters in EM calorimeter
- $E_T > 20$ GeV, $E_T$ isolation < 20%
- $|\eta| < 2.47$ with crack region removed
- Efficiency ~70%

Muons
- Tracks: inner detector and muon system then matched
- $p_T > 20$ GeV, $p_T$ isolation < 25%
- $|\eta| < 2.4$
- Rejection of cosmics
  - $|d_0| < 0.1$ mm and $|z_0| < 1$ cm
- Efficiency ~65%

Lepton isolation Cone (green)

d_0 - min distance between muon trajectory and the event primary vertex in xy-plane
z_0 - parallel to beam direction
Jets and $E_T^{\text{miss}}$

**Jets**
- Anti-$k_T$ algorithm, $R=0.4$
- $p_T>20$ GeV, $\Delta R_{\text{jet,lep}}>0.5$
- $|\eta|<2.8$
- "good" jet requirements
  - rejects noise induced jets, vertex confirmation

$E_T^{\text{miss}}$
- Negative vector sum of $E_T$ and muon $p_T$
- $E_T^{\text{miss}} > 25$ GeV
- Removed if "bad" jets are present

$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$

Leptoquark Analysis

- Background Yield Determination
- Base Event Selection
- Control Regions
- Optimized LQ Selection
- Limit Setting

Leptoquark sighting made possible by the Particle Zoo
Background Yield Determination

• Simulated Background and Signal Samples
  – PDF Set: CTEQ 6.6
  – Generators:
    • ALPGEN (V+jets) (Z+jets in dilepton is semi-data driven)
    • HERWIG, MC@NLO (t\bar{t}, single top, VV)
    • Pythia

• \( N_{\text{pred}} = \text{acceptance} \ast \sigma \ast \mathcal{L}_{\text{integrated}} \)

• Multijet background determined by data driven methods

• Control regions
  – V+jets and t\bar{t} enhanced to validate modeling
Data Driven Background

- **Data Driven method**
  - tails not modeled well by MC
  - not enough events generated
- **lljj (Z+jets)**
  - signal region: tails of Z+jet dist
  - fitting method for 1 lepton and a fake (relative iso variable)
- **evjj (QCD):** Fit to $M_T$
  - $N_D^{\text{sig}} = N_D^Z \frac{N_{\text{sig}}^{MC}}{N_{MC}^Z}$
- **$\mu$vjj (QCD):** ABCD method
  - $E_T^{\text{miss}}$ and $|d_0|$ (uncorrelated)
  - signal region: high $E_T^{\text{miss}}$ and low $|d_0|$}
  - Assumes EWK contribution in region C is negligible, QCD shape same in C and D
Data Driven Background

- **Data Driven method**
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- **lljj (Z+jets)**
  - signal region: tails of Z+jet dist
  - fitting method for 1 lepton and a fake (relative iso variable)
- **evjj (QCD): Fit to $M_T$**
  - $N_D^{\text{sig}} = N_D^Z \frac{N_C^{\text{sig}}}{N_C^{\text{MC}}}$
  - $\Sigma\text{bkgs} = \text{data yield}$
  - minimize LLR
  - $M_T(l, E_T^{\text{miss}}) = \sqrt{2p_T^l E_T^{\text{miss}}} (1 - \cos(\Delta\phi))$
- **$\mu$evjj (QCD): ABCD method**
  - $E_T^{\text{miss}}$ and $|d_0|$ (uncorrelated)
  - signal region: high $E_T^{\text{miss}}$ and low $|d_0|$
  - Assumes EWK contribution in region C is negligible, QCD shape same in C and D

$N_A$, $N_B$, and $N_C$ are yields from data in regions A, B, and C after EWK contribution is eliminated (using MC)
Base Event Selection

• Event Selection
  – At least 1 good primary vertex
    • $\geq 3$ ID tracks
    • $|z_{vtx}| < 15$ cm
  – = 1 good lepton (=2 for dilepton analysis)
  – $\geq 2$ good jets

• Event Selection for lvjj
  – pass $E_T^{miss}$
  – $M_T(l, E_T^{miss}) > 40$ GeV
  – triangle cut for QCD removal
    – extra rejection of residual events with badly measured jets (evjj) ($\Delta \Phi(E_T^{miss}, \text{jet})$ vs. $E_T^{miss}$)
  – opposite lepton veto

