Analysis of DHCAL Muon Events

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General DHCAL Analysis Strategy

Noise measurement
- Determine noise rate (correlated and not-correlated)
- Identify (and possibly mask) noisy channels
- Provide random trigger events for overlay with MC events

Measurements with muons
- Geometrically align layers in x and y
- Determine efficiency and multiplicity in ‘clean’ areas
- Simulate response with GEANT4 + RPCSIM (requires tuning 3-6 parameters)
- Determine efficiency and multiplicity over the whole 1 x 1 m^2
- Compare to simulation and tuned MC
- Perform additional measurements, such as scan over pads, etc...

Measurement with positrons
- Determine response
- Compare to MC and tune 4^{th} (d_{cut}) parameter of RPCSIM
- Perform additional studies, e.g. software compensation...

Measurement with pions
- Determine response
- Compare to MC (no more tuning) with different hadronic shower models
- Perform additional studies, e.g. software compensation, leakage correction...
The DHCAL Project

Argonne National Laboratory
Boston University
Fermi National Accelerator Laboratory
IHEP Beijing
University of Iowa
McGill University
Northwestern University
University of Texas at Arlington

<table>
<thead>
<tr>
<th>DCHAL Collaboration</th>
<th>Heads</th>
</tr>
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<tbody>
<tr>
<td>Engineers/Technicians</td>
<td>22</td>
</tr>
<tr>
<td>Students/Postdocs</td>
<td>8</td>
</tr>
<tr>
<td>Physicists</td>
<td>9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>39</strong></td>
</tr>
</tbody>
</table>

...and integral part of
The DHCAL in the Test Beam

<table>
<thead>
<tr>
<th>Date</th>
<th>DHCAL layers</th>
<th>RPC_TCMT layers</th>
<th>SC_TCM layers</th>
<th>Total RPC layers</th>
<th>Total layers</th>
<th>Readout channels</th>
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<tbody>
<tr>
<td>10/14/2010 – 11/3/2010</td>
<td>38</td>
<td>0</td>
<td>16</td>
<td>38</td>
<td>54</td>
<td>350,208+320</td>
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<tr>
<td>1/7/2011 – 1/10/2011</td>
<td>38</td>
<td>0</td>
<td>8</td>
<td>38</td>
<td>46</td>
<td>350,208+160</td>
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<tr>
<td>1/11/2011 – 1/20/2011</td>
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<td>4</td>
<td>8</td>
<td>42</td>
<td>50</td>
<td>387,072+160</td>
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<tr>
<td>2/5/2011 – 2/7/2011</td>
<td>38</td>
<td>13</td>
<td>0</td>
<td>51</td>
<td>51</td>
<td>470,016+0</td>
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</table>
Beam and Trigger for Muon events

+32 GeV/c secondary beam + 3m Fe
DAQ rate typically 500 - 1000/spill

<table>
<thead>
<tr>
<th>Run</th>
<th># of muon events</th>
</tr>
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<tbody>
<tr>
<td>October 2010</td>
<td>1.4 Million</td>
</tr>
<tr>
<td>January 2011</td>
<td>1.6 Million</td>
</tr>
<tr>
<td>April 2011</td>
<td>2.5 Million</td>
</tr>
<tr>
<td>June 2011</td>
<td>2.2 Million</td>
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</table>
Some cute muon events

Note: Consecutive events (not selected)
Look for random noise hits
Estimation of contributions from noise

Data collection

Trigger-less (all hits) mode for noise, cosmics
Triggered (record hits in 7 time bins of 100 ns each) for noise, testbeam → Only hits in 2 time bins used for physics analysis

Noise measurement

These results from trigger-less mode

Results

Noise rate measured to be 0.1 – 1.0 Hz/cm²
Rate strongly dependent on the temperature of the stack

<table>
<thead>
<tr>
<th>Noise rate [Hz/cm²]</th>
<th>0.1</th>
<th>0.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{noise}}$/event in DHCAL + TCMT (2 time bins)</td>
<td>0.0094</td>
<td>0.047</td>
<td>0.094</td>
</tr>
<tr>
<td>$N_{\text{noise}}$/event in DHCAL + TCMT (7 time bins)</td>
<td>0.033</td>
<td>0.165</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Contribution from noise negligible for most analysis
Tracking

