Inclusive Search for Same-Sign Dileptons at ATLAS

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on behalf of the
ATLAS Collaboration

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August 10, 2011
**Same-sign leptons**

Same-sign leptons appear in a range of models:
- SUSY - produced in lepton cascade topologies
- Heavy Majorana neutrinos
- Universal extra dimensions
- Doubly-charged Higgs bosons (eg) Type-II Seesaw

\[
H^{\pm\pm} \rightarrow l^\pm l^\pm \quad \text{OR} \quad H^{\pm\pm} \rightarrow W^\pm W^\pm \rightarrow l^\pm \nu l^\pm \nu
\]

An *inclusive* search is a promising testing ground for new physics.
Selection with lepton kinematics, not other event activity.
Backgrounds

Understanding and estimating the backgrounds is the most challenging part of the SS analysis.

Three SM background contributions:

1. Production of same sign dileptons in diboson processes

   Main contribution from $ZZ$, $WZ$

   Less significant contribution from $WWjj$ and $t\bar{t}W$

2. SM processes with opposite sign leptons and the charge of one lepton is mis-measured -- called charge flip

   More dominant with electrons

3. Hadronic decay leptons - “fakes”

   Dijet events

   $Wj \rightarrow l\nu j$
2010 Analysis

- Three channels: $\mu\mu$, $e\mu$, $ee$
- 34 pb$^{-1}$

lepton candidates required to have $p_T > 20$ GeV

one lepton must have triggered the event

$|\eta| < 2.47$

high quality tracks: requirements on the minimum number of track hits; for muons, the charge as measured in the inner detector matches that measured by the muon system

isolation: sum of transverse energy in calorimeter deposition in cone of radius $\Delta R = 0.2$ required to be less than 15% of lepton transverse energy

leptons must originate from the same primary vertex and have same charge

- Analysis-approach:
  - data-driven fake background estimate
  - simulation used to estimate background from dibosons
  - data and simulation used to estimate charge flip

arXiv:1108.0366v1 [hep-ex]: submitted to JHEP
2010 Analysis Results

- Agreement between observed data and the SM prediction for all channels

- Fiducial cross section limit set on generic same-sign production cross section:

\[ m_{ll} > 110 \text{ GeV} \]

<table>
<thead>
<tr>
<th></th>
<th>( n_{\text{obs}} )</th>
<th>( n_{\text{pred}} )</th>
<th>( \sigma_{\text{obs}}^{0.05} \text{ [pb]} )</th>
<th>( \sigma_{\text{exp}}^{0.05} \text{ [pb]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ee )</td>
<td>0</td>
<td>3.1( \pm 2.1 \pm 0.5 )</td>
<td>0.15</td>
<td>0.46</td>
</tr>
<tr>
<td>( \mu\mu )</td>
<td>1</td>
<td>2.2( \pm 1.4 \pm 0.4 )</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td>( e\mu )</td>
<td>3</td>
<td>3.2( \pm 2.9 \pm 0.5 )</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>
2010 Analysis Limits

- Cross section upper limits on specific models
  - Heavy Majorana neutrinos
  - Lepton cascades
  - L-R symmetric model
  - Fourth generation d quark

- Exclusion below 460 GeV, assuming Majorana neutrinos are produced by a four fermion operator, and Λ ~ 1 TeV.

- Exclusion below 320 GeV, using $d_4 \bar{d}_4 \rightarrow tW \bar{t}W$ assuming $Br(d_4 \rightarrow tW) = 100\%$
2011 Analysis

- same channels as 2010 analysis, but focus on dimuon
- MUCH more data: 1.07 fb\(^{-1}\)

**Selection improvements**

- only one muon with \(p_T > 20\text{ GeV}\), the other with \(p_T > 10\text{ GeV}\)
  - greater signal acceptance
- track-based isolation requirement: sum of track \(p_T\) within cone of \(\Delta R = 0.4\) less than 10\% of muon \(p_T\) AND less than 5 GeV
  - shown to have less pileup dependence
  - pileup bigger issue in 2011, with ~6 interactions per bunch crossing
- impact parameter significance: \(|d_0|/\sigma(d_0) < 3\)
  - ~99\% efficient for prompt muons; rejection factor of ~3 for b hadron decays
Background estimation

