High-Mass Resonances Decaying to Muon Pairs

Experimental Aspects in the CMS Experiment

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Outline

High Mass Dimuon Spectrum

Experimental Aspects

• CMS Detector
• Muon Reconstruction
  • Resolutions and Efficiencies
  • Measuring Efficiencies from Data

Discovery potential and reach

• Extra dimensions
• $Z' \rightarrow \mu^+\mu^-$
Many scenarios beyond the Standard Model are expected to manifest themselves through modifications in the mass spectrum of high-mass dimuon pairs.

- **Dimuon final states predicted in two classes of large extra dimension models**
    - Observed via non-resonant modifications of the dimuon spectrum
  - **RS (Phys. Rev. Lett. 83 3370-3373, 4690-4693)**
    - Observed via relatively narrow resonances
- **Discover dimuon decays of a new heavy neutral gauge boson**
- **Backgrounds**
  - Drell-Yan, vector boson pair production, ttbar, etc.
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CMS Detector

SUPERCONDUCTING COIL

CALORIMETERS
ECAL Scintillating PbWO₄ Crystals
HCAL Plastic scintillator copper sandwich

IRON YOKE

TRACKERs

Silicon Microstrips
Pixels

MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)

MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla
CMS uses three types of gaseous particle detectors for muon identification:

Drift Tubes (DT): central barrel region (|\(\eta\)|<1.2)
- 4 layers per superlayer; 2-3 superlayers per station
- Precise measurement of position and momentum:
  - Offline: 250 – 100 \(\mu\)m; Online: \(~2\) mm

Cathode Strip Chambers (CSC): endcaps (0.8<|\(\eta\)|<2.4)
- 1 wire plane and 1 cathode plane with strips per gap; 6 gaps per chamber
- Precise measurement of position and momentum:
  - Offline: 100 \(\mu\)m; Online \(~2\) mm

Resistive Parallel Plate Chambers (RPC): barrel and endcaps
- 1-2 PC per DT; 1 RPC per CSC
- Good spatial and time resolution: \(~1\) cm; \(~2\) ns
Reconstruction of muons as a function of pseudorapidity as measured from Monte Carlo studies

- Efficiency is uniform over pseudorapidity
- Efficiency is uniform over energy of muons
- Some special optimization developed for high-energy muon reconstruction
Muon Reconstruction Resolution

Muon $p_t$ resolution as a function of momentum and pseudorapidity

- At low energy, central tracker dominates resolution
- At high energy, using the full detector improves resolution
Dimuon Reconstruction Resolution

\[ J/\psi \rightarrow \mu^+ \mu^- \quad Z' \rightarrow \mu^+ \mu^- \]

Dimuon invariant mass distributions and resolutions for different channels and misalignment scenarios:

- Perfect Alignment
- First-Data
- Long-Term

Dimuon invariant mass distributions and resolutions for different channels and misalignment scenarios.
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General Search Procedure

Search for new physics is performed by comparing the observed distribution of an opposite-sign muon pair with that expected from standard model processes

- Bump search, cross section measurement, etc.
- DY muon pair production is the dominant and irreducible background
  - Essential to measure and understand DY mass spectrum over a large range

- Event Selection
  - Online:
    - Each event must pass a single OR double muon path (L1 and HLT)
      - L1: $pt > 7 \text{ GeV}; \ pt > 3, 3 \text{ GeV}$
      - HLT (non-isolated): $pt > 16 \text{ GeV}; \ pt > 3, 3 \text{ GeV}$
  - Offline
    - At least two opposite-sign muons reconstructed
The overall dimuon efficiencies of the measurement are assumed to be the product of several parts

\[ \varepsilon = \varepsilon_{\text{trigger}} \times \varepsilon_{\text{offline}}^2 \]

\[ \varepsilon_{\text{trigger}} = \varepsilon_{\text{L1}} \times \varepsilon_{\text{HLT}} \]

\[ \varepsilon_{\text{offline}} = \varepsilon_{\text{global}} \times \varepsilon_{\text{isolation}} \times \varepsilon_{\text{id}} \]

\[ \varepsilon_{\text{global}} = \varepsilon_{\text{standalone}} \times \varepsilon_{\text{tracker}} \times \varepsilon_{\text{matching}} \]
Tag-And-Probe method is a method to determine reconstruction efficiencies from physics processes

• GOAL: Efficiency table as a function of $\eta$ and $p_t$
• used by electron/photon analyses; extensively used in CDF and DØ

• Choose a reference process: $Z \rightarrow \mu^+ \mu^-$
  • Choose a tag muon: “high quality” reconstructed muon
  • Choose a probe track: probable muon based on criteria to study

• Requiring $M_{\mu\mu}$ consistent with $M_Z$ yields a high-purity and almost unbiased sample of probe muons
  • Several different strategies for handling background
    • Side band subtraction, signal + bkgd. fit, etc.
## Description of TAG and PROBE

