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

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Experimental Particle Physics Seminar
University of Pennsylvania
March 20, 2012
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)
  - Describes fundamental particles & their interactions
  - Remarkable success in explaining 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

- 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 rare 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
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 $tt\bar{t}$ production
  - Like-sign lepton final states if both tops decay leptonically
- Previous best limit: $\sigma(Z' \rightarrow ttX) < 17$ 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: $m(H^{\pm \pm} \rightarrow \mu^\pm \mu^\pm) > 277$ GeV (CMS preliminary)
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
Analysis strategy

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

**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, ...

![Graph showing ATLAS Online Luminosity](image)

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

![Graph showing Peak Average Interactions/BX](image)

- ATLAS Online \(\sqrt{s} = 7\text{ TeV}\)
- LHC Delivered
- \(<\mu> \sim 6\)
The ATLAS detector

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

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

Particle identification in ATLAS

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
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
  - Large charged-dependent modulation in Z mass observed
  - Corrected by imposing external constraints during alignment procedure

Minimize residuals:

distance between extrapolated track position & recorded hit position in given module
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**

*ATLAS Preliminary*  
\[ \int L dt = 193 \text{ pb}^{-1} \]

- MC
- data 2011
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 track isolation

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

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Muon_isolation_plot.png}
\caption{Muon isolation efficiency from $Z \rightarrow \mu\mu$ events.}
\end{figure}
Muon track isolation

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- 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 $Z \rightarrow \mu^+\mu^-$ MC
  - Prediction in good agreement with observation

![Graph showing dimuon pairs distribution](image)
Backgrounds

• (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-promp t muons*
Backgrounds

• **(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*: $W^\pm W^\pm / t\bar{t}W$
- **Resulting background:**

<table>
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<tr>
<th>Process</th>
<th>$m(\mu^\pm \mu^\pm) &gt; 15$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ</td>
<td>$48.4 \pm 6.3$</td>
</tr>
<tr>
<td>ZZ</td>
<td>$10.6 \pm 1.4$</td>
</tr>
<tr>
<td>$W^\pm W^\pm$</td>
<td>$2.7 \pm 1.3$</td>
</tr>
<tr>
<td>$t\bar{t}W$</td>
<td>$1.4 \pm 0.7$</td>
</tr>
</tbody>
</table>
Backgrounds

- **(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 in data
- Charge mis-identification rate
- Measure separately for ID/MS using Z events
- \( Q^{ID} = Q^{MS} \rightarrow \) both must be mis-measured for charge flip
- Apply combined rate in MC → upper systematic limit
- Resulting background:

![Graph showing 67% upper limit on charge flip rate](image)

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<tr>
<th>Process</th>
<th>( m(\mu^\pm\mu^\pm) &gt; 15 \text{ GeV} )</th>
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<tr>
<td>charge-flip</td>
<td>0 +2.7/-0.0</td>
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</table>
Backgrounds

• (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 $d_0$ 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

$$m_T(W) = \sqrt{2p_T^\mu p_T^\nu (1 - \cos(\phi^\mu - \phi^\nu))}$$

probes **heavy-flavor** decays

probes also **decay-in-flight**

Abstract.

The CDF collaboration has analyzed $\sim 200$ pb$^{-1}$ of Tevatron Run II data taken with the CDF II detector between February 2002 and September 2003 to measure the W boson mass. With a sample of 63964 $W \rightarrow e\nu$ decays and 51128 $W \rightarrow \mu\nu$ decays, we measure $M_W = 80413 \pm 34\text{(stat)} \pm 34\text{(syst)}$ MeV/c$^2$. The total measurement uncertainty of 48 MeV/c$^2$ makes this result the most precise single measurement of the W boson mass to date.