Non-prompt ("fake") muons are dominant background (83%)
- 1) semi-leptonic b-hadron decays
- 2) pion and kaon decay-in-flight

- Data-driven technique applied to obtain event yield for fakes
- From heavy-flavor-enriched control samples, obtain fake rate
  \[ \text{fake rate} = \text{fraction of non-prompt muons that pass isolation requirement} \]
  (among those passing other selection requirements)
- differences among control samples used to derive systematic uncertainty
- at least 30\% uncertainty
- 80\% systematic in low \( p_T \) bins
- fake rate approximately flat (7\%) above 100 GeV

- With fake rate, extract background estimate from pairs where one or both muons in the signal region are non-prompt

Other backgrounds
- charge-flip: estimate obtained from data driven upper limit on charge-flip rate
- SM background from dibosons: estimate obtained from MC

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{The central value for the probability of a non-prompt muon to pass the isolation requirement is shown versus \( p_T \), with which a non-prompt muon pass the isolation requirement is measured by selecting events where either the MS or the ID charge is mismeasured. These cuts are placed to enhance QCD jet production compared to a sample at low \( p_T \). As systematic uncertainty, for statistical uncertainty is large, but for this cut is measured in data using a dimuon event. Since this also has a moderate dependence on \( \eta \), the latter samples both muons from semi-leptonic b-hadron decays, are used. The measured probability is also compared to the probability for prompt leptons to pass the isolation cut, to be less than 10 GeV and at least one jet with \( |\eta| > 0.2 \).}
\end{figure}
Control region with intermediate isolation

- To test the fake rate method, fake enhanced control region considered
- All other muon selections the same, except for intermediate isolation:
  - if $p_T < 50 \text{ GeV}$: $0.2 > \frac{p_{T\text{cone}0.4}}{p_T} > 0.1$
  - if $p_T > 50 \text{ GeV}$: $5 > \frac{p_{T\text{cone}0.4}}{p_T} > 10 \text{ GeV}$

- Agreement between observation and prediction within systematic uncertainties

**same-sign**

**opposite-sign**

![Data](image1.png)  
**ATLAS Work in Progress**

\[ \int Ldt = 1.07 \text{ fb}^{-1} \]

- 2 intermediate isolation (LS)

**prediction:** 73  
**observation:** 90

![Data](image2.png)

**ATLAS Work in Progress**

\[ \int Ldt = 1.07 \text{ fb}^{-1} \]

- 2 intermediate isolation (OS)

**prediction:** 224  
**observation:** 267  
(m$_{\mu\mu} < 60 \text{ GeV}$)
# Systematic uncertainties

<table>
<thead>
<tr>
<th>Category</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon identification efficiency</td>
<td>1%</td>
</tr>
<tr>
<td>Muon isolation efficiency</td>
<td>2.5%</td>
</tr>
<tr>
<td>Muon momentum measurement</td>
<td>0.5%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.4%</td>
</tr>
<tr>
<td>Luminosity uncertainty</td>
<td>3.7%</td>
</tr>
<tr>
<td>Non-prompt background estimate (binned in $p_T$ and $\eta$)</td>
<td>30-100%</td>
</tr>
<tr>
<td>Diboson cross section</td>
<td>15%</td>
</tr>
</tbody>
</table>

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**Figure 1:** The central value for the probability of a non-prompt muon to pass the isolation requirement, with which a non-prompt muon passes the isolation requirement, is shown versus $p_T$. At lower $p_T$, the probability is close to 100%, and it decreases to about 7% at 100 GeV. Above 100 GeV, the probability is, within uncertainties, constant. The corresponding probability for prompt leptons to pass the isolation cut is measured in data and found to be negligible.

