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

Efe Yazgan for the CMS ECAL/HCAL Collaborations
Department of Physics, Texas Tech University, Lubbock, TX, USA
E-mail: efe.yazgan@cern.ch

Abstract. The response of the combined CMS barrel calorimeters to hadrons, electrons and muons over a range from 2 to 350 GeV/c has been measured. The analysis of the differences in calorimeter response to charged pions, kaons, protons and antiprotons and a discussion of the underlying phenomena are presented. Techniques to correct the signals from the considerably different electromagnetic (EB) and hadronic (HB) barrel calorimeters in reconstructing the energies of hadrons are also presented. Above 5 GeV/c, these corrections improve the energy resolution of the combined system where the stochastic term equals 84.7% and the constant term is 7.4%. The corrected mean response remains constant within 1.3% rms.

1. Introduction
The CMS calorimeters have distinct hadronic (HCAL) and electromagnetic (ECAL) systems. The central HCAL is made of brass and scintillators [1] while the ECAL comprises lead tungstate crystals (PbWO$_4$) [2]. The calorimeters are divided into the barrel (HB and EB) and the end-cap (HE, EE and pre-shower, ES) sections inside a cryostat of 5.9 m inner diameter, containing a superconducting solenoid coil providing a 4 T magnetic field. The HB design maximizes the number of interaction lengths ($\lambda_I$) inside the cryostat and is limited to $5.8\lambda_I$ at $\eta = 0$. The EB adds $\sim 1.1 \lambda_I$. The outer hadron calorimeter (HO) was constructed to sample the energy leakage outside of cryostat [3]. There are also two very forward calorimeters (HF) made of iron and quartz fibers [4]. Figure 1 shows the calorimeters inside and around the solenoid coil.

This paper reports the responses of the barrel calorimeters to beam particles. The measurements were performed with production modules and front-end electronics as in the final CMS detector configuration. A special beam line was constructed to measure the calorimeter response down to 2 GeV/c. This was necessary since a large fraction of the particles reaching the CMS calorimeters at the LHC have energies below 20 GeV. More details on the CMS calorimeters can be found in [1, 2].

2. Test Beam Setup
The data were recorded during 2006 at the CERN H2 test beam. Figure 2 is a photograph of the moving platform that held two production HB wedges plus a production EB supermodule (SM) which was placed in front of the HB, and the HO behind the HB. The two-dimensional movement of the platform in the $\phi$ and $\eta$ directions allowed the beam to be directed onto any tower of the calorimeter mimicking a particle trajectory from the interaction point.
Temperature stability is critical for the ECAL as both the response of the crystals and the APDs change with temperature. The temperature was stabilized at 21°C by enclosing the EB SM (except in the beam direction) in 5 cm aluminum plates with cooling water pipes embedded in the plates and by wrapping the entire SM with a thermal blanket.

2.1. H2 Beam Line and Particle Identification

Figure 3 schematically depicts the CERN H2 beam line which is designed to operate in two distinct modes. In the high energy mode (15-350 GeV/c), particles are produced when 400 GeV/c protons from the Super Proton Synchrotron (SPS) strike a production target (T2) 590.9 m upstream of the calorimeters. The maximum usable momentum was 100 GeV/c for electrons and 350 GeV/c for hadrons. In the very low energy (VLE) mode (≤ 9 GeV/c), an additional target (T22) located 97.0 m upstream is used for particle production. As shown in Figure 3, a dog-leg configuration is utilized for the momentum selection of these low momentum particles.

