The CMS Barrel Calorimeter Response to Particle Beams from 2 to 350 GeV/c

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Outline

- Description of barrel calorimeters (EB, HB, HO) and test beam 2006 setup
- H2 beam line, beam clean-up, particle identification and beam composition
- EB+HB Combined calorimeter response
  - \( \pi^{+/-}, K^{+/-}, p, \bar{p}, \mu \)
- Response parametrization and correction
- Summary
**Calorimeters**

*HB/HO:* measure timing, angular direction, hadronic shower energy – calorimetric triggers, jet/met reconstruction.

*Scintillator tiles are read out with embedded wavelength shifting fibers.*

*brass (non-magnetic absorber) & scintillator tiles.*

1 complete EB supermodule (1700 PbWO$_4$ crystals) of width $\Delta\Phi=20^\circ$.

Crystal length = 25.8$X_0$.

Light conversion to signal by 2 APDs / crystal.
Test Beam 2006 Setup

- HB: 40 deg in $\Phi$
- HE: 20 deg $\Phi$
- HO: Ring 0,1,2
- ECAL(SM9): 20 deg in $\Phi$
- +final CMS electronics
H2 Beam Line at the SPS

- Beam cleaning:
  - Single hit in S1, S2 and S4 trigger counters (S1*S2*S4 define 4x4 cm$^2$ area on the front face of the calorimeter)
  - Remove wide angle secondaries: Beam Halo counters (BH1-4) 7x7 cm$^2$ hole.
• Particle ID in the Very Low Energy Mode:
  - Muons: Muon Counters
  - Electrons: CK2 and CK3
  - Protons: CK3 and Time-of-flight counters (TOF)
  - Kaons: TOF and CK3
  - Pions: All the remaining particles.

-- CK3 pressure set depending on the desired discrimination between electrons, pions, and kaons.

-- TOF1 & TOF2 separation ~55 m. $\Delta t \sim 300$ ps. Protons and pions(& kaons) are well separated up to 7 GeV/c w/ TOF system alone.
Beam Composition

• High energy mode
  – no anti-proton contamination in negative beams.
  – Beam almost all protons at 350 GeV/c in positive beams.

• The beam content depends strongly on the momentum.
  – At higher momenta the beam is largely pions.
  – At lower momenta electrons dominate.
Combined Calorimeter (EB+HB+HO)

Response

EB: 7x7 crystals
HB: 3x3 towers
HO: 3x2 towers

Energy Scale:
EB: 50 GeV electron
HB: 50 GeV electron

At 5 GeV:
pion resp. ~62%
proton resp. ~47%
antiproton resp. ~70%
Available Energy

\[ E_{\text{available}}^{(\text{pions,kaons})} \sim KE + m \]
\[ E_{\text{available}}^{(P)} \sim KE \]
\[ E_{\text{available}}^{(\bar{P})} \sim KE + 2m_p \]
\[ \pi^+/\pi^- \text{ Response Ratio} \]

- Response to \( \pi^+ \) > response to \( \pi^- \) increasing with decreasing energy → at 2 GeV \( \pi^+ \) is 10% greater than \( \pi^- \)

**Charge exchange reactions:**

1. \( \pi^+ + n \rightarrow \pi^0 + p \) (1)
2. \( \pi^- + p \rightarrow \pi^0 + n \) (2)

The heavy nuclei in the calorimeter material has 50% more neutrons than protons -- the effect of reaction 1 is larger than 2.
**π⁻/p Response Ratio**

Charge exchange reaction:

\[ \pi^-(\bar{ud}) + p(uud) \rightarrow \pi^0(\bar{u}\bar{u}) + n(udd) \].

But baryon number conservation prevents \( \pi^0 \) creation when the showers are initiated by protons.

\[ p(uud) + n(udd) \rightarrow p(uud) + n(udd) \]
\[ p(uud) + p(uud) \rightarrow p(uud) + n(udd) \]

--- production of \( \pi^0 \) is not favored.

- Response to protons is systematically are smaller than that of \( \pi^- \)
π/\rho \text{ Response Ratio}

- Larger fraction of baryons start showering in EB since the total cross section for \( \rho > \pi^- \).

- Fraction of particles passing through EB without interacting
  - Pions: 41%
    - Produce more \( \pi^0 \). Even though fewer \( \pi^- \) interact, those that interact have larger signal
  - Protons: 35%

- The effective thickness of EB
  - Pions: \( 0.89\lambda_I \)
  - Protons: \( 1.05\lambda_I \)
μ Response

- Noise in a single tower of HB ~200 MeV
  - Very good isolated muon identification.
  - HB trigger electronics is designed to generate an isolated muon trigger.

![Energy Distribution Graph]

150 GeV Muons
Optimization of Energy Reconstruction

- The response for charged hadrons is not a linear function of energy for non-compensating calorimeters, $e/h \neq 1$.
- Moreover, EB and HB have very different values of $e/h$.
- Therefore, corrections are needed to obtain the correct mean particle energy.

Reminder: $e/h$ is the conversion efficiency of em and had energy to an observable signal.
“Bananas” for π Beams

![Graphs showing MIP in EB](image)

- MIP in EB
- e/h = 1 line.
Response Optimization

- **Apply thresholds:**
  - 7x7 EB crystals < 0.8 GeV
  - 3x3 HB towers < 1.0 GeV
  - 3x2 HO towers < 2.0 GeV

- \(<\pi/e>\) for HB as a function of \(<E_{HB}>\) using MIP in EB events.

