DHCAL with Minimal Absorber: Measurements with Positrons

Benjamin Freund, Coralie Neubüser, José Repond
Argonne National Laboratory
McGill University

CALICE-Meeting
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DHCAL with Minimal Absorber

- Testbeam taken at Fermilab in November 2011
- 50 layers of 2-plate RPCs with an active area of 96x96 cm² with and 460,800 1 x 1 cm² readout channels
- 2.54 cm spacing between each layer which feature a front-plate (2 mm copper) and rear plate (2 mm steel)
- Each cassette has a thickness of 12.5 mm corresponding to
- A radiation length of: \(X_0 = 0.4\)
- And a nuclear interaction length of: \(\lambda_0 = 0.04\)

Total radiation length \(X_0 = 20\)
Total nuclear interaction length \(\lambda_0 = 2\)
Data collected at Fermilab

- Fermilab Test Beam Facility
- Secondary beam (1-66 GeV/c) mixture of electrons, muons and pions
- Spill duration 4.0 seconds
- Cerenkov counters for PID
- Data collected in November 2011 have a momentum range of 1 – 10 GeV/c

<table>
<thead>
<tr>
<th>Momentum [GeV/c]</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>107,384</td>
</tr>
<tr>
<td>2</td>
<td>116,858</td>
</tr>
<tr>
<td>3</td>
<td>61,915</td>
</tr>
<tr>
<td>4</td>
<td>83,562</td>
</tr>
<tr>
<td>6</td>
<td>109,485</td>
</tr>
<tr>
<td>8</td>
<td>108,860</td>
</tr>
<tr>
<td>10</td>
<td>225,998</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>814,062</strong></td>
</tr>
</tbody>
</table>
Hit and Event selection

Pads close to ground lead fire at a relative high rate

Area of 2 x 5 c² at the edge of chambers are removed from both data and simulation

Data recorded in seven time bins (100 ns)
Most hits occur in time bin 19 and 20 (time to trigger)
Remove events with most hits in other time bins to reduce events with multiple particles
Remove hits outside these bins to reduce noise (<1%)

Sometimes the same pad fires several times in an Event
These double hits are removed in data (~0.1%)
Small fraction of DHCAL chips were dead (<1%)
Areas corresponding to these chips are removed in simulation
To reduce number of events with multiple particles and upstream interactions:
Require only one cluster with at most four hits in first layer (cuts 10-20%)
## Event Selection

**Data**

<table>
<thead>
<tr>
<th>Momentum [GeV/c]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing cuts</td>
<td>99.9</td>
<td>99.8</td>
<td>99.9</td>
<td>99.8</td>
<td>99.95</td>
<td>99.95</td>
<td>99.96</td>
</tr>
<tr>
<td>Requirements on first layer</td>
<td>88.5</td>
<td>87.0</td>
<td>80.3</td>
<td>80.3</td>
<td>88.1</td>
<td>86.6</td>
<td>88.2</td>
</tr>
<tr>
<td>More than 5 active layers</td>
<td>88.1</td>
<td>86.4</td>
<td>80.0</td>
<td>79.8</td>
<td>88.0</td>
<td>86.5</td>
<td>88.1</td>
</tr>
<tr>
<td>Cerenkov signal</td>
<td>60.3</td>
<td>31.7</td>
<td>40.0</td>
<td>30.7</td>
<td>53.9</td>
<td>41.7</td>
<td>33.0</td>
</tr>
</tbody>
</table>

**Simulation**

<table>
<thead>
<tr>
<th>Momentum [GeV/c]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td>Timing cuts</td>
<td>100.0</td>
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**Cerenkov provides PID**

Percentage of events surviving the various event selection criteria:

- Nearly all of the Events survive selection cuts!
Equalization of the RPC Response

- So called “full calibration” using through-going muons are used to equalize the response of the 150 RPCs
- Efficiency $\varepsilon$ and multiplicity $\mu$ are calculated for every RPC
- Calibration factors $c_i$ for RPC $i$ are the product of the multiplicity and efficiency of the RPC divided by the average multiplicity $\mu_0$ and efficiency $\varepsilon_0$
  \[ c_i = \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} \]
- Then the corrected number of hits $N'_i$ is calculated as:
  \[ N'_i = c_i N_i \]

Average values for November data:
\[ \varepsilon_0 = 0.917, \mu_0 = 1.573 \]
Equalization of the RPC Response

Difference between runs much reduced after equalization!

