CMS HCAL Test Beam Results and Comparison with GEANT 4 Simulation

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on behalf of the
CMS HCAL Collaboration

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CMS Calorimeter system

ECAL: PbWO$_4$ crystals

Sampling calorimeter
Scintillator
Brass (70%Cu, 30%Zn)

Wedge, 20°

See Julie Whitmore's talk for details
The test beam setup is designed to preserve the interaction point-like geometry of CMS.
Test beam setup

2 Hadron barrel wedges
1 Hadron endcap wedge
Hadron outer calorimeter

7x7 crystals ECAL
Material for Magnet
Movable table in \( \eta-\phi \) plane
ECAL and HO

View from top

ECAL

7x7 crystals = 14x14 cm

Beam

HO

HB2

HB1

ECAL is readout by PMTs. Light guides are attached to the front face of the crystals.
• Detailed HCAL geometry with HB1&HB2 read-out schema.
• ECAL – PbWO$_4$ crystals, Al box and Al block behind ECAL.
• Beam line - trigger counters and wire chambers
Physics lists tested against the test beam data:

- **LHEP**: LEP/HEP parametrized models for inelastic scattering.
- **QGSP**: Quark Gluon String model for the “Punch-through” interactions.
- **QGSC**: QGSP + Chiral invariant phase-space decay.
- **FTFP**: diffractive string excitation similar to that in FRITOF and Lund

In this comparison is used Geant 4.6.2.p02

- Parametrized: LHEP-3.7
- Model based: QGSP-2.8

QGSC-2.9 and FTFP-2.8 produce very similar to QGSP-2.8 results.
Available beam tunes:
- pions 2-300 GeV
- muons 80/150 GeV
- electrons 9-100 GeV

P-ID:
- Cerenkov counter (CK2) - electron
- Cerenkov counter (CK3) - pion / kaon / proton
- Scintillators (V3, V6, VM) – muon tagging
**Beam contamination and cleaning**

Beam contamination before the clean up:

<table>
<thead>
<tr>
<th>$P_{beam}$ [GeV]</th>
<th>mu [%]</th>
<th>el- [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>150</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>11</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>70</td>
</tr>
<tr>
<td>9</td>
<td>1.5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>3.5</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>85</td>
<td>7</td>
</tr>
</tbody>
</table>

+ interaction in the beam line

2 and 3 GeV are not used

Beam cleaning:

- The particle Id counters are used for beam with momentum from 2 to 15 GeV
- Calorimeter based cuts: use the particle Id capabilities of the calorimeters.

High energy muons a tagged by the muon veto counters with 99% efficiency. Low energy muons form pion decay are evaluated to be less then 1.5% for 9 GeV and below.

Electrons are clearly identify by ECAL/HCAL energy deposition.

Any remaining uncertainty in the beam contamination and interaction in the beam line is added to the systematics of the measurement.

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CALOR06 – CMS HCAL Test Beam Results
The uniformity calibration is done with Co\(^{60}\), per-tower and per-layer.

Reconstructed energy:

\[ E_{\text{rec}} = a \times E_{\text{ECAL}} + b \times E_{\text{HCAL}} \]

Energy scale:

**ECAL**: 100 GeV e-

**HCAL**: 50 GeV pi- with MIP in ECAL.

See Mayda Velasco's talk.
Energy spectra ECAL+HCAL: data vs GEANT4

Good agreement between data and GEANT4 prediction.

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CALOR06 – CMS HCAL Test Beam Results
GEANT4 models correctly the calorimeter response to pions in broad energy range. Correct representation of the single hadron response at low energy is important for simulation of the calorimeter response to jets. Some discontinuity is observed at 7-10 GeV in the GEANT4 prediction.
HCAL alone: MIP in ECAL is required. HO is not used in this measurement to compensate the HB leakage on the back.

LHEP models better the high energy calorimeter response. QGSP has less leakage on the back due to shorter shower.

HCAL alone response to pions
Proton over pion response ratio

Protons have 15% lower response than pions at this energies.

Significant difference in the calorimeter response to protons with respect to pions is observed in the data and is well represented in the GEANT4 simulation.

We will remeasure it this summer with improved particle Id.
Longitudinal shower profile measurement

Optically masked out

Modified read-out: redesigned optical decoding units to allow longitudinal shower measurement

Electromagnetic shower profile in HCAL

Very good agreement between test beam data and GEANT4 prediction.

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CALOR06 – CMS HCAL Test Beam Results
Longitudinal shower profile measurement (cont.)

LHEP and QGSP show good agreement with test beam data at low and intermediate energies.
MIP in ECAL
MIP in L0
QGSP physics list has shorter shower profile for incident particles with high momentum.

Longitudinal shower profile measurement (cont.)

QGSP

LHEP

pi 300 GeV
ECAL response is higher in GEANT4 at low energy: geometry or physics or ...?
Cluster-based response compensation

Fractional energy resolution for pions.

Uses test beam data to fit the intrinsic electron to hadron response (e/h) and the average neutral fraction $f_0$ of the ECAL and HCAL as a function of the raw total calorimeter energy, $E + H$. 

$\sigma/E$

Dan Green

70% Stochastic

8% Constant

E [GeV]
Conclusions and Outlook

- Calorimeter response for momentum range 5-300 GeV/c was measured with test beam in 2004.

- GEANT4 is in good overall agreement with the data.
- LHEP shows best agreement.

- We observed small discrepancy in the following quantities:
  1) Longitudinal shower shape for 150-300 GeV/c pions, modeled by QGSP physics list.
  2) Discontinuity in the calorimeter response in 7-10 GeV/c range.
  3) ECAL response to very low energy pion beam is higher in the GEANT4 simulation.

- We plan to repeat the measurements this summer with ECAL production super-module and improved particle Id.