Leptons: $e, \mu$ and $\nu$

Jets: $u, c$ and $d, s$
Base Event Selection Plots

<table>
<thead>
<tr>
<th>channel</th>
<th>predicted</th>
<th>observed</th>
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<tbody>
<tr>
<td>eejj</td>
<td>610±240</td>
<td>626</td>
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<tr>
<td>evjj</td>
<td>6090^{+990}_{−1130}</td>
<td>6088</td>
</tr>
<tr>
<td>μμjj</td>
<td>830^{+200}_{−150}</td>
<td>853</td>
</tr>
<tr>
<td>μνjj</td>
<td>9490±2490</td>
<td>9248</td>
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</tbody>
</table>

uncertainties are systematic and statistical
systematic uncertainty from V+jets
is dominant uncertainty

$$M_T(l, E_{T}^{ miss}) = \sqrt{2 p_T E_{T}^{ miss} (1 - \cos(\Delta\phi))}$$

$$S_T = \sum p_T(jet_1, jet_2, lepton_1, E_{T}^{ miss} / lepton_2)$$
Control Regions: Electron channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>eejj: $Z+\geq$ 2 jets</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>V+jets</td>
<td>150±23</td>
<td>0.3±0.1</td>
</tr>
<tr>
<td>Top</td>
<td>2.0±0.3</td>
<td>24±4</td>
</tr>
<tr>
<td>diboson</td>
<td>2.0±0.3</td>
<td>0.8±0.1</td>
</tr>
<tr>
<td>QCD</td>
<td>4.0±14.4</td>
<td>0.0±0.1-0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>158±25</td>
<td>25±4</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>140</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>evjj: $W+=$ 2 jets</th>
<th>$W+\geq$ 3 jets</th>
<th>ttbar</th>
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</thead>
<tbody>
<tr>
<td>V+jets</td>
<td>2080±680</td>
<td>580±190</td>
<td>180±60</td>
</tr>
<tr>
<td>Top</td>
<td>21±4</td>
<td>44±9</td>
<td>210±40</td>
</tr>
<tr>
<td>diboson</td>
<td>17±4</td>
<td>8.3±1.9</td>
<td>2.1±0.5</td>
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<tr>
<td>QCD</td>
<td>64±14</td>
<td>68±15</td>
<td>29±7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2180±710</td>
<td>700±200</td>
<td>420±80</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>2344</td>
<td>722</td>
<td>425</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

\[ \int L \, dt = 35 \, \text{pb}^{-1} \]

eejj: $Z+\geq$ 2 jets

evjj: $W+=$ 2 jets

Data 2010 (\(S_T^e=7\) TeV)
## Control Regions: Electron channels

<table>
<thead>
<tr>
<th>eejj</th>
<th>(Z^{+\geq2\text{jets}})</th>
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<td>(\text{QCD})</td>
<td>4.0+14.-4.</td>
<td>0.1-0.1-0.</td>
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\[
\int L \, dt = 35 \, \text{pb}^{-1}
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**lljj**: ttbar

**evjj**: ttbar

---

Events / 20 GeV

**ATLAS Preliminary**

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\int L \, dt = 35 \, \text{pb}^{-1}
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Events / 20 GeV
## Control Regions: Muon channels

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<tr>
<td>V+jets</td>
<td>190±24</td>
<td>0.3±0.1</td>
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</tr>
<tr>
<td>Top</td>
<td>2.7±0.5</td>
<td>24±4</td>
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<td>diboson</td>
<td>0.2±0.1</td>
<td>0.8±0.1</td>
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</tr>
<tr>
<td>QCD</td>
<td>6.1±11.5</td>
<td>0.±0.1-0.</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>200±25</td>
<td>25±4</td>
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<tr>
<td><strong>Data</strong></td>
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<tr>
<th></th>
<th>μνjj</th>
<th>W+=2 jets</th>
<th>W+≥3jets</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>V+jets</td>
<td>3250±1060</td>
<td>900±30</td>
<td>250±80</td>
<td></td>
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<tr>
<td>Top</td>
<td>14±3</td>
<td>53±1</td>
<td>260±50</td>
<td></td>
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<tr>
<td>diboson</td>
<td>28±6</td>
<td>14±3</td>
<td>3.0±0.7</td>
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<tr>
<td>QCD</td>
<td>300±100</td>
<td>130±50</td>
<td>54±32</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3590±1080</td>
<td>1100±330</td>
<td>570±120</td>
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<td><strong>Data</strong></td>
<td>3588</td>
<td>1120</td>
<td>547</td>
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### ATLAS Preliminary