10 GeV muons

\[ \chi^2 = 126.5 \]

\[ \chi^2 = 10.3 \]
Monte Carlo Simulation Strategy

- Experimental set-up
  - Beam \((E, \text{particle}, x, y, x', y')\)
  - Points \((E \text{ depositions in gas gap: } x, y, z)\)

- GEANT4

- Measured signal \(Q\) distribution

- RPC response simulation

- Hits

- Comparison

- DATA

**Parameters**
- Distance cut \(d_{\text{cut}}\) (within which only 1 avalanche)
- Charge adjustment \(Q_0\) (if needed)
- Threshold \(T\) (of discriminator)

- Sum of 2 gaussians used as charge spread functions

With muons – tune **the charge spread functions**, \(T\), \(d_{\text{cut}}\), and \(Q_0\)
With positrons – tune \(d_{\text{cut}}\)
Pions – no additional tuning (absolute prediction of pion response)
Sources of error

- Error from equalization

Take half the average difference as error

Error symmetric in general but only downwards for resolution
Systematic errors

Sources of error

- Error from equalization
- 2.5% on beam momentum
- Rate capability (take only first half second of spill)

RPC lose efficiency exponentially during spill 1-2% effect

Profile of number of hits vs Spilltime
Systematic errors

10 GeV $e^+$

Number of hits per layer for positrons

Sources of error

- Error from equalization
- 2.5 % on beam momentum
- Rate capability (take only first half second of spill)

Include difference only in positive systematic error
Systematic errors

Sources of error

• Error from equalization
• 2.5% on beam momentum
• Rate capability (take only first half second of spill)
• Contamination from muons and pions estimated less than 1%
• Contamination form accidental noise hit was estimated to 0.2 hits per event in the entire stack
  ➢ Noise negligible, nevertheless noise events from accidental noise runs added to simulation
Gaussian fit in a ±2σ range to get mean response for every energy
Data and simulation agree very well for 3-10 GeV

Fitted with power law

\[ N = a \times E^m \]

Fit for simulation excludes 1-2 GeV

Data:

\[ a = 131.8 \pm 3.5 \]
\[ m = 0.76 \pm 0.02 \]

Simulation:

\[ a = 129.4 \pm 0.3 \]
\[ m = 0.73 \pm 0.001 \]

Saturation due to large pad size compared to the density of showers

Use fit function to reconstruct energy!
Reconstructed energy of positrons

Gaussian fit in a $\pm 2\sigma$ range to get resolution
Good agreement for stochastic term

Reason for better resolution in data not understood!

<table>
<thead>
<tr>
<th></th>
<th>Constant term [%]</th>
<th>Stochastic term [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>6.8±0.2</td>
<td>14.3±0.4</td>
</tr>
<tr>
<td>Simulation</td>
<td>8.2±0.1</td>
<td>14.3±0.2</td>
</tr>
</tbody>
</table>
Longitudinal shower shape

Good agreement for simulation and data

Fit with gamma distribution (which provides a good fit for energy loss in matter) to estimate leakage and shower maximum

\[ \frac{dN}{dz} = N_0 b \frac{(bz)^{a-1} e^{-bz}}{\Gamma(a)} \]

Estimated leakage is used to correct the response
Longitudinal shower shape

Good agreement for shower maximum

Errors come only from the fit
Transversal shower shape

- Fit hits in first 5 layers to determine the shower axis
- Calculate distance $R$ of every hit to that shower axis
- Shower in simulation tends to be more dense
- Accelerated decrease for $R>50$ due to limited detector size and shape (square)

6 GeV $e^+$

![Graph showing the relationship between $R$ and events normalized to unity.](image-url)
The mean radius of hits greater for data

- Shower denser for simulation!
  (not due to the rate related loss of efficiency)
Density defined as number of neighbors in a 3x3x3 cube around the hit (0 to 26)

Simulation tuned to density distribution but density not well reproduced
Density information can be used to linearize response.

Every density bin $D_i$ is multiplied with a weight $w_i$ found by minimizing the $\chi^2$ function:

$$\chi^2 = \sum_{i=1}^{7} \sum_{\text{Events}} \left( \sum_{j=0}^{26} w_j D_{ij} - \alpha E_i^{\text{beam}} \right)^2 \frac{1}{E_i^{\text{beam}}}$$

Fit parameters:

<table>
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<tr>
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<th>Before leakage</th>
<th>After leakage</th>
<th>Linearized</th>
</tr>
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<tbody>
<tr>
<td>$a$</td>
<td>131.8±3.5</td>
<td>132.1±3.5</td>
<td>100.2±2.2</td>
</tr>
<tr>
<td>$m$</td>
<td>0.76±0.02</td>
<td>0.78±0.02</td>
<td>0.95±0.02</td>
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Density information can be used to linearize response

Every density bin $D_i$ is multiplied with a weight $w_i$ found by minimizing the $\chi^2$ function

Improves the linearity but the response is still not perfectly linear

Fit parameters

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<td>$0.78 \pm 0.02$</td>
<td>$0.95 \pm 0.02$</td>
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</table>
Density information can be used to linearize response.