Clustering of hits

Performed in each layer individually
Use closest neighbor clustering (one common side)
Determine unweighted average of all hits in a given cluster \((x_{\text{cluster}}, y_{\text{cluster}})\)

Loop over layers

for layer \(i\) request that all other layers have \(N_{\text{cluster}}^i \leq 1\)
request that number of hits in tracking clusters \(N_{\text{hit}}^i \leq 4\)
request at least 10/38(52) layers with tracking clusters
fit straight line to \((x_{\text{cluster}} z)\) and \((y_{\text{cluster}} z)\) of all tracking clusters \(j\)
calculate \(\chi^2\) of track

\[
\frac{\chi^2}{N_{\text{track}}} = \sum_{j \neq i} \frac{(x_{\text{cluster}}^j - x_{\text{track}}^j)^2}{1} + \sum_{j \neq i} \frac{(y_{\text{cluster}}^j - y_{\text{track}}^j)^2}{1}
\]

request that \(\chi^2/N_{\text{track}} < 1.0\)
inter/extrapolate track to layer \(i\)
search for matching clusters in layer \(i\) within

\[
R = \sqrt{(x_{\text{cluster}}^i - x_{\text{track}}^i)^2 + (y_{\text{cluster}}^i - y_{\text{track}}^i)^2} < 2.5 \text{ cm}
\]

record number of hits in matching cluster
Alignment

For each readout board $i$ plot residual in $x/y$

$$R^i_x = x^i_{\text{cluster}} - x^i_{\text{track}}$$
$$R^i_y = y^i_{\text{cluster}} - y^i_{\text{track}}$$

Most distributions look OK

Dimensions in [cm]

Few have double peaks

...as does simple a
Toy MC + RPCSIM
Mean residuals for each Front-end board versus layer#

Mean of residual distributions

**x-residual**
- Variations of $< 3$ mm
- **Alignment of layers by hand**
- Correlation between the 6 boards within a layer

**y-residual**
- Variations $<0.5$ mm
- **Cassette resting on CALICE structure**
- Systematic trend compatible with cassettes being lower in center of stack by $\sim 0.5 – 0.7$ mm
Residuals for each Front-end board or layer

1 entry/readout board

1 entry/layer

Note

Mean by construction close to 0
External tracking not available
After alignment each readout board in x

RMS = 62 μm

RMS = 52 μm
After alignment in y

Note even more expanded y-scale

RMS = 21 μm

RMS = 14 μm
Run 610055 using alignment obtained with 610063: alignment in x

As expected, not quite as good, but still acceptable
Scan across pad

\[ x = \text{Mod}(x_{\text{track}} + 0.5, 1.) \text{ for } 0.25 < y < 0.75 \]
\[ y = \text{Mod}(y_{\text{track}} - 0.03, 1.) \text{ for } 0.25 < x < 0.75 \]

**Data 630011**

**Simulation**

**Note** These features **not** implemented explicitly into simulation
Simulation distributes charge onto plane of pads...
Angles of muon tracks

Data

GEANT4 + RPCSIM

Data

Note

Incident angle distribution in MC tuned to reproduce data
Simulation acceptable
Efficiencies, multiplicities

Select ‘clean’ regions away from

- Dead ASICs (cut out 8 x 8 cm$^2$ + a rim of 1 cm)
- Edges in x (2 rims of 0.5 cm)
- Edges in y (6 rims of 0.5 cm)
- Fishing lines (12 rectangles of ±1 cm)
- Layer 27 (with exceptionally high multiplicity)

Measure average response

Note: Simulation of RPC response tuned to **Vertical Slice Test**
DHCAL shows **higher efficiency** and **lower multiplicity** (thinner glass)
Tuning, tuning, tuning...