1. Introduction

The W boson mass is an important Standard Model (SM) parameter. It receives self-energy corrections due to vacuum fluctuations involving virtual particles. Thus, the W boson mass probes the particle spectrum in nature, including particles that have yet to be observed directly. The hypothetical particle of most immediate interest is the Higgs boson. The W boson mass can be calculated at tree level using the three precise measurements of the Z boson mass, the Fermi coupling $G_F$ and the electromagnetic coupling $\alpha_{em}$. In order to extract information on new particles, we need to account for the radiative corrections to $M_W$ due to the dominant top-bottom quark loop diagrams. For fixed values of other inputs, the current uncertainty on the top quark mass ($m_t$) measurement$^{170}$ $170.9 \pm 1.8$ GeV/c$^2$[1] corresponds to an uncertainty in its W boson mass correction of 11 MeV/c$^2$. Measurements of the W boson mass from Run I of the Tevatron and LEP with uncertainties of 59 MeV/c$^2$[2] and 33 MeV/c$^2$[3] respectively, yield a world average of $80392 \pm 29$ MeV/c$^2$[3]. It is clearly profitable to reduce the W boson mass uncertainty further as a means of constraining the Higgs boson mass.

2. Measurement Strategy

At the Tevatron, W bosons are mainly produced by valance quark-antiquark annihilation, with initial state gluon radiation (ISR) generating a transverse boost. The transverse momentum ($p_T$) distribution of the decay lepton has characteristics Jacobian edge whose location, while sensitive to the W boson mass, is smeared by the transverse boost of the W boson. The neutrino $p_T$ ($p_T^\nu$) can be inferred by imposing $p_T$ balance in the event. The transverse mass, defined as $m_T = \sqrt{2p_T^l p_T^\nu (1 - \cos(\phi^l - \phi^\nu))}$, includes both measurable quantities in the W decay and provides the most precise quantity to measure $M_W$. We use the $m_T$, $p_T^l$ and $p_T^\nu$ distributions from $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays to extract the W boson mass. These distributions do not lend themselves to analytic parameterizations, which leads us to use a Monte Carlo simulation to predict their shape as a function of $M_W$. The shape predictions depend on an number of...
Resulting isolation probability

- Isolation requirement: $p_{T\text{cone40}}/p_{T(\mu)} < 0.08$ & $p_{T\text{cone40}} < 5$ GeV

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

• Contribution to signal region estimated using matrix method

• Define two set 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

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

- Predict intermediately isolated region
  - Both muons fail signal region isolation but pass looser isolation cut
  - Muons pass other selection cuts
    - $d0_{significance} < 3$
    - Like-sign muons
  - Predict $14^{+4/-5}$ & observe 18 - good agreement!

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

• Require at least one muon to FAIL the $d_0$ 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

<table>
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<tr>
<th>Source of uncertainty</th>
<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>
<td>±1%</td>
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This table shows the sources of systematic uncertainty, the processes they affect, and the effect on the prediction. Notably, the muon identification and isolation efficiency affect the background prediction, and the non-prompt muon estimate affects the 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!

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of muon pairs with $m(\mu^+\mu^-)$</th>
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<tbody>
<tr>
<td></td>
<td>$&gt;15$ GeV</td>
</tr>
<tr>
<td>prompt muons</td>
<td>63.1 $\pm$ 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
  • Counting experiment in bins of invariant mass
• Translate from number of pairs to a cross section → fiducial efficiency

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

• 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: \( H^{\pm\pm}, t_Rt_R, b' \text{ quark, } W_R \)
Fiducial cross-section limits

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

<table>
<thead>
<tr>
<th>Mass range [GeV]</th>
<th>(\sigma^{fid}_{95%} ) expected [fb]</th>
<th>(\sigma^{fid}_{95%} ) observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>All muon pairs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m(\mu^\pm\mu^\pm) &gt; 15)</td>
<td>(58^{+19}_{-17})</td>
<td>58</td>
</tr>
<tr>
<td>(m(\mu^\pm\mu^\pm) &gt; 100)</td>
<td>(30^{+11}_{-9})</td>
<td>16</td>
</tr>
<tr>
<td>(m(\mu^\pm\mu^\pm) &gt; 200)</td>
<td>(13.7^{+5.7}_{-4.4})</td>
<td>8.4</td>
</tr>
<tr>
<td>(m(\mu^\pm\mu^\pm) &gt; 300)</td>
<td>(8.0^{+3.3}_{-2.6})</td>
<td>5.3</td>
</tr>
</tbody>
</table>

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

\(\sigma(pp \to \mu^\pm\mu^\pm) \) fid 95\% CL [fb]

\(p_T(\mu) > 20 \text{ GeV, } |\eta(\mu)| < 2.5\)
\(\Delta R(\mu, \text{jet/e/}\mu) > 0.4\)
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 $t_{R}\bar{t}_{R}$ production**