In the VLE mode, two Cherenkov counters (CK2 and CK3), two time-of-flight counters (TOF1 and TOF2) and muon counters (Muon Veto Wall (MVW), Muon Veto Front (MVF) and Muon Veto Back (MVB)) were used to positively tag electrons, pions, kaons, protons, antiprotons and muons. CK2, which is filled with CO2, was used to identify electrons in the VLE mode. CK3 was filled with Freon134a [5] and its pressure was set depending on the desired discrimination between electrons, pions, and kaons. At lower beam momenta, \( P_b \leq 3 \text{ GeV/c} \), it was set to tag electrons. At higher momenta \( P_b > 4 \text{ GeV/c} \), CK3 was used to separate...
pions from kaons and protons. Time-of-flight counters (TOF1 and TOF2) were separated by \(\sim 55\) m. The time resolution obtained by this system was \(\sim 300\) ps. Protons were well-separated from pions/kaons up to 7 GeV/c with the TOF system alone. Pions and kaons have \(\pm 1\sigma\) TOF overlap at 5.6 GeV/c, while kaons and protons overlap at 9.5 GeV/c. Figures 4 and 5 display the identified particles in -3 and -8 GeV/c hadron beams. Energetic muons were tagged with MVF and MVB counters as well as the MVW counters. MVF and MVB were large \((80 \times 80\) cm\(^2\)) scintillation counters and were placed well behind the calorimeters. To absorb the soft muon component in the beam, an 80-cm thick iron block was inserted in front of MVB. MVW consisted of 8 individual scintillation counters, each measuring \(30 \times 100\) cm\(^2\), placed closely behind the HB. In addition, six delay-line chambers, four scintillation counters (S1-S4) and four scintillation beam halo counters (BH1-BH4) were used. The resolution afforded by the delay-line chambers was \(\sim 350\) \(\mu\)m in both the \(x\) and \(y\)-coordinates. The beam trigger typically consisted of the coincidence S1-S2-S4 which defined a \(4 \times 4\) cm\(^2\) area on the front face of the calorimeter. The S4 counter pulse height was used to eliminate multi-particle events off-line since it gave a distinct distribution for single and multi-particles in the beam (see Figure 6). BH counters, each measuring \(30 \times 100\) cm\(^2\) in size, were arranged such that the beam passed through a \(7 \times 7\) cm\(^2\) opening. These counters were positioned 17 cm downstream of the last trigger scintillator S4 and were effective in vetoing the beam halo and large-angle particles that originated from interactions in the beam line.

Figure 4. The distributions of the time of flight between TOF1 and TOF2 are shown for different particles.

Figure 5. The same as Figure 4 but for a -8 GeV/c hadron beam. The solid blue and purple lines indicate fits to data.

Figure 6. The signal distribution from the S4 trigger scintillator (left) for 50 GeV/c \(e^-\)s displays multi-particle events where up to three particles are discernable. The plot on the right shows the signal distribution of one of the four halo counters for 3 GeV/c negative pion beam. The red histograms indicate pedestal distributions.

In the high energy mode of the beam line where the data were taken with negative beams, there was no \(p\) contamination. If the beam line was configured for positive particles, at
350 GeV/c, the beam consisted almost purely of protons. At 20 and 30 GeV/c, the proton identification in the \( \pi^+ \) beam was possible when CK3 was pressurized to 1.7 bar of CO₂. The particle content depends on the momentum, \( P_b \). At the higher end, pions dominate. At lower momenta, the beam consists mostly of \( e^- \)s. The beam consisted of 31% pions, 0.4% kaons, and 5.6% protons at +4 GeV/c, and the rest were \( e^- \)s. At +8 GeV/c, the beam contained 72% pions, 2% kaons and 7% protons, and the remaining were \( e^- \)s. In the negatively charged beam, the particle mixture was approximately the same but the \( \bar{p} \) fraction was much reduced compared to that of the \( p \) in the positive beam. To enrich the hadron content of beam triggers at low energies, a S1-S2-S4-MVF trigger was employed.

3. Calibration of Calorimeters

Both the EB and HB calibrations were carried out with 50 GeV/c \( e^- \)s. The \( e^- \) beam was directed at the center of each HB tower. Similarly, the EB calibration data were collected by pointing the beam to a selected set of crystals that formed a tight grid pattern. For the EB, the signals from 7 × 7 crystals, and for the HB the signals from 3 × 3 towers were summed. In the case of the HO, the total energy was estimated by adding signals from 3 × 2 towers.

The response of each HB scintillator tile of each layer was also measured by using a 5-mCi Co\(^{60}\) moving wire radioactive source [6].

The HO modules were first calibrated by 150 GeV/c \( \mu^- \) beam. A clear \( \mu \) peak was observed in Ring 0 and Ring 2. In Ring 1 the \( \mu \) peak was measurable but not as cleanly separated from pedestal. Next, the HO energy scale was determined by 300 GeV/c \( \pi^- \) beam impinging on \( \eta \) tower 4 of the HB. For this measurement, it was required that the energy in the EB be less than 1.2 GeV. The energy scale was determined by requiring the best energy resolution in HB+HO, as measured by rms width, for the 300 GeV/c \( \pi^- \) beam.