Note: Tuning done ‘by hand’
Very large statistics of both data and simulation → large $\chi^2$
No significant improvements after trial #70
Best fit

$\chi^2 = 1285$

Note:
- High statistics (error bars « dots)
- Efficiency well reproduced
- Low multiplicity well reproduced
- Tail problematic (excess of 0.6% in the data)

Efficiency = 93.6% in data
93.8% in MC

Multiplicity = 1.563 in data
1.538 in MC

Mean = 1.461 in data
1.443 in MC

Further improvements
- Systematic studies of track selection, functional form...
Include 2\textsuperscript{nd} exponential in charge distribution

\[ \chi^2 = 1233 \]

**Tail**

Able to reproduce (qualitatively)

**MC**

Higher statistics
\[ \rightarrow \] Larger $\chi^2$
(Absolute value meaningless)

**Tuning**

Still in progress (literally)
(Done by hand)
Response over the entire plane

Implemented dead areas of data in MC (= corresponding hits deleted)

Note

x-axis in [cm] not [pad number]
Simulation using single exponential

x-distribution

Well reproduced, apart from edges (needs special treatment)

y-distribution

Inter-RPC gaps well reproduced
Fishing lines well reproduced
Edges again problematic (needs special treatment)
Average response over the entire plane (using 1 exponential only)

Note: There are systematic uncertainties → due to track selection → still need to be studied

These numbers exclude the dead areas

Some tuning of the MC still needed

**Efficiency** = 90.9% in data
92.1% in MC

**Multiplicity** = 1.611 in data
1.535 in MC

**Mean** = 1.464 in data
1.411 in MC
Response versus layer number

Dead areas, fishing lines, and edges are excluded

\[
\text{Log}(z) \quad \leftarrow \quad \text{same plot} \quad \rightarrow \quad \text{Lin}(z)
\]

Note

Reasonable uniformity from layer to layer
Calibration constants, etc...

Tail catcher is cooler
→ lower efficiency, multiplicity

Calibration factors = mean of multiplicity distribution = \( \varepsilon \cdot \mu \)
Calibration constants as function of time

![Graph showing variation of calibration constants over time with secondary beam measurements.](chart.png)

**Note**

Variations of +7.0 to -2.5%
Data points of equal color indicate same day measurements
Track segment analysis

Method

Use clusters (= source clusters) in 2 layers to study layer in between (=target cluster)
  e.g. use \( L_{i-1} \) and \( L_{i+1} \) to look at \( L_i \)

Source clusters

Required to have at most 3 hits
Lateral distance between source clusters at most 3 cm
No additional hits within 7 cm of source clusters

Target cluster

Search for within radius of 2 cm from line between source clusters

Comparison of

Muon runs analyzed with tracks
Muon runs analyzed with track segments
Pion run analyzed with track segments

Clear correlation between different methods
... but systematic differences
Conclusions

Analysis of muon events has begun

Preliminary results have been presented

- Geometrical alignment
- Response across pad
- Performance parameters in ‘clean’ regions
- Performance parameters over the entire plane
- Performance as function of time
- Comparison with track segment method

Results compared to GEANT4 + RPCSIM simulation

- RPCSIM tuned to reproduce performance in ‘clean’ regions
- Reasonable agreement with data observed

Data appear to be of very high quality
Backup Slides
Simulation Strategy

Experimental set-up
Beam (E, particle, x, y, x', y')

GEANT4

Points (E depositions in gas gap: x, y, z)

RPC response simulation

Measured signal Q distribution

Hits

Comparison

Parameters
Exponential slope a
Threshold T
Distance cut $d_{cut}$
Charge adjustment $Q_0$

With muons – tune a, T, ($d_{cut}$), and $Q_0$
With positrons – tune $d_{cut}$
Pions – no additional tuning
RPCSIM Parameters

Distance $d_{\text{cut}}$

Distance under which there can be only one avalanche (one point of a pair of points randomly discarded if closer than $d_{\text{cut}}$)

Charge $Q_0$

Shift applied to charge distribution to accommodate possible differences in the operating point of RPCs

Slope $a_1$

Slope of exponential decrease of charge induced in the readout plane

Slope $a_2$

Slope of 2nd exponential, needed to describe tail towards larger number of hits

Ratio $R$

Relative contribution of the 2 exponentials

Threshold $T$

Threshold applied to the charge on a given pad to register a hit