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Detection of muons at 150 GeV/c with a CMS Preshower Prototype

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Abstract

The analysis of 150 GeV/c muon data collected during a test of a CMS Preshower prototype is presented. The test took place in 2004 in the H4 beam at CERN. The muon signal extraction is possible after pedestal subtraction and common mode correction. The results of a Geant-4 based simulation, developed for the Preshower prototype test, are also presented. The results of the simulation are found to be in excellent agreement with the data. It is also demonstrated that by combining the results of the data analysis and simulation an absolute calibration of the CMS Preshower detector system can be performed.

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1 Introduction

The CMS Preshower [1] is a fine grain detector, which will be placed in front of the endcaps of the Electromagnetic Calorimeter with a fiducial coverage of $1.653 < \eta < 2.6$. It consists of two orthogonal layers of silicon strip sensors (1.9 mm pitch) positioned behind two planes of lead absorbers to form a sandwich of absorber-Si strip sensors-absorber-Si strip sensors. The main purpose of the Preshower detector is to identify two closely spaced photons from a π^0 decay in order to separate them from single photons. A good π^0 rejection is very important in the search of the decay H $\rightarrow\gamma\gamma$.

The total energy deposition of an electron or photon in the Electromagnetic Calorimeter is the sum of the energy deposited in the Preshower and in the crystals. To achieve a high precision measurement of the total energy deposition, Preshower must estimate the energy deposited in the lead with a \sim 5% accuracy. This is achieved with custom high dynamic range front-end electronics (PACE3 [2]) producing analogue voltage samples of the energies deposited in the silicon sensors (proportional to the energy deposited in the lead). The analogue samples from the PACE3 are digitized by AD41240 [3] 12-bit 40 MHz ADCs and transmitted to off-detector readout electronics using high speed optical links. The signals produced by the sensors are dependent on several factors, including:

- Incident particle type
- Angle of incidence (which varies with η and ϕ)
- Sensor capacitance (nominal thickness is $320 \,\mu\text{m} \pm 15 \,\mu\text{m}$, so the capacitance can vary by $\pm 5\%$)
- Charge collection efficiency of the sensors (which decreases with the neutron/proton fluence since the expected particle fluence in the inner part of the Preshower detector is calculated to be 1.6×10^{14} cm⁻² for neutrons and 0.4×10^{14} cm⁻² for charged hadrons [4]).

The PACE3 can operate in a "calibration mode", with a high gain and limited dynamic range in order to record the passage of single minimum ionizing particles (mips) with good S/N ratio. The "normal mode" of operation of the PACE3 has a lower pre-amplifier gain and higher dynamic range. An internal calibration circuit providing accurate charge injection into any combination of channels allows the two modes of operation to be inter-calibrated. The average gain of the PACE3 pre-amplifier stage is:

- In "calibration mode" : average gain ~ 20 mV/mip
- In "normal mode" : average gain ~ 3.2 mV/mip

where a "mip" corresponds to a most probable energy deposit of 83.7 keV [5] (equivalent to about 3.7 fC of charge) in a 320 μ m Si thick sensor. The gain may vary from chip to chip by a small amount [6], which can be measured using the internal calibration circuit. The range of the gain for the accepted PACE3 chips is:

- In "calibration mode" : gain from 18.5 mV/mip to 22 mV/mip
- In "normal mode" : gain from 2.8 mV/mip to 3.4 mV/mip.

Most of the above can be taken into account prior to operation in CMS using the PACE3 internal calibration circuit and simple geometrical analysis. It is also foreseen to pre-calibrate each Preshower ladder with cosmic rays, enabling a first correspondence between ADC counts and "mips" to be made. However, the change in the sensor charge collection efficiency with time necessitates an absolute calibration of each sensor/front-end with real particles (muons and/or pions [7]) in-situ in CMS at regular intervals – perhaps once per year.