4. Combined Calorimeter (EB+HB) Response

Figure 7 shows the combined response of EB+HB to a variety of particles vs. momentum. At 5 GeV/c, the \( \bar{p} \) response is ~70% of the \( e^- \) response. The responses to charged pions and protons are 62% and 47% of the \( e^- \) response at the same energy, respectively. At a given momentum, the available energy that is converted to a calorimeter signal varies by particle type. The available energy for protons is their kinetic energy. For \( \bar{p} \), the available energy equals the kinetic energy plus twice the rest mass of proton. For pions and kaons, the available energy is their kinetic energy plus their mass. In Figure 8, the same data are plotted against the available energy. One expects roughly the same response characteristics for all hadrons, which is approximately observed in the data, but there are subtle differences which we discuss next.

The response to \( \pi^+ \) is systematically larger than the \( \pi^- \) response, increasing as the energy decreases. This is due to the characteristics of the charge exchange reactions, \( \pi^+ + n \rightarrow \pi^0 + p \) (I) and \( \pi^- + p \rightarrow \pi^0 + n \) (II). In these reactions, a large fraction of the pion energy is carried by the final-state \( \pi^0 \), that develops electromagnetic showers. The response to pions interacting this way is close to 1. Since the heavy nuclei contained in the calorimeter consists of ~50% more neutrons than protons, the relative effect of reaction (I) is larger than that of reaction (II), and therefore, the response to \( \pi^+ \) should be larger than the \( \pi^- \) response at lower energies where charge exchange is important. This difference, at 2 GeV/c, is ~10%.

The response to protons is systematically lower than that of negative pions. This effect, which is also observed at high energy, is a result of the fact that \( \pi^0 \) production is, on average, smaller in proton induced showers. This is a consequence of baryon number conservation, which favors the production of leading baryons, while pion induced reactions may have leading \( \pi^0 \)s. This effect was observed in the HF calorimeter [7], where it caused a response difference ≥10%. Since the \( e/h \) values of EB and HB are smaller than for the HF, the effects are correspondingly smaller, but nevertheless significant.
Figure 7. The response of the combined calorimeter system to six different particles vs beam momentum. Both the EB and HB are calibrated with 50 GeV/c $e^−$s.

Figure 8. Same as in Figure 7 but the calorimeter response is plotted against the available energy.

Since the inelastic cross section for protons is larger than for pions, a larger fraction of the baryons start showering in the EB. It is found from 30 GeV/c $\pi^+$ and 30 GeV/c proton data that 41% of the pions penetrate the EB without starting a shower, versus 35% of the protons. The effective thickness of the EB is thus $1.05\lambda_I$ for protons and $0.89\lambda_I$ for pions.

The fraction of the beam energy deposited in the EB decreases from $\sim 60\%$ at 2 GeV/c to $\sim 25\%$ at 300 GeV/c. At the same incident momentum, protons deposit on average less energy than pions in the EB, while antiprotons deposit more. Antiprotons start their showers, on average, earlier than pions and therefore a larger fraction of the energy ends up in the EB. One would expect the same for proton induced showers. However, when a proton interacts in the EB, the interactions have limited energy transferred to secondary $\pi^0$s. This suppresses the proton signal in the EB, despite the fact that protons are more likely to start their showers in the EB compared to pions.

Pions deposit, on average a larger fraction of their energy in the HB. Since the $e/h$ value of the HB is smaller than for the EB, the pions benefit more from the increased response to the non-electromagnetic shower components. The net result of the energy sharing is that for beam momenta less than 10 GeV/c, the total energy measured is smallest for antiprotons, then protons and then pions. This effect is observed in Figure 8.

Figure 9 shows the response of 150 GeV/c muons in the HB using $3 \times 3$ HB towers. Since the noise in a single tower of the HB is equivalent to $\sim 0.2$ GeV, this calorimeter system is superb in identifying single isolated muons. The HB trigger electronics is also designed to generate an isolated muon signal (bit) based on this capability. The mean energy deposited by a 150 GeV/c muon is 2.4 GeV.