- **μμjj**: $Z+\geq 2$ jets
  - $\int L \, dt = 35 \, pb^{-1}$
  - Events / 20 GeV

- **μνjj**: $W+2$ jets
  - $\int L \, dt = 35 \, pb^{-1}$
  - Events / 5 GeV
Control Regions: Muon channels

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<tr>
<td>QCD</td>
<td>6.11±5.5</td>
<td>0.01±0.0</td>
</tr>
<tr>
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<td>25±4</td>
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**Events / 20 GeV**

- **μμjj**: ttbar
- **μνjj**: ttbar

**ATLAS Preliminary**

\[ \int L \; dt = 35 \text{ pb}^{-1} \]

Data 2010 (\(\sqrt{s} = 7 \text{ TeV}\))

- V+jets
- Top
- QCD
- Diboson
Optimized Leptoquark Selection

- **Grid Search**
  - systematic Search over a grid of points
  - regular grid inefficient

- **Search region**: value of MC signal events
  - use every signal event to form grid
  - n-Dimensional

- **Significance calculated and plotted**
  - matched to each cut

- **Minimize Poisson probability**
  - background fluctuation is signal + background

\[
\int dBe \sum_{i=N}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_B} \frac{-(B - \bar{B})^2}{2\sigma_B^2} P(i; B)
\]
Optimization on LQ signal

- 4-D grid space
  - dilepton channels:
    - \( M(l,l) \) - Invt. mass of leptons
    - \( M_{\text{ave}}(LQ) \) - Ave. LQ mass
    - \( p_{T}^{\text{all}} \)
    - \( S_T - \Sigma p_T \) (2 jets, 2 leptons)
  - single lepton channels:
    - \( M_T(l, E_T^{\text{miss}}) \)
    - \( M(LQ) \) – Invt. LQ mass
    - \( M_T(LQ) \) – Transverse LQ mass
    - \( S_T - \Sigma p_T \) (2 jets, lepton, \( E_T^{\text{miss}} \))

\[
\begin{array}{ccc}
\text{eejj and } \mu\mu jj & \text{eujj} & \mu\nu jj \\
M_{ll} > 120 \text{ GeV} & M_T > 200 \text{ GeV} & M_T > 160 \text{ GeV} \\
M_{LQ} > 150 \text{ GeV} & M_{LQ} > 180 \text{ GeV} & M_{LQ} > 150 \text{ GeV} \\
p_{T}^{\text{all}} > 30 \text{ GeV} & M_{LQ}^T > 180 \text{ GeV} & M_{LQ}^T > 150 \text{ GeV} \\
S_T^l > 450 \text{ GeV} & S_{T'} > 410 \text{ GeV} & S_{T'} > 400 \text{ GeV}
\end{array}
\]
Systematics

<table>
<thead>
<tr>
<th>Channel</th>
<th>$V + \text{jets}$</th>
<th>$\ell\ell_{jj}$</th>
<th>$\nu_{jj}$</th>
<th>Top</th>
<th>$\ell\ell_{jj}$</th>
<th>$\nu_{jj}$</th>
<th>Diboson</th>
<th>$\ell\ell_{jj}$</th>
<th>$\nu_{jj}$</th>
<th>LQ (300 GeV)</th>
<th>$\ell\ell_{jj}$</th>
<th>$\nu_{jj}$</th>
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<tr>
<td>Production Cross Section</td>
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<td>Modeling</td>
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<tr>
<td>Electron Energy Scale &amp; Resolution*</td>
<td>+13, -0.2</td>
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<td></td>
<td>10</td>
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<td>7</td>
<td>1</td>
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<td>8</td>
<td>1</td>
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<td>Muon Momentum Scale &amp; Resolution**</td>
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<tr>
<td>Pile up</td>
<td>&lt; 0.1</td>
<td>5</td>
<td>&lt; 0.1</td>
<td>4</td>
<td>&lt; 0.1</td>
<td>6</td>
<td>&lt; 0.1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Systematics</td>
<td>39*</td>
<td>+49, -45</td>
<td>47*</td>
<td>57</td>
<td>(+22, -16)</td>
<td>+26, -31</td>
<td>22</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Numbers are in percentages
Systematics

