Digital Electromagnetic Calorimetry with Extremely Fine Spatial Segmentation

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Trend in Calorimetry

**Tower geometry**

Energy is integrated over large volumes into single channels

Readout typically with high resolution

Individual particles in a hadron jet not resolved

**Imaging calorimetry**

Large number of calorimeter readout channels ($\sim 10^7$)

Option to minimize resolution on individual channels

Particles in a jet are measured individually

**Calorimeters in HEP**

- ODF
- DELPHI
- OPAL
- ALEPH
- ZEUS
- H1
- D0
- LHCb
- ALICE
- CMS
- ATLAS
- NODA
- DPCAL

![Image of calorimeter data](image-url)
The DHCAL prototype

Description
Hadronic sampling calorimeter
Designed for future electron-positron collider (ILC)
54 active layers (~1m²)
Resistive Plate Chambers with 1 x 1 cm² pads
→ ~500,000 readout channels

Electronic readout
1 – bit (digital)

Tests at FNAL
with Iron absorber in 2010 - 2011

Tests at CERN
with Tungsten absorber 2012
DHCAL with Minimal Absorber

- Special testbeam taken at Fermilab in November 2011 in minimal absorber configuration without absorber plates

- 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
  - 0.29 radiation lengths ($X_0$)
  - 0.034 Interaction lengths ($\lambda_I$)

**Total thickness: 15 $X_0$**

Or $1.7\lambda_I$

Unprecedented details of low energy electromagnetic showers!
Data sample collected at Fermilab

- Data collected at Fermilab Test Beam Facility
- Secondary beam mixture of electrons, muons and pions
- Spill duration 4.0 seconds
- Čerenkov counters for PID
- Data collected in November 2011 has 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 k</td>
</tr>
<tr>
<td>2</td>
<td>117 k</td>
</tr>
<tr>
<td>3</td>
<td>62 k</td>
</tr>
<tr>
<td>4</td>
<td>84 k</td>
</tr>
<tr>
<td>6</td>
<td>109 k</td>
</tr>
<tr>
<td>8</td>
<td>109 k</td>
</tr>
<tr>
<td>10</td>
<td>226 k</td>
</tr>
<tr>
<td>TOTAL</td>
<td>814 k</td>
</tr>
</tbody>
</table>
# Event selection

Percentage of events surviving the various event selection criteria

<table>
<thead>
<tr>
<th>Data</th>
<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></td>
<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></td>
<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></td>
<td>At least 6 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></td>
<td>Čerenkov 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>
<tr>
<td>Simulation</td>
<td>Timing cuts</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
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<td>98.3</td>
<td>97.9</td>
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<td>97.6</td>
<td>97.2</td>
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<td>97.2</td>
<td>97.1</td>
<td>96.8</td>
</tr>
</tbody>
</table>

PID provided by Čerenkov signal (not simulated)
Equalization of the RPC response

- 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 average multiplicity $\mu_0$ and efficiency $\varepsilon_0$ divided by the multiplicity and efficiency of RPC $i$

$$c_i = \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i}$$

- Then the corrected number of hits $N_i'$ is calculated as:

$$N_i' = c_i N_i$$

Average values for November data:

\[\varepsilon_0 = 0.917, \mu_0 = 1.573\]
Simulation

- GEANT4 based simulation gives raw points of ionisation
- Simulation of RPC charge avalanche & read-out by standalone program (RPC_sim)
  - Charge generated randomly following parametrization (taken from analog RPC tests)
  - Radial charge distribution modeled by double-Gaussian
    \[ f(r) = (1 - R) \cdot e^{-\frac{r^2}{(2\sigma_1)^2}} + R \cdot e^{-\frac{r^2}{(2\sigma_2)^2}} \]
  - Close-by avalanches suppression \( d_{cut} \)
  - Threshold to convert charge to hits (TT)
- Tuning
  - \( \sigma_1, \sigma_2, R \) and TT tuned using muons
  - \( d_{cut} \) tuned using positrons (3 & 10 GeV)
- Initially FTFP_BERT physics list was used
  - Led to unsatisfactory agreement (see later)
- Now using ‘Option 3’ or ‘EMY’ (optimized for low energies)
  - Main differences:
    - Reduced range size in computation of the step limit by ionization process and improved treatment of multiple scattering
Response to positrons

Gaussian fit in a $\pm 2\sigma$ range to estimate the mean response as a function of the energy

Data

Simulation (FTFP_BERT_EMY)
Response to positrons

Data and simulation agree reasonably well for all energies.

Good agreement achieved for both FTFP_BERT_EMY and FTFP_BERT.

Fitted with power law

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

Data

\[ m = 0.76 \pm 0.02 \]
\[ a = 131.8 \pm 2.8 \]

FTFP_BERT_EMY

\[ m = 0.836 \pm 0.001 \]
\[ a = 115.8 \pm 0.1 \]

Saturation due to large pad size compared to the dense electromagnetic showers. Inverse fit function used to reconstruct energy.
Reconstructed energy of positrons

Gaussian fit in a $\pm 2\sigma$ range to estimate the resolution
Electromagnetic Energy Resolution

Good agreement only for EMY physics list

Fit with standard parametrization

\[ \frac{\sigma}{E} = c \Theta \frac{\alpha}{\sqrt{E/GeV}} \]

<table>
<thead>
<tr>
<th></th>
<th>c [%]</th>
<th>( \alpha ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>6.3 ± 0.2</td>
<td>14.3 ± 0.4</td>
</tr>
<tr>
<td>FTFP_BERTEMY</td>
<td>6.2 ± 0.1</td>
<td>13.4 ± 0.2</td>
</tr>
</tbody>
</table>
Longitudinal shower shape

Good agreement for simulation and data

Fit with gamma distribution to estimate average leakage and shower maximum

\[
\frac{dN}{dz} = N_0 \frac{\left(\frac{z-\mu}{\beta}\right)e^{-\frac{z-\mu}{\beta}}}{\beta \Gamma(\gamma)}
\]

\(\gamma\) shape parameter
\(\beta\) scale parameter
\(\mu\) location parameter

Mean response is corrected for leakage
Longitudinal shower shape

Excellent agreement for shower maximum

**Diagram:**
- **Shower Maximum [layer]** vs **Beam energy [GeV]**
- **Data** represented by red dots
- **Simulation** represented by blue squares

**Legend:**
- **CALICE Min-DHCAL**
Transverse shower shape

- Hits in first 5 layer are fit to a straight line to determine shower axis
- Distance R is calculated with respect to shower axis
- Relatively good agreement observed for data and simulation
Hit density

Density is defined as number of neighbors in 3x3x3 cube around the hit (0 to 26)

Density information can be used to linearize the response

Some limitations in the simulation still persist.
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

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

Fit parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>
Improves the resolution 2-10%

Weights can then be used to linearize electromagnetic subshower events

Expect significantly improved resolution

<table>
<thead>
<tr>
<th></th>
<th>Constant term [%]</th>
<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>
Conclusions

- Fine segmentation allows the study of electromagnetic interactions with unprecedented level of spatial detail
- Data taken with the DHCAL with minimal absorbers at Fermilab are compared to simulations
- Standard Geant4 electromagnetic simulation package fails to reproduce data well
- EMY option allows big improvement in the agreement
- Analysis of pion data is underway