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Understanding the Performance of CMS Calorimeter

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Abstract. The performance of the CMS hadron calorimeter is studied using test beam facilities at CERN. Two wedges of brass-scintillator calorimeter are exposed to negative and positive beams with momenta between 3 and 300 GeV/c. Light produced in the scintillators are collected using wavelength shifting fibres and read out using Hybrid photo-diodes. Each of the wedges has 17 layers of scintillators. In one of these wedges signal from all 17 layers are grouped together while in the other each layer is read out separately. The response, energy resolution, longitudinal and lateral shower profiles are measured.

Keywords. CMS, Calorimeter, Test beam

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1. Introduction

Although Standard Model of particle physics has been tested very precisely at LEP and Tevatron experiments, the Higgs boson, which is presumed to be responsible for Electroweak Symmetry breaking, is yet to be observed experimentally. There are many more theoretical models like Supersymmetry (SUSY), Extra Dimensions which are proposed to incorporate higher symmetries at TeV energy scale giving a more natural description of particles and their interactions. Hadron colliders are optimum choice to explore the physics at TeV scale. Motivated by these reasons, the Large Hadron Collider (LHC) [1] at CERN is designed to collide protons at 14 TeV centre of mass energy with an unprecedented peak luminosity of 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. CMS [2] and ATLAS [3] are two general purpose detectors optimised to detect every possible signature of Higgs boson or any new physics over a wide range of final state topologies.

For some models of SUSY processes, the lightest particle is weakly interacting and escapes the detector giving a huge imbalance in the transverse momentum ($\mathrm{p_T^{miss}}$) in addition to the partons which manifest themselves as high $\mathrm{p_T}$ jets. Keeping in view these signatures, the Hadron Calorimeter (HCal) of CMS [4] is designed to have a large geometric coverage ($|\eta| < 5$) to get good $\mathrm{p_T^{miss}}$ resolution and a fine segmentation in the $\eta \times \phi$ plane (0.0875×0.0875 for $|\eta| \leq 1.74$). It is of utmost importance to understand the response of the calorimeter system to particles over a wide range of energies. CMS HCal collaboration has been carrying out dedicated experiments using single particle beams derived from 450 GeV protons given by SPS at CERN.

2. Detector Setup

The central part (barrel) of CMS HCal ($|\eta| < 1.39$) is a sampling calorimeter with 17 layers of scintillator tiles (4-8 mm thick) interleaved between layers of cartridge brass (60-66 mm thick). The barrel HCal (and also the endcap) sits completely inside the solenoid giving 4 Tesla magnetic field. The light from scintillator towers is collected using WaveLength Shifting (WLS) fibres and is directed to Hybrid Photo Diodes (HPD). To ensure adequate sampling, a layer of scintillator has been added outside the solenoid coil for $|\eta| < 1.4$ and is called Outer Hadron Calorimeter (HO). It will be used to identify late starting showers. HCal is physically divided into two halves each having 18 wedges. Each wedge subtends 20 degrees in ϕ and contains 4 ϕ slices. The Electromagnetic Calorimeter (ECal) of CMS is made of 23 cm long lead tungstate crystals providing ∼25.8 radiation length. ECal is laterally segmented into $\eta \times \phi$ = 0.0175×0.0175. It provides one additional interaction length (λ_{int}) so that the minimum depth of calorimeter is 10 λ_{int}

A prototype CMS calorimeter setup was exposed in 2004 to positive as well as negative hadron beams of energy between 3 GeV and 300 GeV in a test environment (TB2004). The main motivation of this activity is to study the resolution and response of the calorimeter system to pions and to validate the physics lists of the simulation toolkit GEANT4 [5] which will be the main tool to evaluate the detector effects during LHC runs.

The experimental setup consists of two wedges of the barrel HCal with different readout configurations:

HB1: with 4 segments in ϕ (1-4), being read out using default grouping keeping the lateral tower intact (16 segmentation along η) and only one longitudinal sampling;

HB2: with 4 segments in ϕ (5-8), being read out by grouping 5 η towers (5-9) but keeping the information of individual layers (1-17).

The wedges are preceded by a 7×7 matrix of lead tungstate crystals acting as the ECal and followed by a mock-up structure of the CMS magnet and three rings of HO, each having 6 ϕ slices (trays).

Data are collected with pion and electron beams in the energy range 3 GeV to 300 GeV and also with 150 GeV muons.