5. Optimization of Energy Reconstruction

The $e/h$ values are different for the EB and the HB, and thus corrections have to be applied to obtain the correct particle energy from the EB+HB+HO system. Figure 10 displays the measured EB versus HB energy for a number of pion beams. The events with near zero EB energy are due to the non-interacting $\pi^0$s in the EB. In a compensating calorimeter ($e/h = 1$), the events would normally lay about a straight line as indicated in Figure 10, and the line would intersect both axes at the beam energy. This is not the case for the EB+HB system, and we
choose to optimize the energy measurement in two major steps. The first correction is carried out for the energy response, and the second step involves correction of non-linear response as a function of the EB energy fraction. First, thresholds are applied to the EB and HB energy clusters that are constructed from $7 \times 7$ EB crystals, $3 \times 3$ HB and $3 \times 2$ HO towers. If the energy in the cluster is less than the threshold, the cluster energy is set to zero. The thresholds are set at least $3\sigma$ away from the noise levels, and are 0.8, 1.0 and 2.0 GeV for the EB, HB and HO, respectively.

The next task is to parametrize the $\pi/e$ for the HB as a function of the mean HB energy, using the events that deposit only minimum ionizing energy in the EB ($E_{\text{EB}} < 1.2$ GeV). Figure 11 displays the $\pi/e$ for the HB as a function of the log of the observed HB energy. The plot (in semi-log) shows two lines with a break point at about 8 GeV.

Figure 9. The HB response to 150 GeV/c $\mu^-$ from tower 4 ($\eta = 0.3$). The solid curve represents a fit using combined Gaussian and Landau distributions.

Figure 10. The “raw” EB vs “raw” HB energy scatter plot for incident $\pi^-$ beam momenta of 300, 100, 20, 8, 4 and 2 GeV/c. The straight line indicates the expected behavior of an ideal calorimeter system.

Figure 11. $\pi/e$ vs $E_{\text{HB}}$ for events interacting in the HB.

Figure 12. Measured $(\pi/e)_{\text{EB}}$ vs $E_{\text{EB}}$ after correcting the energies of pions that interacted in the EB.
The $\pi/e$ ratio is defined as $[1 + (e/h - 1)f_0]/(e/h)$. The electromagnetic fraction, $f_0$, is parametrized using Wigmans' function [8], where $f_0 = 0.11 \log P_b$ and $P_b$ is the beam momentum. The fit above 8 GeV gives $e/h = 1.4$. Below $\sim$8 GeV, $\pi/e$ can be represented by the following function, $0.179 \log(E_{HB}) + 0.413$. Further studies are underway to determine the physics behind the logarithmic function describing the low momentum data points.

![Graph](image-url)

**Figure 13.** The $\pi/e$ corrected response ratio for 100 GeV/c pions of the combined system as a function of the EB fraction.

Next, the mean $\pi/e$ for the EB, $\langle(\pi/e)_{EB}\rangle$, is estimated using the known beam momentum as a function of the observed mean EB energy, $(E_{EB})$, for each beam momentum. $\langle(\pi/e)_{EB}\rangle = (E_{EB})/(P_{b} - E^{*}_{HB})$ where $E^{*}_{HB}$ is the event-by-event corrected HB energy, $E_{HB}/(\pi/e)_{HB}$. We calculate this ratio for events where the pion shower is shared between the EB and the HB with the requirement that $0.2P_{b} \leq E_{EB} \leq 0.6P_{b}$. The mean $\pi/e$ for EB as a function of the logarithm of the observed EB energy shows a linear behavior (see Figure 12). The function representing $\langle(\pi/e)_{EB}\rangle$ is equal to $0.057 \log(E_{EB}) + 0.49$. After correcting the EB energies event-by-event using the above function, $E^{*}_{EB} = E_{EB}/(\pi/e)_{EB}$, we find that the $\pi/e$ correction overestimates the energies for events with large EB energy fractions, $Z = E_{EB}/(E_{EB} + E_{HB}) > 70\%$ (see Figure 13). This is expected since these events correspond to the cases when a hadronic shower in the EB fluctuates largely to neutral particles.