<table>
<thead>
<tr>
<th>Channel</th>
<th>V+jets</th>
<th>Top</th>
<th>Diboson</th>
<th>LQ (300 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$l\ell jj$</td>
<td>$\ell \nu jj$</td>
<td>$l\ell jj$</td>
<td>$\ell \nu jj$</td>
</tr>
<tr>
<td>Production Cross Section</td>
<td>4</td>
<td>13</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Modeling</td>
<td>34*, 45**</td>
<td>40</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Electron Energy Scale &amp; Resolution*</td>
<td>+13, -0.2</td>
<td>5</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Muon Momentum Scale &amp; Resolution**</td>
<td>20</td>
<td>5</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>6</td>
<td>+22, -13</td>
<td>+9, -18</td>
<td>32</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>16</td>
<td>10</td>
<td>0.3</td>
<td>26</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.3</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
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Numbers are in percentages
Systematics

• Modeling
  – varying event generator-level parameters

• Jet Energy Scale and Resolution
  – varied by uncertainties
  – 5% added (quark/gluon response)
  – included in $E_T^{\text{miss}}$

• Pile-up
  – multiple minimum bias events per bunch crossing
  – sub-detectors sensitive to bunch crossings before and after interesting physics interaction
Confidence Level Evaluation

- Overview
- Semi-Frequentist approach
- Log-Likelihood Ratio Test
- Confidence levels
Semi-Frequentist approach

- “Frequency” a result will occur
- Collie (COnfidence Level Limit Evaluator)
  - likelihood Ratio test
  - “as Frequentist as possible”
    - Bayesian treatment of systematics

T. Junk, arXiv:hep-ex/9902006v1

\[ L(b \mid x) = \frac{(b)^x e^{-b}}{x!} \]

\[ \Lambda(\bar{x}) = \prod_{i} \prod_{j} \frac{L((s + b)_{ij} \mid x_{ij})}{L(b_{ij} \mid x_{ij})} \]

- \(s = \text{signal}\)
- \(b = \text{background}\)
- \(x = \text{data}\)
- \(L = \text{likelihood}\)
Log-Likelihood Ratio Test

- Generate Null and Test hypothesis
- Distributions of LLR(s+b) and LLR(b)

\[
LLR(x) = -2 \log(\Lambda)
\]

\[
LLR(x) = \sum_i \sum_j s_{ij} - x_{ij} \ln \left(1 + \frac{s_{ij}}{b_{ij}}\right)
\]

signal + background background only

our result \( LLR(x') = LLR(x) \)

W. Fisher, Fermilab-TM-2386-E
Confidence levels

- Confidence levels integral of LLR distribution
- CL relative to outcome
  - observed/expected limits
- Expected data
  - median bkg outcome
  - $CL_b$ is 50% if bkg is well modeled
- Poor modeling -> $CL_s$ method
- Exclusion: 95% CL
  - increase parameter until $1 - CL_s = 0.95$