The probability for prompt leptons to pass the isolation cut is measured in data and found to be negligible. The probability for non-prompt muons to pass the isolation cut is measured in simulated events where either the MS or the ID charge is mismeasured. The probability for non-prompt muons to pass the isolation cut is measured in simulated events where either the MS or the ID charge is mismeasured. The probability for non-prompt muons to pass the isolation cut is measured in simulated events where either the MS or the ID charge is mismeasured. The probability for non-prompt muons to pass the isolation cut is measured in simulated events where either the MS or the ID charge is mismeasured. The probability for non-prompt muons to pass the isolation cut is measured in simulated events where either the MS or the ID charge is mismeasured. The probability for non-prompt muons to pass the isolation cut is measured in simulated events where either the MS or the ID charge is mismeasured.
Signal region prediction: invariant mass

- non-prompt background is dominant
- smaller contribution from dibosons
- since charge flip rate is small for muons, no contribution
Signal region muon kinematics

- data comparison coming soon!
Event yield with systematics

2010 with 34 pb⁻¹:

<table>
<thead>
<tr>
<th></th>
<th>( n_{\text{obs}} )</th>
<th>( n_{\text{pred}} )</th>
<th>( n_{\text{fake}} )</th>
<th>( n_{\text{sim,charge-flip}} )</th>
<th>( n_{\text{sim,diboson}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ee )</td>
<td>10</td>
<td>21.8±9.4±3.8</td>
<td>11.1±9.4±2.8</td>
<td>10.1±0.9±2.5</td>
<td>0.6±0.0±0.1</td>
</tr>
<tr>
<td>( \mu\mu )</td>
<td>9</td>
<td>6.1±2.8±1.2</td>
<td>4.8±2.8±1.2</td>
<td>—</td>
<td>1.3±0.0±0.1</td>
</tr>
<tr>
<td>( e\mu )</td>
<td>25</td>
<td>17.5±9.3±3.7</td>
<td>15.0±9.3±3.7</td>
<td>0.5±0.2±0.1</td>
<td>2.1±0.0±0.2</td>
</tr>
</tbody>
</table>

2011 with 1.07 fb⁻¹ (\( \mu\mu \)):

<table>
<thead>
<tr>
<th>Sample</th>
<th>( M_{\ell\ell} &gt; 15 ) GeV</th>
<th>( M_{\ell\ell} &gt; 100 ) GeV</th>
<th>( M_{\ell\ell} &gt; 200 ) GeV</th>
<th>( M_{\ell\ell} &gt; 300 ) GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-prompt muons</td>
<td>227^{+67}_{-119}</td>
<td>26.1^{+11.2}_{-12.4}</td>
<td>3.25^{+1.97}_{-1.79}</td>
<td>0.49 ± 0.35</td>
</tr>
<tr>
<td>charge flip</td>
<td>0.0^{+2.0}_{-0.0}</td>
<td>0.0^{+0.6}_{-0.0}</td>
<td>0.6^{+0.4}_{-0.0}</td>
<td>0.0^{+0.4}_{-0.0}</td>
</tr>
<tr>
<td>( W^\pm Z )</td>
<td>34.9 ± 5.2</td>
<td>16.2 ± 2.7</td>
<td>5.08 ± 0.98</td>
<td>1.17 ± 0.33</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>7.97 ± 1.22</td>
<td>3.04 ± 0.52</td>
<td>0.56 ± 0.11</td>
<td>0.16 ± 0.045</td>
</tr>
<tr>
<td>( W^\pm W^\pm jj )</td>
<td>1.79 ± 0.91</td>
<td>1.16 ± 0.59</td>
<td>0.53 ± 0.27</td>
<td>0.17 ± 0.09</td>
</tr>
<tr>
<td>( t\bar{t}W^\pm )</td>
<td>0.81 ± 0.40</td>
<td>0.41 ± 0.21</td>
<td>0.12 ± 0.06</td>
<td>0.042 ± 0.025</td>
</tr>
<tr>
<td>sum</td>
<td>272^{+67}_{-119}</td>
<td>46.9^{+11.5}_{-12.7}</td>
<td>9.55^{+2.22}_{-2.06}</td>
<td>2.03^{+0.63}_{-0.49}</td>
</tr>
</tbody>
</table>
| data                | observed yield coming soon!

