Search for Anomalous Production of Prompt Like-sign Muon Pairs in ATLAS

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OUTLINE

‣ Motivation

‣ Analysis strategy

‣ LHC & ATLAS
  • Inner detector
    • tracking performance & alignment
  • Muon system
    • muon reconstruction & identification

‣ Analysis details
  • Event selection
  • Background determination
  • Results & interpretation

‣ Outlook
Standard Model ... and beyond

- The Standard Model (SM)
  - Describing fundamental particles & their interactions
  - Remarkably successful in describing experimental data

- Predicts all force carriers to be massless
  - Higgs mechanism
  - Narrow mass range left for SM Higgs

ATLAS combined 95% upper CLs limits as function of $m_H$

arXiv:1202.1408
Standard Model ... and beyond

• What the Standard Model cannot explain
  • Neutrino masses
  • Dark matter
  • Matter/anti-matter asymmetry
    • These questions probed by the LHC experiments

• Exploring a new energy regime → start with inclusive analyses
  • Analysis presented today based on like-sign muon pairs

Like-sign muons

• Pairs of prompt leptons with same charge rarely produced in the SM
  • WZ / ZZ
• Production rate can be enhanced in new physics models

• Experimental motivation
  • Trigger objects
  • High reconstruction efficiency

Prompt muon
Produced at primary event vertex or from decay of short-lived state (muons from b-hadrons considered non-prompt)
Like-sign muons & new physics

• Many potential new physics models give rise to like-sign leptons
  • Supersymmetry
  • 4th generation quarks
  • Heavy Majorana neutrinos
  • FCNC giving like-sign top quarks
  • Models with doubly charged Higgs bosons
• ...
Like-sign muons & new physics

Supersymmetry
- Introduces supersymmetric partners to SM particles differing by 1/2 in spin

- Key motivations
  - The hierarchy problem
    - Stabilize Higgs mass to radiative corrections
  - Gauge coupling unification
  - Dark matter candidate

- Assuming conservation of matter parity
  - SUSY particles pair-produced
  - Lightest SUSY particles cannot decay

\[ \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\mu}^\pm, \tilde{\tau}^\pm, \tilde{\nu}, \tilde{\psi}, \tilde{\psi}^- \]

\[ \text{direct gaugino production} \]

\[ \text{gluino cascade decay} \]
Like-sign muons & new physics

Like-sign top quark production
• Produced through exchange of flavor-changing $Z'$ boson
• Could explain forward-backward asymmetry observed at the Tevatron in ttbar production
  • Like-sign lepton final states if both tops decay leptonically
• Previous best limit: $\sigma(Z' \to ttX) < 17 \text{ pb}$ (CMS)

Doubly charged Higgs
• Doubly charged Higgs bosons predicted in many new physics models
  • Higgs triplet models
  • Left-right symmetric model
• Dominant production is Drell-Yan pair-production
• Previous best limit: $m(H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) > 277 \text{ GeV}$ (CMS preliminary)
Analysis strategy

• Perform *inclusive search* in $\mu^\pm \mu^\pm$ final state
  • Base selection cuts only on muon properties
  • Cover largest possible phase space where backgrounds under control

• Understanding & constraining *backgrounds*
  • Prompt muons from SM sources
  • Non-prompt muon background
  • Charge mis-identified muons

• Results & interpretations
Analysis strategy

- Perform **inclusive search** in $\mu^+\mu^-$ final state
  - Base selection cuts only on muon properties
  - Cover largest possible phase space where backgrounds under control

- Understanding & constraining **backgrounds**
  - Prompt muons from SM sources
  - **Non-prompt muon background**
  - Charge mis-identified muons

- Results & interpretations

Main analysis challenge
- Understanding contribution of non-prompt muons
  - Heavy flavor: $b/c$ hadron decays
  - Pion/kaon decay-in-flight
- Handles for reducing this background
  - Muon isolation
  - Track impact parameter
Analysis strategy