Calibration of HCal Towers

Relative calibration of HCal tiles is done using radioactive source. Each of the scintillator trays is equipped with a stainless steel tube through which a wire carrying a radioactive source on its tip can run along its length. The radioactive source used was 3 mCi Cs^{137} isotope. The HPD for HO is operated at 8 kV and 10 kV. Typical signal obtained from 5 tiles of a HO tray is shown in Figure 1. This shows some leakage of signal to the neighbouring tiles when the source is at the edge of a tile. So signals from neighbouring tiles should be added with proper weight to get total signal. The pedestal is obtained by fitting a straight line with zero slope to the part of the signal when the source is far away from the tile under consideration. The pedestal subtracted signals from a tile and its two adjacent ones are then fitted using an iterative procedure to extract the calibration constants (see Figure 1).

The HCal towers are also calibrated using high energy muons. The observed muon spectra are fitted with a sum of Gaussian (pedestal) and a convolution of Gaussian and

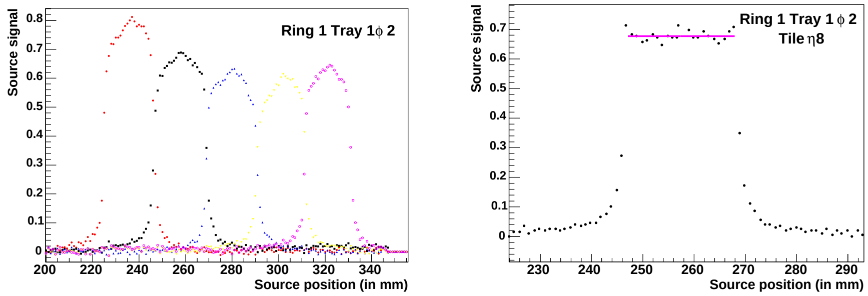

Figure 1. (a) Pedestal subtracted signal from the five tiles of a HO tray (b) Final fit to radioactive source data for one HO tile (η=8, ϕ=2.)

Landau distributions (signal). The width and spread of Gaussian is fixed using pedestal distribution and its relative contribution is fitted (see Figure 2). The peak of the convoluted Landau-Gauss is used to get the calibration constant.

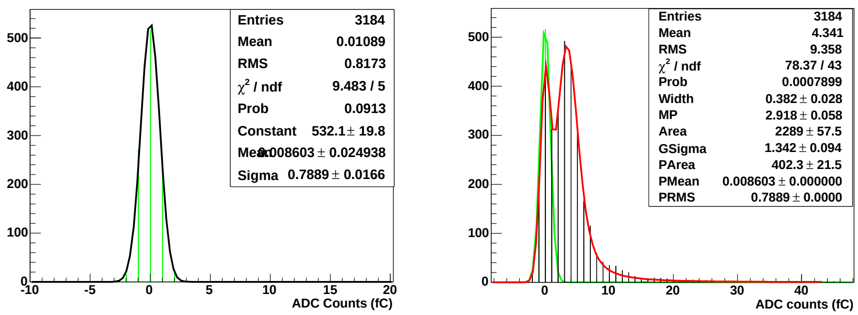

Figure 2. (a) Pedestal subtracted signal from random trigger events fitted to a Gaussian distribution. (b) Fit to the muon spectrum using a Gaussian convoluted Landau for signal and Gaussian for pedestal.

Calibration constants obtained from the two methods show positive correlation giving confidence to the determination of calibration coefficients.

Energy Measurements

Two sets of data exist, with and without the crystal matrix in front of the HCal barrel. They are analysed separately but for both the analyses the same set of calibration constants is used, namely the ones obtained using radioactive source. As the shower develops, it spreads laterally in the neighbouring towers of the central tower where beam is shot. Signals in adjacent towers of HCal ($|\Delta\eta| \leq 2$, $|\Delta\phi| \leq 1$) are summed up separately for barrel (HB) and HO. Signals from all the 49 crystals are summed up to get the signal in ECal. The energy is measured from a linear sum of signals in ECal (when ECal is present in the setup), HB and HO:

$$\mathrm{Energy} = \alpha_{\mathrm{EC}} \cdot \mathrm{S}_{\mathrm{EC}} + \alpha_{\mathrm{HB}} \cdot \mathrm{S}_{\mathrm{HB}} + \alpha_{\mathrm{HO}} \cdot \mathrm{S}_{\mathrm{HO}}$$

where α's are energy scale factors.

HCal Alone Setup

The energy scale factor for HB is obtained using data from 50 GeV pion run and ignoring the signal in HO. Energy measured from HB alone for a 300 GeV pion run is shown in Figure 3. This shows a tail on the low energy side indicating shower leakage from HB. Energy deposited in HO is added to this energy measurement in such a way to have a minimum RMS/Mean. Gaussian nature of distribution is restored after adding HO and an improvement in resolution is achieved (see Figure 3).