<table>
<thead>
<tr>
<th>Tag Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction</td>
<td>Global muon $p_t &gt; 30$ GeV</td>
</tr>
<tr>
<td>Isolation</td>
<td>Isolated Global muon $p_t &gt; 20$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Probe Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden</td>
<td>Global muon that is also a TAG</td>
</tr>
<tr>
<td>Matched</td>
<td>Global muon that is not a TAG</td>
</tr>
<tr>
<td>Unmatched</td>
<td>Tracker track AND Standalone muon found, but they are not associated with a Global Muon</td>
</tr>
<tr>
<td>Tracker Only</td>
<td>Only a tracker track</td>
</tr>
<tr>
<td>Stand Alone Muon</td>
<td>Only a standalone muon</td>
</tr>
<tr>
<td>Isolated</td>
<td>Isolated muon</td>
</tr>
<tr>
<td>Non-isolated</td>
<td>Non-isolated muon</td>
</tr>
</tbody>
</table>
Efficiency Calculations

Standalone, Tracking, Matching, and Isolation efficiencies calculated with simple event counting

\[ \varepsilon_{\text{standalone muon}} = \frac{2N_{GG} + N_{GM} + N_{GU}}{2N_{GG} + N_{GM} + N_{GU} + N_{GT}} \]

\[ \varepsilon_{\text{tracker track}} = \frac{2N_{GG} + N_{GM} + N_{GU}}{2N_{GG} + N_{GM} + N_{GU} + N_{GS}} \]

\[ \varepsilon_{\text{matching}} = \frac{2N_{GG} + N_{GM}}{2N_{GG} + N_{GM} + N_{GU}} \]

\[ \varepsilon_{\text{isolation}} = \frac{2N_{II}}{2N_{II} + N_{IN} + N_{NI}} \]
TAG and PROBE Selection

Tag: Global muon with pt > 30 GeV
Probe: additional cuts minimize background

- **Global muon (isolated)**
  - $p_T > 10$ GeV
  - $\Delta\phi_{\text{Tag,Probe}} > 1.5$

- **Standalone muon (isolated)**
  - $p_T > 10$ GeV
  - $\Delta\phi_{\text{Tag,Probe}} > 1.5$

- **Tracker track (isolated)**
  - $p_T > 15$ GeV
  - $\Delta\phi_{\text{Tag,Probe}} > 1.5$

- **Isolation Study**
  - $P_t > 20$ GeV, $|\eta|<2.0$, $M_{\mu\mu} \in (70,110)$GeV
Efficiencies from Tag-and-Probe method are compatible with efficiencies calculated from Monte Carlo studies.
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Discovery Potential (ADD)

Significance as a function of the mass scale for 3 and 6 extra dimensions

Discovery reach on $M_s$ as a function of luminosity
Integrated luminosity required for a discovery for various values of the coupling $c = 0.01, 0.02, 0.05$ and 0.1 (from top to bottom)

Discovery reach for various luminosities.
Discovery Potential (Z')

Cross section times the branching ratio for 3 TeV Z' of the Sequential Standard Model (red) as a function of the \(\mu^+\mu^-\) invariant mass \(M_{\mu\mu}\), compared with the production of muon pairs in a few main background sources.

Integrated luminosity required for a 5-sigma discovery as a function of the Z' mass for various Z' models.
Conclusion

CMS Detector optimized for muon detection

New Physics signals in high-mass resonances

- New bosons
- Extra dimensions

Special Optimization and Methods developed for detecting high energy muons and measuring efficiencies and resolutions from data
Local Reconstruction

DT Local Reconstruction
Single cell: drift time is converted to position with respect to the wire
R-φ and R-θ views reconstructed independently
In superlayer R-ϕ: σ ≈ 146 µm

CSC Local Reconstruction
Build 2D points:
• φ measured by strips
• R measured by wires
Build segment: fit 2D points from 6 layers
Position resolution: σ ≈ 100÷200 µm

RPC Local Reconstruction
Strips in double gap measure φ
Primarily for trigger use, but still used in reconstruction
Muon Reconstruction Stages

- Muon in Silicon Tracker
- Hits and Track Segments
- Global Muon Track
- Standalone Muon Track
Software Design

Level-1 Trigger
- The only CMS hardware trigger
- Level-1 Trigger gives us a physics object (pt, direction, etc.)

Offline and High-Level Trigger (HLT)
- Reconstruction software: reusable for offline and HLT
- Require seeds – initial values of 5 trajectory parameters
  - Level-1 Trigger provides seed for HLT
  - Segments chambers provide offline seed
- Offline reconstruction makes use of complete calibration, alignment, etc.

Requirements
- Object-Oriented design
- Flexibility to adapt to unforeseen conditions and cope with imperfect detector
- Scheduled Reconstruction: reject events as soon as possible
- Regional reconstruction
  - Use data in a region around a seed
  - Reconstruction/selection applied to seed regions only
Standalone Muon Reconstruction

All muon detectors (DT, CSC and RPC) are used

Seed generation:
• Online: Level-1 trigger → Level-2 reconstruction
• Offline: patterns of muon system segments

Fit:
• Kalman filter technique applied to DT/CSC/RPC measurements
  • Use segments in barrel and 3D hits in endcaps
• Trajectory building works from inside out
• Apply $\chi^2$ cut to reject bad hits
• Track fitting works from outside in
• Fit track with beam constraint

Propagation:
• Non constant magnetic field
• Propagation through iron between stations
Global Muon Reconstruction

- Start from standalone reconstructed muon

**Online**
- Tracker Seed based on Level-2 standalone muon
- Regional Tracker track reconstruction from Seed
  - Propagate from innermost layers out
  - Resolve ambiguities
  - Final fit of trajectories

**Offline**
- Tracker tracks already reconstructed
- Match best tracker track to standalone muon
- Refit of both tracks’ information