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- Results & interpretations
  - Search data for overall excess
  - Narrow resonance search - mass peak in dimuon mass spectrum
  - If no significant deviations observed?
    - *Put constraints on cross-section of non-SM contributions within fiducial region*
    - *Constraints on mass of doubly charged Higgs bosons*

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**Fiducial region**
Defined by the analysis event selection
The LHC

• Excellent performance in 2011
  • > 5 fb\(^{-1}\) of integrated luminosity
  • Max instantaneous luminosity \(\sim 3.6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\)
• ATLAS data-taking efficiency \(\sim 93.5\%\)
  • DQ efficiency of 90-96%
• High luminosity \(\rightarrow\) high pileup
• Several interactions / bunch-crossing
  • Challenge for trigger, lepton isolation, ...

**Graphs:**

- **ATLAS Online Luminosity**
  - \(\sqrt{s} = 7 \text{ TeV}\)
  - LHC Delivered: 5.61 fb\(^{-1}\)
  - ATLAS Recorded: 5.25 fb\(^{-1}\)
  - Data used in this analysis: 1.6 fb\(^{-1}\) after DQ

- **Peak Average Interactions/BX**
  - \(\langle \mu \rangle \sim 6\)
  - LHC Delivered
The ATLAS detector

- General purpose detector
  - Barrel & 2 endcaps
- Inner tracking system
- Calorimeters to $|\eta| < 4.9$
  - EM & hadronic sections
- Toroidal muon system

Particle identification in ATLAS

- Pseudo-rapidity
  \[ \eta = -\ln(\tan\theta/2) \]
- Angular distance
  \[ \Delta R = (\Delta \phi^2 + \Delta \eta^2)^{1/2} \]

46 x 25 meter
Inner detector tracking system

- Tracking central part of object reconstruction
- Inner detector
  - **Pixel** - silicon pixels, the innermost detector ~5 cm from beam line
  - **SCT** - silicon microstrips
  - **TRT** - straw tube transition radiation tracker
- Immersed in 2T solenoid field

**Tracker requirements**
- Provide precision tracking for $|\eta| < 2.5$
- Precise primary & secondary vertex
  - b-tagging
- Transition radiation for electron identification

**Resolutions, 100 GeV track**
- impact parameter ~12 µm
- transverse momentum ~5 GeV

- 6.2m long

![Diagram of detector system with dimensions and resolutions](diagram.png)
Inner detector alignment

- Precise knowledge of detector element positions crucial
  - Accurate momentum measurements & charge determination
  - Precise vertex reconstruction
- Alignment of > 35,000 d.o.f.
  - Use high-p_T tracks from collisions & cosmic rays
- Systematic biases
  - Observed large charged-dependent modulation in Z mass vs muon φ
  - Corrected by imposing external constraints during alignment procedure

Minimize residuals: distance between extrapolated track position & recorded hit position in given module

![Graph showing id tracks and mass distribution](image-url)
The muon system

- Cross-sectional view of the ATLAS muon system
  - Tracking
  - Triggering
- Three air-core superconducting toroids ~0.5 T field

Muon $p_T$ trigger thresholds:
- Level 1 (online hardware-based): 10 GeV
- High-level trigger: 18 GeV
Muon identification

• Several different muon identification algorithms
  • Muon spectrometer stand-alone muon
  • Inner detector track matched to track segments in muon system
  • **Combined muon**
    • Stand-alone muon combined with inner detector track for joint momentum measurement
    • Independent charge measurements from ID & MS → used for this analysis

![Combined muon reconstruction efficiency vs η](image.png)

**ATLAS** Preliminary

\[ \int Ldt = 193 \text{ pb}^{-1} \]

- MC
- data 2011

Combined muon reconstruction efficiency vs η
analysis: selection, backgrounds & systematics
Event selection: muons

- Basic selection requirements
  - $|\eta| < 2.5$
  - Transverse momentum: $p_T > 20$ GeV
  - Track impact parameter
    - Transverse $|d_0| < 0.2$ mm
    - Longitudinal $|z_0 \sin \theta| < 5$ mm

