Muon Identification in ATLAS and CMS

Oliver Kortner

Max-Planck-Institut für Physik

Hadron Collider Physics Conference, Durham, May 2006
Outline

1. Introduction: Motivation and Identification Strategy.
2. The ATLAS and CMS Muon Systems.
4. Muon Identification at Low Transverse Momenta.
Introduction
Motivation and Identification Strategy
Muons are the only charged primary collision products traversing the calorimeters.

→ Clean signature of muonic final states.

Example physics processes with muonic final states:
- \( H \rightarrow ZZ^* \rightarrow \mu \mu \ell \ell \),
- \( A \rightarrow \mu \mu \),
- \( Z' \rightarrow \mu \mu \).

Good muon identification and reconstruction is crucial for physics at the LHC.
Need for efficient muon detection and identification over wide momentum range!
Muon Identification Tasks

Inclusive muon cross sections

- $c \rightarrow \mu$
- $b \rightarrow \mu$
- $t \rightarrow \mu$
- $W \rightarrow \mu$
- $Z/\gamma^* \rightarrow \mu$
- $\pi/K \rightarrow \mu$
- Shower muons
- Punch-through

$|\eta_{\mu}| < 2.7$

Muon identification tasks

- Identification of "prompt" muons from $c$, $b$, $t$, $W$, and $Z/\gamma$ decays.
- Rejection of muon from $\pi/K$ decays, shower muons, and hadronic punch-through.
**Muon Identification Strategy**

### Muon identification concept

<table>
<thead>
<tr>
<th>Goal</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimization of hadronic punch-through</td>
<td>Muon system surrounding the calorimeters</td>
</tr>
<tr>
<td>Suppression of muons from $\pi/K$ decays in flight</td>
<td>$p_t$ measurement in the muon system with $\frac{\Delta p_t}{p_t} \lesssim 10%$ $\oplus$ requirement of a well matching inner-detector track</td>
</tr>
<tr>
<td>Suppression of shower muons</td>
<td>As $\pi/K \rightarrow \mu$ $\oplus$ requirement of a small energy deposit in the calorimeters</td>
</tr>
</tbody>
</table>
The ATLAS and CMS Muon Systems
Limiting Factors of the Muon Systems

Energy loss in the calorimeters:
- Energy loss $\sim 3$ GeV with $\lesssim 20\%$ fluctuation.
- Larger fluctuations can be measured by the calorimeters
  → Negligible influence on $\frac{\Delta p_t}{p_t}$ for $p_t \gtrsim 10$ GeV/c.

Multiple scattering (MS) in the calorimeters:
- Negligible for ATLAS: $\left. \frac{\Delta p_t}{p_t} \right|_{MS} \sim 10^{-3}$.

Multiple scattering and bending power in the muon system:
- $\frac{\Delta p_t}{p_t} \propto \sqrt{\text{material in the muon system} \ [X_0]} \int B \, dl$.

Resolution of the muon chambers:
- Spatial resolution $\sigma$ of the muon chambers is the limiting factor for $\frac{\Delta p_t}{p_t}$ for high $p_t \sim 1$ TeV/c.
- $\frac{\Delta p_t}{p_t} \propto \sigma$ for $p_t \sim 1$ TeV/c.
The ATLAS and CMS Muon Systems

Two concepts for the muon system

**ATLAS**

- Focus on stand-alone muon reconstruction.
- Air-core toroid → minimization of multiple scattering.

**CMS**

- Focus on high $\int B\,dl$ in the inner detector and compactness.
- Instrumented return yoke of the solenoid to achieve high bending power.
The ATLAS Muon Spectrometer

- Fast trigger chambers: TGC, RPC (<10 ns time resolution).
- High resolution tracking detectors: CSC, MDT (40 $\mu$m spatial resolution).
- Optical alignment system with 50 $\mu$m resolution.
- Pseudorapidity coverage: $|\eta| \leq 2.7$. 

Outline
- Introduction
- Muon systems
- Tracking
- Low $p_t$
- Status
- Summary
### Fast trigger chambers: **RPC** (<10 ns time resolution).

- High resolution tracking detectors: **CSC, DT** ($\leq 100 \mu m$ spatial resolution).
- Laser alignment of muon and inner detector with 200 $\mu m$ precision.
- Pseudorapidity coverage: $|\eta| \leq 2.4$. 

---

**Material:**

- $\sim 150 X_0$
- $B = 2 \text{T}$
Magnets

ATLAS Air-Core Toroid

- No limitation of \( \frac{\Delta p_t}{p_t} \) by MS.
- Accurate B-field measurement possible.
- Uniform \( \frac{\Delta p_t}{p_t} \) independent of \( \eta \).