$$CL_s = \frac{CL_{s+b}}{CL_b}$$
Results

<table>
<thead>
<tr>
<th>Source</th>
<th>$eejj$</th>
<th>$enjj$</th>
<th>$\mu\mu jj$</th>
<th>$\mu\nu jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V + \text{jets}$</td>
<td>$0.50 \pm 0.28$</td>
<td>$0.65 \pm 0.38$</td>
<td>$0.28 \pm 0.22$</td>
<td>$2.6 \pm 1.4$</td>
</tr>
<tr>
<td>Top</td>
<td>$0.51 \pm 0.23$</td>
<td>$0.67 \pm 0.39$</td>
<td>$0.52 \pm 0.23$</td>
<td>$1.6 \pm 0.9$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$0.03 \pm 0.01$</td>
<td>$0.10 \pm 0.03$</td>
<td>$0.04 \pm 0.01$</td>
<td>$0.10 \pm 0.03$</td>
</tr>
<tr>
<td>Other Bkg.</td>
<td>$0.02 \pm 0.03$</td>
<td>$0.06 \pm 0.01$</td>
<td>$0.00 \pm 0.01$</td>
<td>$0.0 \pm 0.0$</td>
</tr>
<tr>
<td><strong>Total Bkg</strong></td>
<td>$1.1 \pm 0.4$</td>
<td>$1.4 \pm 0.5$</td>
<td>$0.8 \pm 0.3$</td>
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</tr>
<tr>
<td>Data</td>
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<td>LQ(250 GeV)</td>
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<tr>
<td>LQ(350 GeV)</td>
<td>$7.7 \pm 1.7$</td>
<td>$2.6 \pm 0.6$</td>
<td>$9.4 \pm 2.1$</td>
<td>$3.0 \pm 0.7$</td>
</tr>
<tr>
<td>LQ(400 GeV)</td>
<td>$3.5 \pm 0.8$</td>
<td>—</td>
<td>$4.4 \pm 1.0$</td>
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| LQ(250 GeV)  | 38 ± 8     | 9.6 ± 2.1   | 45 ± 10      | 13 ± 3       |
| LQ(300 GeV)  | 17 ± 4     | 5.1 ± 1.1   | 21 ± 5       | 6.4 ± 1.4    |
| LQ(350 GeV)  | 7.7 ± 1.7  | 2.6 ± 0.6   | 9.4 ± 2.1    | 3.0 ± 0.7    |
| LQ(400 GeV)  | 3.5 ± 0.8  | —           | 4.4 ± 1.0    | —            |
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</table>

\[\mu_{jj}\]

\[\mu_{\nu jj}\]
Results

$S_T = \sum p_T(jet_1, jet_2, lepton_1) E_T^{miss} / lepton_2$

\[ \int L dt = 35 \text{ pb}^{-1} \]
Cross Section Limits

- **ATLAS combined result**
  - observed: red
  - expected: blue dashed
- **Max Sensitivity**
  - dilepton: $\beta=1$
  - single lepton: $\beta=0.5$
- **Stronger exclusion in di-muon channel**
- **CMS**
  - dilepton results published
  - publishing single-lepton channel and combined results
Cross Section Limits

\[ \sigma_{pp \to LQ+jj} \times (m^2+2k(1-\beta)) : \beta=0.5 \text{ pb} \]

\[ \sigma_{pp \to LQ+jj} \times (m^2+2k(1-\beta)) : \beta=1 \text{ pb} \]

\[ \sqrt{s} = 7 \text{ TeV} \quad \int Ldt = 35 \text{ pb}^{-1} \]

1st Generation LQ  \quad ATLAS Preliminary

2nd Generation LQ  \quad ATLAS Preliminary
In Summary

• Data in high signal-to-background matches background-only predictions
  – 95% CL upper bounds on production cross section
• 1st generation:
  – MLQ > 376 (319) GeV for $\beta=1$ (0.5)
• 2nd generation:
  – MLQ > 422 (362) GeV for $\beta=1$ (0.5)
• LHC set world’s most stringent from direct LQ pair production searches with 2010 data
• Future Prospects: order of a TeV LQ (discovery – hopefully) 2011 with 5 fb$^{-1}$
Backups!
The Standard Model

• Forces Mediated by integer spin bosons
  – Strong
    • 8 massless gluons, couple only to quarks, confinement
    • relative strength of 1 with $10^{-15}$ m (~nucleus) range
  – Electromagnetic
    • photons, couple to charged particles
    • relative strength $10^{-3}$ with infinite range
  – Weak
    • $W^\pm/Z$, couple to all SM particles
    • relative strength of $10^{-6}$ with $10^{-18}$ m (~0.1% dia. proton) range

[1]
The ATLAS Detector

Electromagnetic and Hadronic Calorimeter

Muon Systems

Magnets

Inner Detector/Tracking
Monte Carlo

- Signal and background samples
  - ALPGEN interfaced to HERWIG and JIMMY and PYTHIA
- Designed to model interactions
  - Hard Scatter, Initial and Final State Radiation, Hadronization, Soft Interactions... etc.
- PYTHIA and HERWIG/JIMMY - Parton Shower model
- ALPGEN - Matrix Element model
  - useful for multi-jet events but other generators handle hadronization and shower more completely
- Detailed detector simulation: GEANT4
  - Ionization and showering in detector, energy deposition in calorimeters, trajectory in magnetic field
GRL and Trigger lists