- Muon quality selection
  - **Charge:** $Q_{ID} = Q_{MS}$
  - *Impact parameter significance:* $|d_0|/\sigma(d_0) < 3$
    - long tails for non-prompt muons
  - **Track-based isolation**

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**Impact parameter significance**

*for non-isolated muons (in same-sign dimuon events)*
Muon isolation

- Track isolation
  - Scalar $p_T$ sum of tracks with $p_T > 0.5$ GeV in cone of $\Delta R < 0.40$ ($p_T^{\text{cone40}}$)
  - Track selection
    - $|d_0| < 10$ mm, $|z_0| < 10$ mm & $\geq 4$ silicon hits
    - Helps reduce dependence on pileup
  - Require: $p_T^{\text{cone40}}/p_T(\mu) < 0.08$ & $p_T^{\text{cone40}} < 5$ GeV
    - Tighter at low $p_T$ where background most severe

- Reasonable modeling by simulation
  - Discrepancies addressed for systematic uncertainty

![Graph showing muon isolation efficiency with data and MC plots]
Muon isolation

- Track isolation
  - Scalar $p_T$ sum of tracks with $p_T > 0.5$ GeV in cone of $\Delta R < 0.40$ ($p_T^{\text{cone}40}$)
  - Track selection
    - $|d_0| < 10$ mm, $|z_0| < 10$ mm & $\geq 4$ silicon hits
    - Helps reduce dependence on pileup

- Require: $p_T^{\text{cone}40}$
  - Tighter at low $p_T$

- Reasonable modeling by simulation
  - Discrepancies addressed for systematic uncertainty

- **Efficiency of isolation + impact parameter cuts**
  - Prompt muons (from $Z \rightarrow \mu\mu$): 87-97% depending on $p_T$
  - Non-prompt muons from $b/c$ hadrons: $\sim 3.5\%$
Event selection: dimuon pairs

- Select pairs of good muons with equal charge
- Invariant mass:
  - $m(\mu\mu) > 15$ GeV

- Opposite-sign control region
  - Verify understanding of prompt isolated muons from Drell-Yan
    - estimate using using $Z \rightarrow \mu^+\mu^- MC$
  - Prediction in good agreement with observation

![Graph showing muon pairs distribution](image-url)
Backgrounds

- Understanding & accurately estimating backgrounds most crucial part of the analysis

1. SM production of prompt like-sign dimuons: **dibosons**

2. Prompt opposite-sign dimuons where one muon is mis-measured: **charge-flip**

3. Muons from hadronic decays: **non-prompt muons**
Backgrounds

- Understanding & accurately estimating backgrounds most crucial part of the analysis

1. SM production of prompt like-sign dimuons: dibosons

2. Prompt opposite-sign dimuons where one muon is mis-measured: charge-flip

3. Muons from hadronic decays: non-prompt muons

- Dominant & irreducible background
- Well-modeled in simulation → MC-based prediction
  - WZ / ZZ: normalize to NLO cross section
  - Smaller contributions from: W^±W^± / ttW
- Resulting background:

<table>
<thead>
<tr>
<th>Process</th>
<th>m(μ^±μ^±) &gt; 15 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>48.4 ± 6.3</td>
</tr>
<tr>
<td>ZZ</td>
<td>10.6 ± 1.4</td>
</tr>
<tr>
<td>W^±W^±</td>
<td>2.7 ± 1.3</td>
</tr>
<tr>
<td>ttW</td>
<td>1.4 ± 0.7</td>
</tr>
</tbody>
</table>
Backgrounds

- Understanding & accurately estimating backgrounds most crucial part of the analysis

1. SM production of prompt like-sign dimuons: *dibosons*

2. Prompt opposite-sign dimuons where one muon is mis-measured: *charge-flip*

3. Muons from hadronic decays: *non-prompt muons*

- Estimate from MC, cross-check using data
- Charge mis-identification rate
- Measure separately for ID/MS using Z events
- $Q^{ID} = Q^{MS}$ → both must be mis-measured for charge flip
- Apply combined rate to opposite-pairs in MC → upper systematic limit
- Resulting background:

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<tr>
<td>charge-flip</td>
<td>0 $+2.7/-0.0$</td>
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67% upper limit on charge flip rate

ATLAS Work in progress
Backgrounds

• Understanding & accurately estimating backgrounds most crucial part of the analysis

• (1) SM production of prompt like-sign dimuons: dibosons

• (2) Prompt opposite-sign dimuons where one muon is mis-measured: charge-flip

• (3) Muons from hadronic decays: non-prompt muons

  • Predominantly from heavy-flavor decays
  • Largely suppressed through selection cuts
  • Estimated using data-driven techniques
  • Determine rate with which non-prompt muons pass isolation selection
Non-prompt isolation probability

• Derive rate in regions enhanced in non-prompt muons

- **High $d0_{\text{significance}}$ (>5)**
  - *Dimuon sample*
    - analysis is dimuon events - most similar to signal region
    - require $15 < m(\mu\mu) < 55$ GeV
  - *Single muon sample*
    - higher statistics

- **Low $m_T$ region**
  - *Exactly one muon & at least one jet*
  - $m_T < 10$ GeV
    - reduce contribution of prompt muons from $W$
    - remaining prompt muon contribution subtracted based on MC

$M_W = 80413 \pm 34^{\text{stat}} \pm 34^{\text{syst}}$ MeV/$c^2$
Resulting isolation probability

- Isolation requirement: $p_{T\text{cone}40}/p_T(\mu) < 0.08$ \& $p_{T\text{cone}40} < 5 \text{ GeV}$

- Non-prompt isolation probability vs $p_T$ for different control samples: 5-8%
  - Central value derived using muons with $d0_{\text{significance}} > 5$
  - Difference between samples used to assess systematic uncertainty
  - For high $p_T$, statistical uncertainty large $\rightarrow$ assign 100% systematic uncertainty

![Graph showing non-prompt isolation probability vs muon $p_T$](image)
Signal region predictions

• Contribution to signal region estimated using matrix method

• Define two sets of muons, exclusive of each other
  • $T$ tight = PASS isolation
  • $L$ loose = FAILS isolation

• Separate dimuon pairs into $TT$, $TL$, $LT$, $LL$

• Method relates observed dimuon composition to underlying real/fake composition
  • Inputs are the rates with which prompt & non-prompt muons pass isolation

督察 Cross check prediction using non-prompt muon enhanced control regions!
Control region: intermediate isolation

- Predict intermediate isolation
  - Both muons fail signal region isolation but pass looser isolation cut
  - Muons pass other selection cuts
    - $d\sigma_{\text{significance}} < 3$
    - Like-sign muons
  - Predict $14^{+4/-5} \& \text{observe } 18$ - good agreement!

For higher statistics compare $p_T(\mu_2) > 10$ GeV - good modeling
Control region: high $d_0^{\text{significance}}$

- Require at least one muon to **FAIL** the $d_0^{\text{significance}}$ cut (> 3)
  - Require both muons to pass all other selection cuts
    - **Signal region isolation**
    - **Like-sign muons**
  - Predict $29^{+7/-9}$ & observe 12 - **1.8 sigma downward fluctuation**

For higher statistics compare $p_T(\mu_2) > 10$ GeV - **good modeling**
Systematic uncertainties

- Several systematic uncertainties may change signal acceptance & background estimate
- Small uncertainties on lepton identification

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<th>Processes affected</th>
<th>Effect on prediction</th>
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<td>Muon identification</td>
<td>Signal WZ, ZZ, W±W±, tW</td>
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*affected signal & prompt background*
Systematic uncertainties

- Several systematic uncertainties may change signal acceptance & background estimate
- Small uncertainties from lepton identification
- Cross section uncertainties & limited MC statistics

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- Cross section uncertainties & limited MC statistics
- Uncertainties on non-prompt muon background

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analysis: results & interpretations
Results: kinematics

- Invariant mass of muon pair
- Leading & subleading muon \( p_T \)

- No significant excess observed in data!
Results: kinematics

- Separate into 4 mass regions
  - > 15 GeV
  - > 100 GeV
  - > 200 GeV
  - > 300 GeV

- Observation in good agreement with SM predictions!
  - Proceed to put limits...