The second step in the correction is to linearize by fitting the non-linear response to the correction function shown in Figure 13. $\langle(E^{*}_{EB} + E^{*}_{HB})/P_{b}\rangle = 0.412Z^{3} - 0.096Z^{2} - 0.084Z + 1.00$. This set of corrections has been determined to be insensitive to the beam momentum and 100 GeV/c data is a good representation for all other beam momentum data. Figure 14 displays the energy resolution and the response linearity of the combined EB+HB calorimeters for pions. The circles represent the “raw” and the squares represent the corrected data. The data in Figure 14 are compiled after having fit each energy response with a Gaussian down to 5 GeV/c. The energy resolution is parametrized as $\sigma/E = a/\sqrt{E} + b$ where $a$ is the stochastic and $b$ is the constant term, and the terms are added in quadrature. The “raw” resolution of the EB+HB system is such that $a = 110.7\%$ and $b = 7.3\%$ as indicated by open circles within 5 to 300 GeV/c in Figure 14 (left). After applying the corrections, the energy resolution improves, as indicated by the solid red squares ($a = 84.7\%$ and $b = 7.4\%$). The corrected mean response remains constant within 1.3% $rms$ as depicted in Figure 14 (right).

6. Summary and Conclusions
The CMS barrel calorimeter has been exposed to particle beams with momenta from 2 to 350 GeV/c. The particle identification detectors separated electrons, muons, pions, and protons over a substantial energy range. The response to different hadrons is studied and simple interesting regularities are observed. The ratio of negative charged to positive charged pion response, the ratio of negative pion to proton response and the ratio of pions to antiprotons are explored. The linearity and energy resolution for negative pions are optimized. The low energy response is explored where previously used parametrizations no longer fit the data well. The corrected data are linear within 1.3% $rms$ for $P_{b} \geq 5$ GeV/c. The stochastic and the constant terms are 84.7% and 7.4%, respectively. The calorimeter remains non-compensating, so that a substantial
deviation from $E^{-1/2}$ scaling is unavoidable. The correction method works for single isolated particles and the test beam environment. Direct application of the correction method to jets is difficult 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.

Acknowledgments
The results presented in this paper are partially based on the doctoral theses of J. Damgov [9], K. Gümiuş [10] and E. Yazgan [11]. This project was carried out with financial support from CERN, Department of Atomic Energy and Department of Science and Technology of India, U.S. Department of Energy, U.S. National Science Foundation, RMKI-KFKI (Hungary, OTKA grant T 016823), Croatian Ministry of Science, Education and Sport (under grant No. 023-0982887-3064), French CNRS/Institut de Physique Nucleaire et de Physique des Particules, French Commissariat a l’Energie Atomique, Greek General Secretariat for Research and Technology, Italian Istituto Nazionale di Fisica Nucleare, Federal Agency for Science and Innovations of the Ministry for Education and Science of the Russian Federation, Federal Agency for Atomic Energy of the Russian Federation, Russian Academy of Sciences, Ministry of Education of Serbia, Swiss Funding Agencies, Scientific and Technical Research Council of Turkey (TÜBİTAK), Turkish Atomic Energy Agency (TAEK), Bogazici University Research Fund (Grant no: 04B301), Science and Technology Facilities Council (UK).

References
[1] CMS Collaboration, The Hadron Calorimeter Project Technical Design Report, CERN/LHCC 97-31 (1997).
[2] CMS Collaboration, The Electromagnetic Calorimeter Technical Design Report, CERN/LHCC 97-33 (1997).
[3] B. S. Archaya et al, The CMS Outer Calorimeter, CMS NOTE-2006/127.
[4] S. Abdullin et al, Eur. Phys. J. C 53 (2008) 139.
[5] Freon134a is an ozone-friendly gas. Based on the measurements during the beam test, we find Freon 134a’s refractive index to be 1.00065, which is also consistent with the estimates based on its molecular weight.
[6] M. Adams et al, Nucl. Instrum. Methods A511 (2003) 311.
[7] N. Akchurin et al, Nucl. Instrum. Methods A408 (1998) 380.
[8] R. Wigmans, Nucl. Instrum. Methods A265 (1988) 273.
[9] J. Damgov, Ph. D. thesis, Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Science, Sofia, Bulgaria (unpublished), 2008.
[10] K. Gümiş, Ph. D. thesis, Texas Tech University (unpublished), 2008.
[11] E. Yazgan, Ph.D. thesis, Middle East Technical University, Ankara, Turkey, Fermilab-thesis-2007-13.