• Good Runs List
  – All parts of detector working nominally, LHC running nominally
  – General requirements (ptag data10 7TeV and db DATA and partition ATLAS)
    LHC beam energy at 3.5 TeV (lhcb beamenergy 3400-3600)
  – The stable beam flag (lhcb stablebeams T)
  – Silicon and muon systems warm starts completed (ready 1)
  – The magnets on (mag s > 6000 and mag t > 18000)
  – Data quality flags (dq GLOBAL STATUS, CP TRACKING, CP EG ELECTRON
    BARREL, CP EG ELECTRON ENDCAP, CP MU MSTACO, CP JET JETB, CP JET JETEA,
    CP JET JETEC, CP MET METCALO, CP MET METMUON, LUMI, L1CAL, L1MUE,
    L1MUB, TRELE, TRMUO)
  – Run period dependent luminosity block and summary flags equal to good
    status. For periods A and B, this is LBSUMM#DetStatus-v03-repro04-01 g.
  – For other periods this is LBSUMM#DetStatus-v03-pass1-analysis-2010X g with
    X the period (C-J).

• Electron Trigger
  – $E_T > 15$ GeV
  – “medium” electron requirement
Triangle cut for QCD removal
Data/MC Scale Factors
QCD Estimation: Matrix Method

Loose Sample:
Low $p_T$

$E_T$ for loose and tight e’s

Tight Sample:
2 high $p_T$ Electrons

$E_T$ ratio

ATLAS work in progress

$\epsilon_{QCD}$
Methodology

Bin by Bin

- QCD normalization and shape comes from following:
  - \( N_l^i = N_{\text{ele}}^{\text{real}} + N_{\text{QCD}}^{\text{fake}} \)
  - \( N_t^i = \varepsilon_{\text{ele}}^{\text{real}} N_{\text{ele}}^{\text{real}} + \varepsilon_{\text{QCD}}^{\text{fake}} N_{\text{QCD}}^{\text{fake}} \)
  - fill \( i^{\text{th}} \) bin

\[
\varepsilon_{\text{QCD}}^{\text{fake}} N_{\text{QCD}}^i = \varepsilon_{\text{QCD}}^{\text{fake}} \frac{\varepsilon_{\text{ele}}^{\text{real}} N_l^i - N_t^i}{\varepsilon_{\text{ele}}^{\text{real}} - \varepsilon_{\text{QCD}}^{\text{fake}}}
\]

Reverse Isolation

- shape from loose-tight
- normalization from following:

\[
\varepsilon_{\text{QCD}}^{\text{fake}} N_{\text{QCD}} = \varepsilon_{\text{QCD}}^{\text{fake}} \frac{\varepsilon_{\text{ele}}^{\text{real}} N_l - N_t}{\varepsilon_{\text{ele}}^{\text{real}} - \varepsilon_{\text{QCD}}^{\text{fake}}}
\]

- depends on tight/loose definition
- \( \varepsilon_{\text{QCD}} \sim 45\% \)
- \( \varepsilon_{\text{ele}} \sim 95\% \)
  - from \( Z\rightarrow ee + N_{\text{jets}} \) MC
  - data/MC correction factor \( \sim 1.0 \)
Multijet Background: $M_T$ fit method

- Data Driven method
  - not modeled well by MC
  - not enough events generated
- Fit to $M_T$
  - $\Sigma bkgds = \text{data yield}$

$$M_T(l, E_T^{\text{miss}}) = \sqrt{2 p_T^l E_T^{\text{miss}} (1 - \cos(\Delta \phi))}$$
Control Regions

• lljj
• Z+jets
  – $81 < Z_{\text{mass}} < 101$ GeV
• ttbar
  – both e and $\mu$
  – ≥2 jets

• Inuujj
• W+jets
  – $M_T < 150$ GeV
  – exactly 2 jets
    • $S_T < 175$ GeV
  – ≥3 jets
    • $S_T < 200$ GeV
• ttbar
  – $M_T < 150$ GeV
  – ≥4 jets
  – $p_T(j_1) < 50$ GeV, $p_T(j_2) < 40$ GeV, $p_T(j_3) < 30$ GeV