Ben Cerio  
SS dilepton analysis
Conclusion

- An inclusive search for anomalous production of same-sign dileptons was performed with the 2010 dataset, and is in progress for the 2011 data.
- In 2010, no excess beyond the Standard Model was observed, and competitive limits were placed on four BSM models.
- With a factor of 30 more data, expect that the limits with the 2011 dataset will be MUCH more stringent, if no disagreement with SM is found.
- Currently investigating limits on specific model: doubly charged Higgs bosons.
Backup
Large Hadron Collider

- proton-proton collider
- four detectors along beamline
  - ATLAS
  - CMS
  - LHCb
  - ALICE

ATLAS Online Luminosity
\[ \sqrt{s} = 7 \text{ TeV} \]

<table>
<thead>
<tr>
<th>Total Integrated Luminosity [fb(^{-1})]</th>
<th>26/02</th>
<th>27/03</th>
<th>25/04</th>
<th>25/05</th>
<th>23/06</th>
<th>23/07</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC Delivered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS Recorded</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total Delivered: 1.46 fb(^{-1})</td>
<td></td>
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</tr>
<tr>
<td>Total Recorded: 1.39 fb(^{-1})</td>
<td></td>
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</tr>
</tbody>
</table>
ATLAS detector

- Inner detector (yellow) - responsible for particle tracking
- Calorimeters (green and orange) - records energy of electromagnetically and strongly interacting particles
- Muon system (blue) - measures muon momentum
Systematic uncertainties

- Muon identification efficiency: 1%
- Muon isolation efficiency: -2.5%
- Muon momentum measurement: 0.5%
- Trigger efficiency: 0.4%
- Luminosity uncertainty: 3.7%
- Non-prompt background estimate: 30-100%
  evaluated separately in each invariant mass bin
- Diboson cross section
  - WZ/WW: 15%
    depending on cuts, k-factor varied from 1.4 to 1.7
  - WWjj, ttbarW: 50%
Derivation of fake rate

- Heavy-flavor enhanced control samples used to derive fake rate

1) Dimuon sample
   - two muon trigger with lower threshold of 10 GeV
   - two muons passing selection except for isolation and $d_0$ significance
   - $15 < M_{\mu\mu} < 45$ GeV
     suppresses Drell-Yan
   - $d_0$ significance > 5

2) Same trigger sample
   - use same trigger as analysis for $p_T > 20$ GeV
   - $d_0$ significance > 5
   - control sample factors in fake rate dependence on muon trigger

3) Low $m_T$ sample
   - single muon trigger used, and away side jet with $p_T$ greater than 20 GeV required
   - $m_T < 10$ GeV
     - reduces contribution from prompt muons from $W$
   - this sample probes fake rate from decay-in-flights in addition to heavy flavor decays

\[ \text{fake rate} \]

\[ \text{central value & systematic uncertainty} \]

- differences among control samples used to derive systematic used to derive systematic uncertainty
- at least 30\% uncertainty
- 80\% systematic in low $p_T$ bins
- fake rate approximately flat (7\%) above 100 GeV
Application of fake rate

- Background estimate from matrix method
- Two sets of muons
  - TIGHT - pass isolation
  - LOOSE - fail isolation
- Four observables: $N_{TT}$, $N_{TL}$, $N_{LT}$, $N_{LL}$

$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r r & r f & f r & f f \\ r (1 - r) & r (1 - f) & f (1 - r) & f (1 - f) \\ (1 - r) r & (1 - r) f & (1 - f) r & (1 - f) f \\ (1 - r) (1 - r) & (1 - r) (1 - f) & (1 - f) (1 - r) & (1 - f) (1 - f) \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$

- Fake rate and signal efficiency used to relate observables to true composition in signal region

$$N_f = r f N_{RF} + f r N_{FR} + f f N_{FF}$$

- Invert first equation to get signal prediction, $N_{TT}$

$$N_{TT} = r r N_{RR} + r f N_{RF} + f r N_{FR} + f f N_{FF}$$

MC-derived