- Correct HB energy using \(\pi/e\) function

- Determine \(<\pi/e>\) for EB as a function of \(<E_{EB}>\) using the corrected HB energies and the beam energy constraint.

- Correct EB energy using \(\pi/e\) function

- Correct the remaining non-linearity as a function of EB energy fraction.

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**HB Response to \(\pi\)'s**

- \(E(HB) > 8\) GeV:
  \[
  \pi/e = \left[1 + \frac{(e/h-1)f_0}{e/h}\right]
  \]
  \(f_0 = 0.11\log E_{HB}\) (Wigmans)
  \(\rightarrow e/h = 1.4\)

- \(E(HB) < 8\) GeV:
  \[
  0.18\log(E_{HB}) + 0.14
  \]

**EB Response**

- \(<\pi/e>_{EB} = 0.057\log(E_{EB}) + 0.490\)

w/ events that have significant energy both in EB & HB.
Total Response vs EB Fraction

\[ Z = \frac{E_{EB}^*}{E_{EB}^* + E_{HB}^*} \]

hadronic shower in EB fluctuates largely to neutrals. So we do the final step of correction as a function of Z.
“Bananas” of the Corrected Barrel System

\[ \pi^- 20 \text{ GeV/c} \]

Corrected HB (GeV) vs. Corrected EB (GeV)

- **20 GeV**
- **100 GeV**
Corrected Resolution and Response

- Linearity restored within 5% for \( p \geq 5 \) GeV and 2-3% for \( p \geq 9 \) GeV.

\[
\frac{\text{rms}}{E} = a'/\sqrt{E} + b'
\]

\[
\frac{\sigma}{E} = a/\sqrt{E} + b
\]

\( \sigma/E = a/\sqrt{E} + b = 84\%/\sqrt{E} + 7\% \) in \( P = 5-300 \) GeV/c
Summary & Conclusions 1

- The CMS barrel calorimeter has been exposed to particle beams with momenta 2-350 GeV/c.
- The particle identification detectors separated electrons, muons, pions, kaons, and protons over a substantial energy range.
- HO was used to reduce the effects of leakage at high energies.
Summary & Conclusions 2

- The response to different hadrons is studied.
  - Simple interesting regularities are observed.
    - $\pi^-/\pi^+$ response, $\pi^-/p$ response, $\pi/\bar{p}$ response
- Linearity for negative pions was optimized
  - TB06 explored the low energy response where previously used parametrizations no longer fit the data well. Important to understand and apply corrections to data.
  - The corrected data: Linearity restored within 5% for $p\geq5$ GeV and 2-3% for $p\geq9$ GeV.
  - The stochastic and constant term for energy resolution of the combined system are 84% and 7% respectively.
Summary & Conclusions 3

- Correction method works for single isolated particles and the test beam environment.

- Direct application of the method to jets is not possible since jets are formed both from isolated as well as non-isolated objects.
  - If the photons from $\pi^0$s in a jet can be separated from the charged hadrons, then the corrections could be applied on the charged hadrons and then the jet may be better reconstructed.
References

- CMS Physical Technical Design Report, Volume I, Detector Performance and Software, CERN/LHCC 2006-001.
- 'Calibration of the CMS Calorimeters', D. Green, FERMILAB-FN-0704 (2001)
- R. Wigmans, Nucl. Inst. and Meth. A408 (1998) 380
BACKUP
Hadron Outer Calorimeter for High Energy Particles

- Note the reduced low energy leakage tail.
Energy Scale Calibration for HCAL (Electrons; Pions)

Two calibration schemes:
- EC: calibrated with electrons
  1) HC: calibrated with pion (50 GeV)
  2) HC: calibrated with electrons

300 GeV pion

1) Better response, worse resolution.
   MIP in ECAL

2) Better resolution, worse response.

Calibration point for RecHit:
- If jet fragments all into $\pi^0$'s.
- If jet fragments all into charged particles.

$E_{p^-}/E_{e(50)}$

Reco/Beam mom [GeV/c]

$\pi^-$ and $\pi^0$ in ECAL+HCAL

$\gamma$ and $\pi^0$ mixed in jets

Default for CaloTower

$\pi/e=1$ ideal for jet reconstruction.
HCAL Response

\( E(\text{HB}) > 8 \text{ GeV}: \)
\[
\frac{\pi}{e} = \frac{[1 + (e/h - 1)f_0]}{(e/h)}
\]
\( f_0 = 0.11 \log E_{\text{HB}} \) (Wigmans)

\( \Rightarrow e/h = 1.4 \)

Only valid down to 8 GeV!

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We use a different log function for:

\( E(\text{HB}) < 8 \text{ GeV}: \)
\[
0.18 \log(E_{\text{HB}}) + 0.14
\]
Wire Source Calibration

- The response of each HB scintillator tile of each layer measured: 5-mCi Co\(^{60}\) moving wire radioactive source.
- Light attenuation in the optical fibers, loss in fiber connectors, and the HPD gain differences.
- Fiber length increases with \(\eta\).
- Tower-to-tower calibration precision: 2% --> derived by comparing the consistency of the relative source and beam data.

*Calibration constants for the 4 \(\phi\) sectors of HB.*
Raw EB+HB without Noise Cuts

Without the noise cuts, the distributions are gaussian down to 2 GeV/c.