Muon Detector Systems

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Outline

• Why Muons Matter
• Muon Detector Systems
  – Basic Principles
  – Real Examples
• Backgrounds
  – Hadron Punch-through
  – Low E Particles
  – Cosmic Rays
• Design Considerations
  – Momentum Resolution
    • Multiple Scattering
    • Position Measurement
  – Geometric Acceptance
• Design Challenge

• Caveats
  – Limit examples to current and future hadron collider detectors: CDF, DØ, ATLAS, CMS
  – I will be a bit DØ-centric, apologies in advance
  – Many topics will be skipped
    • Drift chamber operation (Becker, last year)
    • Drift chamber aging
    • Details of energy loss (Fisher, this year; Ahlen, last year)
    • Front end electronics (Oliver, this year)
    • Details on triggering
    • …
Design Challenge aka “Homework”

• Brief intro here, details at the end
• Your job is to design a “faster, better, cheaper” detector to discover the Higgs at the LHC in the golden mode $H \rightarrow ZZ \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
• Your detector will be an “iron ball” design
  – Just a muon system
  – Don’t measure electrons, jets, missing ET, etc.
• Optimization: your detector must have sufficient Higgs mass resolution to claim discovery while minimizing the channel count (i.e. the cost)
• Presentations of proposals during the Wednesday session
Google "iron ball detector" and...

1975 PEP Summer Study
Why Muons Matter

• High energy leptons have been a highly productive way to find new particles
  - The J/ψ, τ, Y, W, Z, and top quark discoveries all relied on muons
• No high energy muons in the initial state
  - Signature for interesting physics
  - The goal should be to get them all on tape!

• Physics topics at the Tevatron and LHC that use muons
  - Heavy flavors (b, c)
  - Top quark physics
  - Electroweak
  - Searches for new phenomena: Higgs, SUSY…
• b-tagging via b → μνc
• Relatively easy to trigger on and ID muons but… requires a very large detector system
Muon Properties

• From the Particle Data Group
  – Mass = 105.7 MeV/c²
  – Proper lifetime = 2.2 µs

• However, in hadron collider experiments
  – Muons are stable particles
  – $v \approx c$

• Penetrating
  – Deposit only minimum ionizing energy in detector material
    (up to the critical energy, more later)
  – Only particles to escape a hadron collider detector are
    muons and neutrinos
Purposes of Muon Detector Systems

• Identify muons – at the trigger level and offline
• Optionally – measure the muon’s momentum
• Optionally – act as a “tail catcher” for measuring the energy that leaks out of the calorimeter from very high energy jets
Elements of Muon Detection

- tracker
- calorimeter
- Muon magnet

Measure $p_{in}$ in solenoid field

Absorb hadrons $E_{loss}$ from ionization

Measure $p_{out}$ using
(a) toroid field
solid or air core
or (b) solenoid return field

Detector Layer – multiple planes of
(a) coordinate measurements
(b) fast counters
Real Muon Systems: CDF
• **No** $p_{\text{out}}$ **measurement**

• **Drift chambers**
  - Central: 2-layers (8 planes), 3.4k ch
  - Extension: 1-layer (4 planes), 2.2k ch
  - Intermediate: 1-layer (4 planes), 1.7k ch

• **Scintillator**
  - Central: 1-layer, 270 ch
  - Extension: 2-layer, 320 ch
  - Intermediate: 1-layer, 860 ch
Real Muon Systems: DØ
- Fe Toroid – 2 T
- Drift Chambers
  - Central: 3-layers (10 planes), 6.8k ch
  - Forward: 3-layers (10 planes), 50k ch
- Scintillator
  - Central: 2-layers, 990 ch
  - Forward: 3-layers, 4.8k ch
- Extensive shielding
Real Muon Systems: ATLAS
• Air-core Toroids
• Drift Chambers
  – 3-layers (6/8 planes/layer), 370k ch
  – 30 µm relative chamber alignment
• Central RPCs: 3-layers
• Thin Gap Chambers
Real Muon Systems: CMS
• Return field from solenoid – 2 T
• Central: Drift Chambers
  – 4-layers (32+12 planes), 200k ch
• Forward: Cathode Strip Chambers
  – 4-layers (24 planes), 400k ch
• RPCs: 4-layers (6 planes), 155k ch
Magnets

- **Solid Core Toroid**
  - Iron
  - B ~ 2 T
  - Further filters hadrons
  - Multiple scattering in Fe will limit $p_{\text{out}}$ resolution
Magnets