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

<table>
<thead>
<tr>
<th>$m(Z')$</th>
<th>$\sigma_{95}(t_{R}\bar{t}_{R})$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>$4.2^{+2.3}_{-0.9}$</td>
</tr>
<tr>
<td>150 GeV</td>
<td>$3.3^{+1.9}_{-0.7}$</td>
</tr>
<tr>
<td>200 GeV</td>
<td>$2.9^{+1.6}_{-0.6}$</td>
</tr>
<tr>
<td>$\gg$ 1 TeV</td>
<td>$2.5^{+1.4}_{-0.5}$</td>
</tr>
</tbody>
</table>

($t_{L}$ experimentally constrained from $B_{d} - \bar{B}_{d}$ mixing)
Interpretation of result

- Strong constraints on production cross section of like-sign top quark pairs
- Cross section required for $A_{FB}^{new} > 0$ excluded for $Z'$ model

**$A_{FB}^{new} > 0$ excluded by ATLAS**

$\Delta \sigma_{tt} = [-0.8, 1.7] \text{ pb}$ [1105.4606]

$\Delta \sigma_{tt} = [-1.6, 2.3] \text{ pb}$

Limit CMS 35 pb$^{-1}$

$M_{Z'} = 1 \text{ TeV}$

$M_{Z'} = 100 \text{ GeV}$

Limit, ATLAS 1.6 fb$^{-1}$

J.A. Aguilar Saavedra, shown at TOP2011
Dimuon resonance search

- Search dimuon mass for narrow resonance: *doubly charged Higgs bosons*
  - Predicted by many new physics models
  - Observe good agreement between data & prediction → set limits

- Counting experiment in narrow ranges of dimuon mass
  - ±10% around H^{±±} mass
  - Estimate (acceptance × efficiency) from simulation (46 - 57%), translate to cross-section limit

\[ \sigma_{HH} \times BR(H^{±±} \rightarrow \mu^{±} \mu^{±}) = \frac{N(\mu^{±} \mu^{±})}{2 \times A \times \epsilon \times L \times d t} \]

  \text{relative to number of } H^{±±} \text{ decaying to } \mu^{±} \mu^{±}

- Total acceptance uncertainty ~3.6%
  - PDF uncertainty
  - Interpolation between mass values
  - MC statistics
Results: doubly charged Higgs bosons

- Assuming $\text{BR}(H^{\pm\pm} \to \mu^+\mu^+) = 100\%$ (33)%
  - $m(H^{\pm\pm_L}) > 355\ (244)\ \text{GeV}$
  - $m(H^{\pm\pm_R}) > 251\ (209)\ \text{GeV}$

**Different couplings of $H^{\pm\pm_R}$ / $H^{\pm\pm_L}$ to Z gives right-handed production cross section factor 2 lower**
Outlook

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

• Observe no significant excess in data over SM predictions

• Set constraints on fiducial cross-section of $\mu^\pm \mu^\pm$ production & mass of $H^{\pm\pm}$ bosons
  • Analysis based on 1.6 fb$^{-1}$ of data but ~5 fb$^{-1}$ on disk & soon more to come!
  • Ongoing work of updating to include full 2011 dataset & further fine-tune event selection cuts
BACKUP
Inner detector alignment

**Barrel**

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

$\sqrt{s} = 7$ TeV

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

**Negative muons in endcap A**

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

$\sqrt{s} = 7$ TeV

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

$1.05 < \eta < 2.5$

**Positive muons in endcap A**

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

$\sqrt{s} = 7$ TeV

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

$1.05 < \eta < 2.5$
Combined muon resolutions

- Dimuon mass resolution of combined muons in different pseudorapidity regions
  - Experimental resolution compared to MC predictions using Pythia → $Z \mu\mu$ 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
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
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
Additional control regions

- Additional control regions defined by requiring both muons to pass an intermediate isolation requirement & at least one muon fail the $d0_{significance}$ cut
  - Opposite-sign pairs vs like-sign pairs
  - Good agreement of data & prediction within the uncertainties

---

![Graphs showing data and predictions](image-url)
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

![Dimuon invariant mass spectrum](image_url)
Limits: doubly charged Higgs

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