Muon System

FCC week Berlin, May 29th – June 2nd 2017

W. Riegler, CERN
Reference detector for the CDR

- 4T 10m solenoid
- Forward solenoids
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr
Status of Muon System Studies

The right tools for the right job

- Pen & Paper
  - Analysis benchmarks, high statistics
- Delphes, TkLayout
  - Reco benchmarks, detector studies
- Fast sim & digi + truth tracking
  - Detector studies, full pile-up model
- Partial fast sim + full reco
  - 0.8 min/evt
- Geant4 full sim + full reco
  - 1.4 min/evt
  - 0.02 sec/evt

complexity / time

# detector layouts

we are here
CDR will discuss performance with forward dipoles.
Central tracker:
- first IB layer (2.5 cm): $\sim 1.2 \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}$
- external part: $3 \times 10^{6} \text{ cm}^{-2}\text{s}^{-1}$

Barrel muon chambers: $\sim 300 \text{ cm}^{-2}\text{s}^{-1}$ to $\sim 500 \text{ cm}^{-2}\text{s}^{-1}$

Endcap Muon Chambers: $10^{4} \text{ cm}^{-2}\text{s}^{-1}$

Talk by I. Besana
ATLAS muon system HL-LHC rates (kHz/cm$^2$):
- MDTs barrel: 0.28
- MDTs endcap: 0.42
- RPCs: 0.35
- TGCs: 2
- Micromegas und sTGCs: 9-10

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at a collision energy of 14 TeV. The values are averages, in kHz/cm$^2$, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2R1</td>
<td>162 ± 28</td>
<td>327 ± 60</td>
<td>590 ± 110</td>
</tr>
<tr>
<td>M2R2</td>
<td>15.0 ± 2.6</td>
<td>52 ± 8</td>
<td>97 ± 15</td>
</tr>
<tr>
<td>M2R3</td>
<td>0.90 ± 0.17</td>
<td>5.4 ± 0.9</td>
<td>13.4 ± 2.0</td>
</tr>
<tr>
<td>M2R4</td>
<td>0.12 ± 0.02</td>
<td>0.63 ± 0.10</td>
<td>2.6 ± 0.4</td>
</tr>
<tr>
<td>M3R1</td>
<td>30 ± 6</td>
<td>123 ± 18</td>
<td>216 ± 32</td>
</tr>
<tr>
<td>M3R2</td>
<td>3.3 ± 0.5</td>
<td>11.9 ± 1.7</td>
<td>29 ± 4</td>
</tr>
<tr>
<td>M3R3</td>
<td>0.17 ± 0.02</td>
<td>1.12 ± 0.16</td>
<td>2.9 ± 0.4</td>
</tr>
<tr>
<td>M3R4</td>
<td>0.017 ± 0.002</td>
<td>0.12 ± 0.02</td>
<td>0.63 ± 0.09</td>
</tr>
<tr>
<td>M4R1</td>
<td>17.5 ± 2.5</td>
<td>52 ± 8</td>
<td>86 ± 13</td>
</tr>
<tr>
<td>M4R2</td>
<td>1.58 ± 0.23</td>
<td>5.5 ± 0.8</td>
<td>12.6 ± 1.8</td>
</tr>
<tr>
<td>M4R3</td>
<td>0.096 ± 0.014</td>
<td>0.54 ± 0.08</td>
<td>1.37 ± 0.20</td>
</tr>
<tr>
<td>M4R4</td>
<td>0.007 ± 0.001</td>
<td>0.056 ± 0.008</td>
<td>0.31 ± 0.04</td>
</tr>
<tr>
<td>M5R1</td>
<td>19.7 ± 2.9</td>
<td>54 ± 8</td>
<td>91 ± 13</td>
</tr>
<tr>
<td>M5R2</td>
<td>1.58 ± 0.23</td>
<td>4.8 ± 0.7</td>
<td>10.8 ± 1.6</td>
</tr>
<tr>
<td>M5R3</td>
<td>0.29 ± 0.04</td>
<td>0.79 ± 0.11</td>
<td>1.69 ± 0.25</td>
</tr>
<tr>
<td>M5R4</td>
<td>0.23 ± 0.03</td>
<td>2.1 ± 0.3</td>
<td>9.0 ± 1.3</td>
</tr>
</tbody>
</table>

HL-LHC muon system gas detector technology will work for most of the FCC detector area.
Example ATLAS MDT Drift Tubes
Muon $Pt = 3.9\text{ GeV}$ enters muon system

$Pt = 5.5\text{ GeV}$ leaves coil at 45 degrees

$Pt = 10\text{ GeV}$
Muon system performance estimate

We assume a constant magnetic field inside the coil radius $L_1$.