• Air Core Toroid
  - \( B \sim 0.3-1 \, T \), \( \int B dl \sim 3-9 \, Tm \) in ATLAS
  - Allows precision measurement of \( p_{\text{out}} \)
Detector Layer

- **Coordinate Measurement**
  - Drift Chambers, cathode strip chambers
  - Wire pitch \(\sim 1-10 \text{ cm} \) perp. to \(\mu\) trajectory
  - Resolutions range from 80-700 \(\mu\text{m}\), one limit on momentum resolution
  - Integrate \(~\text{few beam crossings}\)
Detector Layer

- **Fast Trigger Counters**
  - Scintillator + PMTs, Resistive Plate Chambers (RPCs)
  - Resolution ~1-2 ns
  - Tag beam crossing in trigger
  - Reduce backgrounds
Sources of Signals in Muon Systems

- **Physics Processes, Prompt Muons**
  - Heavy flavors: c and b quarks
  - W, Z decays
  - Top quarks
  - Higgs, new phenomena
- **Backgrounds**
  - Pion/kaon decays in flight
  - Hadron punch-through
  - Beam Halo
  - Backscatter
  - Cosmic Rays
  - Random coincidences
Prompt Muon Signature

Real muon

\[ p_{\text{in}} \approx p_{\text{out}} + E_{\text{loss}} \]
Muons are typically “mips” in the momentum range of interest.
Energy Loss of Muons in Matter

Very high energy muons shower like electrons
Radiative losses dominate above the critical energy $E_{\mu c}$
$E_{\mu c} \sim 350$ GeV for muons in Fe
Multiple Coulomb Scattering

- Muons traversing material are deflected from their original trajectory by multiple small-angle Coulomb scatters off nuclei
- $y_{plane}$ and $\theta_{plane}$ are $\sim$ Gaussian distributed

\[
\begin{align*}
\theta_{rms_{plane}} &= \theta_0 \\
y_{rms_{plane}} &= \frac{1}{\sqrt{3}} x \theta_0 \text{ where} \\
\theta_0 &= \frac{13.6 \text{MeV}}{\beta_{cp}} z \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)]
\end{align*}
\]

The multiple scattering contribution to the momentum resolution is proportional to $y_{rms_{plane}}$
Background – Punch-through and Decay-in-Flight

Outer punch-through/decay track points back to parent hadron, but momenta do not match.
Background: Hadron Punch-through

- Define “punch-through” as particles from late-developing hadron showers that get into the μ system
- “Sneak-through” – probability for a hadron to not interact after penetrating a distance x, typically very small

\[ P(x) = e^{-x/\lambda} \]

- Minimize punch-through by
  - Material as measured in nuclear interaction lengths \( \lambda \)
    - “Best μ ID tool is a meter of steel”
  - Good track matches consistent with \( ms \) uncertainty
- Prob \( \sim 10^{-3} - 10^{-4} \) in DØ
Background: Hadron Punch-through

Punch-through is a problem for $\mu$ ID and triggering

CDF

$\text{D}\O$

ATLAS
Background: Beam Halo

Good timing (scintillator, RPC) and tunnel shielding can get rid of most of these
Backscatter Background

- Reduce source: conical beam pipe/calorimeter:
  - Low $\beta$ quad/shielding
  - Forward calorimeter collisions

Or else…

- Shield around quads
- Reject remaining backscatter with timing
Effect of Shielding

No Shielding

With Shielding

Shield reduced rate by factor of 100

50 cm Fe – h & EM
12 cm polyethylene – n
5 cm Pb – gammas
Background: Cosmic Ray Muons

- Cosmic ray muons arrival times are uncorrelated with beam crossings → flat background in time
  - Cut on tight timing window around \( t = 0 \) using fast counters
- Also require track point to the primary vertex
Momentum Resolution

- Two distinct contributions to momentum resolution
  - Multiple Coulomb Scattering in detector material (ms)
  - Finite position measurement resolution (res)
  - Assume $\theta$ well measured, so $\delta \theta$ is negligible
  - Survey is another important contribution
- Conventional to quote $\delta p/p$, but measurement is Gaussian in $1/p$, not $p$

\[
\frac{\delta p}{p} = \sqrt{\alpha^2 + (\beta p)^2}
\]

where $\alpha = \left(\frac{\delta p}{p}\right)_{ms}$ and $\beta p = \left(\frac{\delta p}{p}\right)_{res}$

$\alpha$ and $\beta$ depend on the design of your detector
Momentum Resolution

- Multiple Scattering contribution depends on
  - Material through the “radiation length” $X_0$
    - $X_0 = 1.76$ cm for Fe
  - Path length $L'$ in material
  - B field
  - Units are GeV/c, Tesla, meter