Linearization gives these weights.

Big weights for higher densities to correct for saturation!
Linearization

Improves the resolution 2-10%

Weights can then be used to linearize electromagnetic subshower in pion events

Expect significantly improved resolution

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<tr>
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<th>Stochastic term [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unweighted</td>
<td>6.4±0.2</td>
<td>14.5±0.4</td>
</tr>
<tr>
<td>Weighted</td>
<td>6.5±0.2</td>
<td>12.8±0.3</td>
</tr>
</tbody>
</table>
Conclusion

• DHCAL data with minimal absorber taken at Fermilab are compared to simulations
• Fine segmentation allows detailed study of electromagnetic showers
• In general good agreement between simulation and data but also some differences
• Positrons are used to tune simulation (dcut parameter)
  ➢ Simulation lost predictive power for $e^+$
• First draft of paper written with these results
Backup
Calibration/Performance Parameters

Efficiency ($\varepsilon$) and pad multiplicity ($\mu$)

Track Fits:
- specifically for muon calibration runs
- Identify a muon track that traverse the stack with no identified interaction
- Measure all layers

Track Segment Fits:
- for online calibration
- Identify a track segment of four layers with aligned clusters within 3 cm
- Measure only one layer (if possible)

- Fit to the parametric line: $x=x_0+a_xt$; $y=y_0+a_yt$; $z=t$

A cluster is found in the measurement layer within 2 cm of the fit point?

Yes: $\varepsilon=1$

No: $\varepsilon=0$

$\mu$=size of the found cluster

No $\mu$ measurement

$\varepsilon_0$, $\mu_0$: averages over full stack

muon

8 GeV secondary beam
Calibration Procedures

RPC performance

Average efficiency to detect MIP: \( \varepsilon_0 \sim 96\% \)
Average pad multiplicity: \( \mu_0 \sim 1.6 \)

1. Full Calibration: \[ H_{calibrated} = \sum_{i=RPC_0}^{RPC_n} \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i \]

H_i: Number of hits in layer \( i \)

2. Density-weighted Calibration: Developed due to the fact that a pad will fire if it gets contribution from multiple traversing particles regardless of the efficiency of this RPC. Hence, the full calibration will overcorrect. Utilizes density of hits.

3. Hybrid Calibration: Density bins 0 and 1 receive full calibration.
The 4 RPCSim Versions

<table>
<thead>
<tr>
<th>RPCSim</th>
<th>Spread functions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$R \ e^{-ar} + (1-R) \ e^{-br}$</td>
<td>To help the tail</td>
</tr>
<tr>
<td>4</td>
<td>$e^{-ar}$</td>
<td>Measurement from STAR</td>
</tr>
<tr>
<td>5</td>
<td>$R \ e^{-(r/\sigma_1)^2} + (1-R) \ e^{-(r/\sigma_2)^2}$</td>
<td>Commonly used</td>
</tr>
<tr>
<td>6</td>
<td>$1/(a + r^2)^{3/2}$</td>
<td>Recently came across</td>
</tr>
</tbody>
</table>

The 4 RPCSim Versions

<table>
<thead>
<tr>
<th>RPCSim</th>
<th>Slope a</th>
<th>Slope b</th>
<th>Sigma$_1$</th>
<th>Sigma$_2$</th>
<th>R</th>
<th>Q$_0$</th>
<th>d$_{cut}$</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.0678</td>
<td>0.671</td>
<td></td>
<td></td>
<td>0.345</td>
<td>0.201</td>
<td>0.262</td>
<td>0.3645</td>
</tr>
<tr>
<td>4</td>
<td>0.0843</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.120</td>
<td>0.983</td>
<td>0.241</td>
<td>0.114</td>
<td>0.092</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.0761</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

![Graph showing charge fraction vs radial distance (cm) for different versions of RPCSim]
RPCSim5 Optimization

Average of 3 and 10 GeV

\[ R e^{-\left(\frac{r}{\sigma_1}\right)^2} + (1-R) e^{-\left(\frac{r}{\sigma_2}\right)^2} \]

\( \sigma_1 = 0.07, \sigma_2 = 0.30, R = 0.18 \)

\( T = 0.16, d_{cut1} = 0.09, Q_0 = 1.1, d_{cut2} = 0.15 \)