The measurement points in the tracker of radius $L_0$ are equidistant and have all the same resolution $\sigma_0$.

The measurement point at $L_1$ has a position error $\sigma_1$ that is given by the multiple scattering inside the calorimeters ($\sigma_y$ in the following).

The formula for the momentum resolution is given in the next slide.

Three ways to measure the muon momentum

1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil
Muon system performance estimate

Muon System standalone by measuring the angle of the muon when exiting the coil

\[ \frac{\Delta p}{p} = \frac{2p}{0.3L_1 B} \sqrt{\theta_0^2 + \sigma_{\theta\text{eta}}^2} \quad \theta_0 = \frac{0.0136}{\beta p [\text{GeV}/c]} \sqrt{\frac{L_{\text{Calo}}}{X_0_{\text{Calo}}} \left(1 + 0.038 \log \frac{L_{\text{Calo}}}{X_0_{\text{Calo}}} \right)} \]

Inner Tracker of radius \( L_0 \) with \( N+1 \) equidistant layers of resolution \( \sigma_0 \)

\[ \frac{\Delta p}{p} = \frac{p \sigma}{0.3B L_0^2} \sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{p \sigma}{0.3B L_0^2} \sqrt{\frac{720}{N+5}} \quad N \gg 1 \]

Combined

\[ \frac{\Delta p}{p} = \frac{p \sigma_0}{0.3B L_0^2} \sqrt{\frac{720N^3(c_1\sigma_0^2 + c_2\sigma_1^2)}{(N+1)(N+2)(c_3\sigma_0^2 + c_4\sigma_1^2)}} \]

\[ c_1 = 2[2N(L_0^2 - 3L_0L_1 + 3L_1^2) + L_0^2] \]
\[ c_2 = L_0^2(N + 1)(N + 2) \]
\[ c_3 = 3 \left[ L_0^2(3N^3 - N - 2) - 12L_0L_1(2N^3 - N^2 - N) + 12L_1^2(7N^3 - N^2 - N) \right] + 60N^3 \frac{L_1^4}{L_0^4} - 120N^3 \frac{L_1^3}{L_0^3} \]
\[ c_4 = L_0^2(N - 1)(N + 1)(N + 2)(N + 3) \]

\[ \sigma_y = \frac{1}{\sqrt{3}} L_{\text{Calo}} \theta_0 \]
CMS muon resolution at $\eta=0$

The lines represent the formulas from the previous pages.

\begin{align*}
\ln[2]: & \quad (* \text{ ======= *)} \\
\ln[3]: & \quad N0 = 10; \ \\
\ln[4]: & \quad L = 1.1; \ \\
\ln[5]: & \quad \text{sig0} = 23 \times 10^{-6}; \\
\ln[6]: & \quad L1 = 3; \\
\ln[7]: & \quad (* \text{ sig1=50*10^(-6); *}) \\
\ln[8]: & \quad B0 = 4; \\
\ln[9]: & \quad \text{XOTracker} = 0.7; \\
\ln[10]: & \quad \text{sigtheta} = 170 \times 10^{-6}; \\
\ln[11]: & \quad \text{XOCalo} = 100; \\
\ln[12]: & \quad \text{LCalo} = 2.1;
\end{align*}
CMS muon resolution at $\eta=0$

The CMS muon system performance is well represented by assuming:

- 10 layers of tracker with 23um resolution.
- 170 microrad of angular resolution where the muon exits the coil.
- Better than 100um position resolution where the muon exits the coil.
Comparing CMS to possible FCC resolution

The FCC muon system performance assumes:

13 layers of tracker with 10um resolution and 1.55m radius.

70 microrad of angular resolution where the muon exits the coil.

Better than 25um position resolution where the muon exits the coil.
Combined performance for varying position resolution

With 50μm position 70μRad angular resolution resolution we find ($\eta=0$)

<10% standalone momentum resolution up to 3TeV/c

<10% combined momentum resolution up to 20TeV
Parametrized Muon Performance

Delphes 5% @10TeV
A 50μm position resolution and 70μRad angular resolution for muons exciting the solenoid will give excellent standalone and combined muon resolution at $\eta=0$.

E.g. Two redundant stations of detectors with 50μm position resolution at a separation of 1-2 meters will realize this requirement.

The expected charged particle rates will probably allow the use of present muon system technology.

The distance between the stations must be large enough to make sure that correlated background is eliminated.

The existing magnetic fields around 1.5Tm should be sufficient for that. Simulations have to prove this fact.

The muon trigger performance still has to be studied in detail.