<table>
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<tr>
<th>Sample</th>
<th>Number of muon pairs with $m(\mu^+\mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt; 15 GeV</td>
</tr>
<tr>
<td>prompt muons</td>
<td>63.1 ± 7.8</td>
</tr>
<tr>
<td>non-prompt muons</td>
<td>37.5$^{+10.3}_{-12.4}$</td>
</tr>
<tr>
<td>charge flip</td>
<td>0$^{+2.7}_{-0}$</td>
</tr>
<tr>
<td>total</td>
<td>100.6$^{+13.2}_{-14.7}$</td>
</tr>
<tr>
<td>data</td>
<td>101</td>
</tr>
</tbody>
</table>

>5% probability for background only hypothesis to fluctuate down
Limit setting

• No excess observed → set constraints on like-sign muon production from non-SM sources
  • Do counting experiment in bins of invariant mass
• Translate from number of pairs to a cross section → fiducial efficiency

\[ \sigma_{95}^{\text{fid}}(\mu\mu) = \frac{N_{95}(\mu\mu)}{\epsilon_{\text{fid}} \int L dt} \]

• True fiducial region
  • \( p_T(\mu) > 20 \text{ GeV} \)
  • \( |\eta| < 2.5 \)
  • Separation from truth jet & truth prompt electron/muon with \( p_T > 20 \text{ GeV} \) by \( dR > 0.40 \)
    • emulate isolation cut
  • \( m(\mu\mu) > 15 \text{ GeV} \)

• Fiducial efficiency compared between different new physics models
  • Busy vs clean events
  • Lowest observed efficiency used (range between 44-73%)

Models considered: \( H^{\pm\pm}, t_{Rt}, b' \text{ quark}, W_R \)
Fiducial cross-section limits

• Resulting cross-section limits determined for the four mass ranges considered
• Here combined positive & negative pairs

<table>
<thead>
<tr>
<th>Mass range [GeV]</th>
<th>$\sigma_{95}^{fid}$ [fb]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>expected</td>
</tr>
<tr>
<td>All muon pairs</td>
<td></td>
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<tr>
<td>$m(\mu^\pm\mu^\pm) &gt; 15$</td>
<td>58$^{+19}_{-17}$</td>
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<td>30$^{+11}_{-9}$</td>
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<td>13.7$^{+5.7}_{-4.4}$</td>
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<tr>
<td>$m(\mu^\pm\mu^\pm) &gt; 300$</td>
<td>8.0$^{+3.3}_{-2.6}$</td>
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ATLAS

$\int L dt = 1.6 \text{ fb}^{-1}$
$\sqrt{s} = 7 \text{ TeV}$

$\sigma(pp \rightarrow \mu^\pm \mu^\pm) > 15 \text{ GeV}$, $|\eta(\mu)| < 2.5$
$\Delta R(\mu, \text{jet/e}/\mu) > 0.4$
Limit on like-sign top quark production

- Direct translation of fiducial cross-section limit to specific model

- **Like-sign top production** through exchange of flavor-changing $Z'$ boson
  - Like-sign tops at the LHC dominated by positive pairs
  - Consider only $\mu^+\mu^+$ since expect charge symmetric background

- Need acceptance of model & its uncertainty
  - Evaluate for different values of $Z'$ mass in the four mass bins