Iron Return Yoke of CMS Solenoid

- Uniform B field in the barrel.
- High bending power.
- Limitation of \( \frac{\Delta p_t}{p_t} \) by MS.
- \( \eta \) dependent \( \frac{\Delta p_t}{p_t} \).
Comparison of the Bending Powers

Barrel: \( \approx 4 \times \) higher bending power in CMS, but \( \approx 12 \times \) larger multiple scattering.

\[ \rightarrow \approx 3 \times \text{worse standalone } p_t \text{ resolution in CMS.} \]

Endcap: similar bending powers, \( \approx 10 \times \) large multiple scattering.

\[ \rightarrow \approx 5 \times \text{worse standalone } p_t \text{ resolution in CMS.} \]
### Standalone Transverse Momentum Resolution

#### ATLAS barrel standalone

- **Total**

#### CMS barrel standalone

- **Barrel region**
- **CMS, total**
Standalone Transverse Momentum Resolution

**ATLAS barrel standalone**

- **Total**
- **Multiple scattering in the spectrometer**
- **Energy loss fluctuations**

**CMS barrel standalone**

- **barrel region**
- **CMS, total**

Outline
- Introduction
- Muon systems
- Tracking
- Low $p_t$
- Status
- Summary
Standalone Transverse Momentum Resolution

**ATLAS barrel standalone**

- **Total**
- Chamber alignment
- Multiple scattering in the spectrometer
- Energy loss fluctuations

**CMS barrel standalone**

- barrel region
- CMS, total

**Outline**
- Introduction
- Muon systems
- Tracking
- Low $p_t$
- Status
- Summary
Standalone Transverse Momentum Resolution

ATLAS barrel standalone

- Total
- Chamber resolution
- Chamber alignment
- Multiple scattering in the spectrometer
- Energy loss fluctuations

CMS barrel standalone

barrel region

CMS, total

Outline

Introduction

Muon systems

Tracking

Low $p_t$

Status

Summary
Standalone Transverse Momentum Resolution

**ATLAS barrel standalone**

- Total
- Chamber resolution
- Chamber alignment
- Multiple scattering in the spectrometer
- Energy loss fluctuations

**CMS barrel standalone**

- CMS, total
- Chamber resolution
- Multiple scattering in the muon system

**Outline**
- Introduction
- Muon systems
- Tracking
- Low $p_t$
- Status
- Summary
Better resolution with muon systems and inner trackers

**Barrel**

- ATLAS: standalone
- CMS: standalone

**Endcap**

- ATLAS: standalone
- CMS: standalone

Better inner tracker resolution in CMS mainly due to higher B field.
Track Reconstruction in the Muon System
Both experiments reconstruct muon tracks in the following steps:

1. Definition of regions of activity (RoA).
2. Reconstruction of local straight segments in the RoA.
3. Combination of local segments.
4. Global fit in the muon system.

Finally combination with the inner detector
- to refine the momentum measurement,
- to identify low-$p_t$ muons,
- to identify isolated muons.
High tracking efficiency $> 96\%$ in both detectors.
Track Reconstruction in ATLAS

**Difficulty in ATLAS:** high $n - \gamma$ background.

→ High occupancy ($\sim 10 \times$ CMS).

**Occupancies at** $L = 10^{34}$ cm$^{-2}$ s$^{-1}$ in MDT chambers

(Numbers include a safety factor of 5.)
Muon chamber full of hits and segment candidates.

Trigger road needed to reconstruct the correct track segment.
Test-Beam Measurements

Track-reconstruction in presence of high $\gamma$ background

Efficient track reconstruction for rates within safety margins!

Significant drop of efficiency for higher rates.

Outline

Introduction
Muon systems
Tracking
Low $p_t$
Status
Summary

- Nominal occupancies in middle and outer stations.
- Variation of the occupancy in the inner station.

Results

- Efficiency $> 97\%$.
- Minor efficiency degradation at highest rates.
- Fake rate $< 0.12\%$.

New studies with high background have started recently.
Muon Identification at Low Transverse Momenta
Motivation: identification of soft muons in $b$ quark jets.

Major background: $\pi \rightarrow \mu$ (rate $\propto \frac{1}{p_t}$).

Low energy muons do not traverse the entire muon spectrometers.

→ Only short track segments in the innermost spectrometer layers.
Muon with low transverse momentum are identified by requiring

- a inner detector track extending into the first muon-spectrometer layer,
- an energy deposit in the calorimeters in a small cone around the track compatible with the muon hypothesis,
- muon spectrometer hits/segments extending into the spectrometer as expected from the $p_t$ of the inner-detector track ("muon compatibility").
Example: $p_t = 10$ GeV/c in CMS barrel.

$\Delta R < 0.02$

$\Delta R < 0.08$

→ Discrimination between muons and pions.
Example: $p_t = 10$ GeV/c in CMS barrel.

Clear separation of muons and pions.
Similar performance in ATLAS and CMS:

Efficiency $\sim 80\%$ for $p_t = 5$ GeV/c.
Fake rate $<0.5\%$ in both cases.
Status of the Muon Systems
Status of the ATLAS Muon Spectrometer

- Barrel installation to be completed until August 2006.
- Endcap toroid installation in fall 2006.
- Endcap installation from July 2006 until April 2007.
End of overground installation: fall 2006.

Lowering and underground installation: until April 2007.
Complementary concepts in ATLAS and CMS:

**ATLAS:** Standalone muon spectrometer in air-core toroid.

**CMS:** Instrumented return yoke of inner detector solenoid for high bending power and high momentum resolution in the inner detector.

Transverse momentum resolution:

<table>
<thead>
<tr>
<th></th>
<th>ATLAS:</th>
<th>CMS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_t \leq 400 ) GeV/c</td>
<td>( \leq 4% )</td>
<td>( \approx 8% )</td>
</tr>
<tr>
<td>( p_t \geq 1 ) TeV/c</td>
<td>( \approx 10% )</td>
<td>( \approx 30% )</td>
</tr>
</tbody>
</table>

Muon reconstruction efficiency:  
- \( >96\% \) for \( p_t > 20 \) GeV/c,
- \( \approx 80\% \) for \( p_t = 5 \) GeV/c.