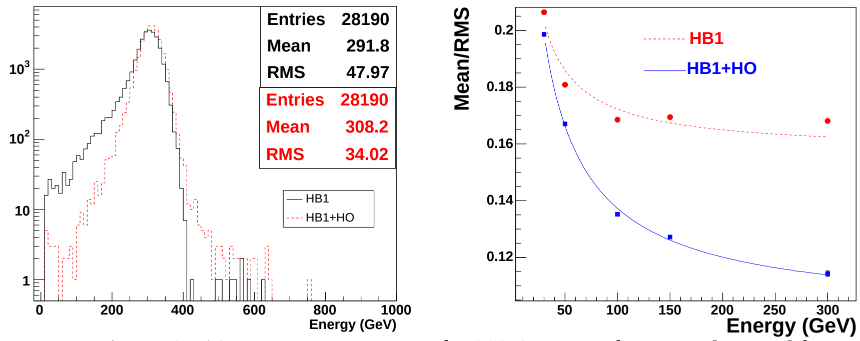

Figure 3. (a) Energy measurement for 300 GeV pion from HB alone and from HB and HO in a setup without ECal. (b) Energy resolution of the set up measured as a function of pion energy without and with HO

Figure 3 also shows the energy resolution (RMS/Mean) as a function of beam energy without and with the contribution of HO. The stochastic term in the resolution is approximately 84% in both the cases (without and with HO) while the constant term improves from 14.6% (without HO) to 11.0% with HO.

Setup with ECal and HCal

Figure 4 shows the energy deposit in ECal versus that in HCal. There one sees a substantial sharing of energy between the two and it has a non-linear structure due to non-matching e/h ratio between the two calorimeters. The energy deposited in ECal are added to that in HCal using a factor of unity to ECal or with a weight factor such that the RMS/mean is minimum for 50 GeV pion. The second method optimises energy resolution for hadrons but spoils the energy measurement for electrons and photons.

Contribution from HO is added to this energy with a weight factor which minimises RMS/Mean of the distribution for pion beam at 300 GeV. Figure 4 shows the energy resolution as a function of beam energy. Again inclusion of HO provides 10% improvement

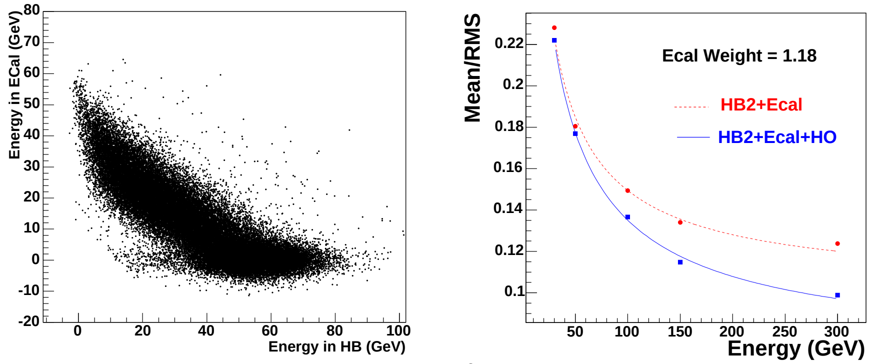

Figure 4. (a) Energy measurement for 50 GeV pion in ECal versus that in HB. (b) Energy resolution for pions as a function of energy in a set up with ECal and HCal

in the energy resolution at 300 GeV. The constant term in the energy resolution improves from 8.9% to 6.1% with HO.

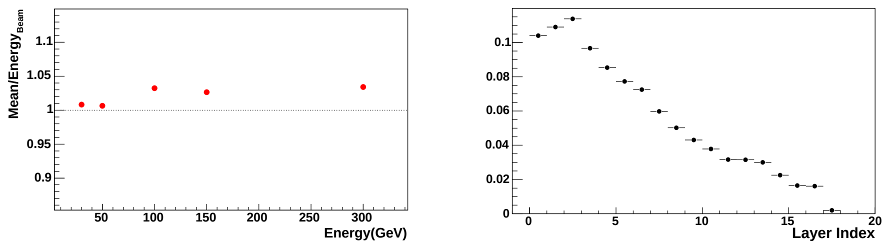

Figure 5. (a) Measured energy by nominal energy for pions as a function of energy in a set up with ECal and HCal; (a) Longitudinal shower profile for 300 GeV pions in HCal.

The ratio of measured to nominal beam energy is plotted as a function of beam energy in Figure 5. One does not see strong deviation from linearity within the energy region 30-300 GeV. The same fi gure shows the longitudinal shower profi le (deposited mean energy as a function of the layer number) in the hadron calorimeter for 300 GeV pions in a setup with ECal and HCal. This distribution is very sensitive to the detail of hadron shower model.

References

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