- **Resulting cross-section limit on $t_{R \bar{R}}$ production**

$$\sigma_{95} = \frac{\sigma_{95}^{fid}(\mu\mu)}{A_{fid}}$$

<table>
<thead>
<tr>
<th>$m(Z')$</th>
<th>$\sigma_{95}(t_{R\bar{R}})$ [pb]</th>
<th>observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>$4.2^{+2.3}_{-0.9}$</td>
<td>3.7</td>
</tr>
<tr>
<td>150 GeV</td>
<td>$3.3^{+1.9}_{-0.7}$</td>
<td>3.0</td>
</tr>
<tr>
<td>200 GeV</td>
<td>$2.9^{+1.6}_{-0.6}$</td>
<td>2.6</td>
</tr>
<tr>
<td>$\gg 1$ TeV</td>
<td>$2.5^{+1.4}_{-0.5}$</td>
<td>2.2</td>
</tr>
</tbody>
</table>

($t_L$ experimentally constrained from $B_d - \bar{B}_d$ mixing)
Interpretation of result

- Strongest limit to date on production cross section of like-sign top quark pairs
- Cross section required for $A_{FB}^{new} > 0$ excluded for $Z'$ model
Dimuon resonance search

• Search dimuon mass for narrow resonance such as doubly charged Higgs bosons
  • Predicted by many new physics models
  • Observe good agreement between data & prediction \rightarrow set limits

• Counting experiment in narrow ranges of dimuon mass
  • \(0.9 \times m(\mu^\pm \mu^\pm) < M(H^{\pm \pm}) < 1.1 \times m(\mu^\pm \mu^\pm)\)
  • Estimate (acceptance \times efficiency) from simulation (46 - 57%), translate to cross-section limit

\[ \sigma_{HH} \times BR(H^{\pm \pm} \rightarrow \mu^\pm \mu^\pm) = \frac{N(\mu^\pm \mu^\pm)}{2 \times A \times \epsilon \times \mathcal{L} dt} \]

  relative to number of \(H^{\pm \pm}\) decaying to \(\mu \mu\)

• Total acceptance uncertainty \sim 3.6%
  • PDF uncertainty
  • Interpolation between mass values
  • MC statistics
Results: doubly charged Higgs bosons

- Assuming $\text{BR} (H^{±±} \rightarrow µ^±µ^±) = 100 \%$
  - $m(H^{±±L}) > 355 \text{ GeV}$
  - $m(H^{±±R}) > 251 \text{ GeV}$
- Assuming $\text{BR} (H^{±±} \rightarrow µ^±µ^±) = 33 \%$
  - $m(H^{±±L}) > 244 \text{ GeV}$
  - $m(H^{±±R}) > 209 \text{ GeV}$

Different couplings of $H^{±±R} / H^{±±L}$ to $Z$ gives right-handed production cross section factor 2 lower

![Graph of ATLAS results](image-url)
Outlook

• Like-sign muons important probe of beyond the SM physics
  • Inclusive analysis sensitive to a wide range of new physics models
  • Dedicated searches can provide further sensitivity

• Observe no significant excess in data over SM predictions
  • Set constraints on fiducial cross-section of $\mu^+\mu^+$ production & mass of $H^{\pm\pm}$ bosons
  • Analysis based on 1.6 fb$^{-1}$ of data but ~5 fb$^{-1}$ on disk & more to come!
    • *Ongoing work of updating to include full 2011 dataset & further fine-tune event selection cuts*

• It’s an excellent time to do high-energy physics - next
  years have all the odds to provide great excitement!
BACKUP
**Inner detector alignment**

**Barrel**

- Spring 2011 alignment
- Summer 2011 alignment
- $Z \rightarrow \mu \mu$ MC

$\int L \, dt = 0.70 \, fb^{-1}$

**Endcap A**

- Spring 2011 alignment
- Summer 2011 alignment
- $Z \rightarrow \mu \mu$ MC

$\int L \, dt = 0.70 \, fb^{-1}$

**Negative muons in endcap A**

**Positive muons in endcap A**
Combined muon resolutions

- Dimuon mass resolution of combined muons in different pseudorapidity regions
- Experimental resolution compared to MC predictions using Pythia → Z µµ events
More on isolation & pileup