- For example, in DØ
  $L' = 1$ m @ normal incidence
  $B = 2$ T
  so the $ms$ error is $\sim 20\%$

\[
\frac{\delta p_T}{p_T}_{ms} = \frac{0.016 \text{GeV/c}}{e \int B_z dl} \sqrt{\frac{L'}{X_0}} \\
\approx \frac{0.053}{B \sqrt{L'X_0}}
\]
Momentum Resolution

- Start with a simple case
- Assume
  - Uniform B field in z-direction
  \[ p_T = 0.3 BR \]
  - small \( \theta \)
  - \( L \) is projected length of track onto bending plane
- To measure \( p_T \), measure the sagitta \( s \)
  - 3 equidistant measurements
Momentum Resolution

\[ s = R - R \cos^2 \theta \approx \frac{R \theta^2}{8} \]

\[ \theta \approx \frac{L}{R} = \frac{0.3BL}{p_T} \]

\[ s = y_2 - \frac{1}{2}(y_1 + y_3) \]

\[ (\delta s)^2 = (\delta y_2)^2 + \frac{1}{4} (\delta y_1)^2 + (\delta y_3)^2 \]

Assume \( \delta y_1 = \delta y_2 = \delta y_3 = \delta y \)

Then \( \delta s = \sqrt{3} \delta y \)
Momentum Resolution

Since \( s \propto \frac{1}{p_T} \) then

\[
\frac{\delta s}{s} = \left( \frac{\delta p_T}{p_T} \right)_{res} \quad \text{so}
\]

\[
\left( \frac{\delta p_T}{p_T} \right)_{res} = \frac{8\sqrt{\frac{3}{2}\delta y}}{0.3BL^2} \cdot p_T
\]

- Make more measurements!
  - \( N \) equidistant measurements
  - \( N \gg 3 \)
  - Same \( \delta y \) for each
  - Uniform B field

- To improve resolution with 3-measurement system
  - Increase \( L \)
  - Increase \( B \)
  - Decrease \( \delta y \)
Momentum Resolution

- Can win further on resolution by
  - Arranging N measurements like the 3-measurement case
    - Clustering measurements also necessary for trigger
  - Primary vertex constraint reduces resolution by factor of $\sim \sqrt{2}$ to 2
- Also by reducing $\delta y$ but…
  - $\#\text{channels} \sim 1/y_{\text{cell}} \sim $$$
  - For our exercise, assume a PWC-type resolution
    $$\delta y = \frac{y_{\text{cell}}}{\sqrt{12}} \text{ where } y_{\text{cell}} \text{ is cell size}$$
  - In practice, do better using drift chambers (see Becker’s talk from last year)
Geometric Coverage

- Important design choice driven by physics and cost
- In hadron colliders, the natural coordinates are not $r, \phi, \theta$ but $r, \phi, \eta$
- Why pseudo-rapidity $\eta$? Light particles are produced such that

$$\frac{d\sigma}{dy} \approx \text{constant ("rapidity plateau")}$$

for $|y| < y_{\text{max}} = \ln \left( \frac{\sqrt{s}}{m} \right)$

where the rapidity $y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right)$.

For $p \gg m$, $y \approx -\ln \tan(\theta/2) \equiv \eta$

$$\Rightarrow \frac{d\sigma}{d\eta} \approx \text{constant}$$

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>90°</td>
</tr>
<tr>
<td>1</td>
<td>40°</td>
</tr>
<tr>
<td>2</td>
<td>15°</td>
</tr>
<tr>
<td>3</td>
<td>6°</td>
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</tbody>
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$\sqrt{s} = 2 \text{ TeV @ Tevatron}$

$\sqrt{s} = 14 \text{ TeV @ LHC}$
Geometric Coverage

- To achieve ~constant rate in each detector element, constant $\Delta \eta \times \Delta \phi$ segmentation is preferred. For example, DØ pixel counters have segmentation of $0.1 \times 4.5^\circ$
In practice, the maximum $\eta$ is selected to have good acceptance for $\mu$'s from "heavy" particles.

For example, at the Tevatron $\eta_{\text{max}} \sim 2$ is sufficient for top.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\eta_{\text{max}}$</th>
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<tbody>
<tr>
<td>CDF</td>
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</tr>
<tr>
<td>DØ</td>
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<tr>
<td>ATLAS</td>
<td>2.7</td>
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<tr>
<td>CMS</td>
<td>2.4</td>
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Summary

Muons went from “Who ordered that?” – I.I. Rabi to being essential to collider physics

Muon detector systems are now standard components of collider detectors

And now for your homework…