- Two types of pileup affecting isolation
  - **In-time pileup** → Overlapping interactions in the same bunch crossing
    - Probe as isolation vs # primary vertices
  - **Out-of-time pileup** → Contributions from activity in previous bunch crossings (related to limited detector readout)
    - Effect dependent on bunch train position
    - Probe as isolation vs # preceding filled bunches (or BCID)

**LAr signal shape**

On average, the effects of pileup in LAr should approximately cancel (energy deposits from pileup contributions integrating out)
Out-of-time pileup

- Out of time pileup & muon isolation
  - **Right** Track isolation independent of BCID
  - **Left** Calorimetric isolation shows clear dependence on BCID
    - Effect of calorimeter pulse shaping

**Calorimetric isolation**

\[
\langle E_T (\Delta R < 0.4) \rangle \quad [\text{GeV}]
\]

\[
\int \text{Ldt} = 730 \text{ pb}^{-1} \quad s = 7 \text{ TeV}
\]

\[
|M_{\mu\mu} - M_Z| < 15 \text{ GeV}
\]

**Track isolation**

\[
\langle \Sigma \text{Track } P_T (\Delta R < 0.4) \rangle \quad [\text{GeV}]
\]

\[
\int \text{Ldt} = 730 \text{ pb}^{-1} \quad s = 7 \text{ TeV}
\]

- Data 2011
- Simulation
In-time pileup

- Study mean isolation vs # vertices
- Pileup dependence on isolation described in MC
  - Stronger pileup dependence with larger cone size
- Track isolation nearly independent on in-time pileup

---

**Calorimetric isolation**

ATLAS Preliminary

\[ \langle E_{T}(\Delta R < 0.1) \rangle \]

\[ \int L dt = 730 \text{ pb}^{-1} \; \sqrt{s} = 7 \text{ TeV} \]

\[ |M_{\mu\mu} - M_{\eta} < 15 \text{ GeV} \]

**Track isolation**

ATLAS Preliminary

\[ \int L dt = 730 \text{ pb}^{-1} \; \sqrt{s} = 7 \text{ TeV} \]

\[ |M_{\mu\mu} - M_{\eta} < 15 \text{ GeV} \]

[Graphs showing isolation vs number of vertices for calorimetric and track isolation]
Systematics for non-prompt background

- **Central value**
  - Derived using muons with \(d_{0}^{\text{significance}} > 5\)
  - Flat above 100 GeV at \(\sim 6\%\)

- **Systematic uncertainty**
  - Estimate from observed differences in measured isolation probability
    - High \(d_{0}^{\text{significance}}\) sample vs low \(m_T\) sample \(\rightarrow\) at least 30\% uncertainty at all \(p_T\)
    - Larger uncertainty at low \(p_T\) (measurement differences) & high \(p_T\) (low statistics)
  - At high \(p_T > 100\) GeV, assign 100\% uncertainty
  - Uncertainty on isolation rate propagated through to obtain estimated effect on non-prompt yield

![Graph showing non-prompt isolation probability vs. \(p_T\)]
Additional control regions

- Additional control regions defined by requiring both muons to pass an intermediate isolation requirement & at least one muon fail the $d_{0}\text{significance}$ cut
  - Opposite-sign pairs vs like-sign pairs
  - Good agreement of data & prediction within the uncertainties
**Results: muon kinematics**

- Distribution of $\eta$ for leading / subleading $p_T$ muons
Results: invariant mass by charge

- Dimuon invariant mass spectrum, separated by positively/negatively charged pairs
Limits: doubly charged Higgs

- Limits on doubly charged Higgs production as function of branching ratio to two muons

\[
\text{BR}(H_L^{±±} \rightarrow \mu^±\mu^±), \quad \text{BR}(H_R^{±±} \rightarrow \mu^±\mu^±)
\]

ATLAS

\[\int L dt = 1.6 \text{ fb}^{-1}\]

\[\sqrt{s} = 7 \text{ TeV}\]