This paper presents results of an analysis of 150 GeV/c muon data collected using a prototype Preshower, in order to validate the absolute in-situ calibration procedure. 150 GeV/c muons are on the most probable energy loss plateau, with a most probable energy deposit of 91 keV in the 320 μ m thick sensors. In silicon this corresponds to about 25000 electrons, or 4 fC.

The experimental setup and the details about our prototype are presented in section 2. The method of extracting the muon signal after pedestal subtraction and common mode correction is presented in section 3. In section 4 the results of a simulation based on GEANT-4 [8] are shown. It is also demonstrated that by combining the results of the data analysis and the Monte Carlo simulation, a correspondence between ADC counts and mips can be obtained.

2 Experimental Setup

At the end of September 2004, a test of a CMS Preshower prototype took place in the H4 experimental hall at CERN. The prototype consisted of two orthogonal "ladders" of sensors as described below and illustrated in Figure 1.

The CMS Preshower is based around silicon sensors measuring 63x63 mm², with an active area of 61x61 mm² and nominal thickness of 320 µm. The sensors are divided into 32 strips (~1.9mm pitch) and DC-coupled to the PACE3 mounted on a PCB hybrid. In addition to providing pre-amplification and shaping of the charge collected by the sensor, the PACE3 performs voltage sampling and storage of up to 16 triggered events in a 192-cell deep analogue pipeline. A sensor and a hybrid are attached to a ceramic plate glued to an aluminum tile to form a "micromodule" (Figure 2, left). The aluminum tiles have a wedge shape (with an angle of 3.8°) that allows overlapping of the sensors in one direction. Four micromodules for each plane were attached to aluminum baseplates as illustrated in Figure 2 (right). The electronic system motherboard (SMB) for each plane was screwed to the aluminium tiles through intermediate aluminum heatsinks. The micromodules are connected to the SMBs (for powering, data readout and control) via polyimide cables embedded in the hybrids. The combination of micromodules, aluminum baseplates and heatsinks, together with an SMB, forms a "ladder". Each of the two ladders was attached to an absorber sandwich (aluminum lead-aluminum). The thicknesses of these two absorbers were nominally $\sim 2X_0$ and $\sim 1X_0$ (as will be the case in CMS). In Table 1 the precise thicknesses, in mm and in radiation lengths, of all material layers that constructed the prototype are presented. The total thickness of the prototype was between 2.83 and 2.90 radiation lengths for normally incident particles, the variation being due to the non-uniform shape of the aluminum tiles. Figure 3 shows one plane of the Preshower prototype. From left to right it is shown: the absorber sandwich, the baseplate, the micromodules (with the silicon sensors), the heatsinks and the system mother board.



Figure 1: The Preshower 2004 beam test setup.



Figure 2: A Preshower micromodule on the left and its placement on a baseplate.

The beam had an approximately elliptical spot with dimensions about $2.3 \times 1.9 \text{ cm}^2$. The prototype was positioned so that the beam spot was roughly in the centre of one sensor in each plane (as shown in Figure 1). For the rest of the paper these sensors will be referred as simply "X" and "Y".

The precise thicknesses of the sensors used in the prototype were 303 μ m for the X plane and 309 μ m for the Y. The prototype was placed on a mechanical table and adjusted to have an inclination of 15° with respect to the beam. This corresponds to a pseudo rapidity of about η =2, the mean rapidity of the Preshower. At this angle and taking into

account the wedge shape of the aluminum tiles, the effective thickness of the silicon sensor in X was 313 μm and in Y 314 $\mu m.$

		Material	Thickness	Thickness
			(mm)	(Radiation Lengths)
First Plane	Absorber	Aluminum	2	0.0225
		Lead	10.1	1.8
		Aluminum	2	0.0225
	Ladder	Aluminum baseplate	2	0.0225
		Micromodule	4 to 7.1	0.0450 to 0.0798
		Aluminum heatsink	1.5	0.0169
		System motherboard	1	0.01125
Second Plane	Absorber	Aluminum	2	0.0225
		Lead	4.2	0.75
		Aluminum	2	0.0225
	Ladder	Aluminum baseplate	2	0.0225
		Micromodule	4 to 7.1	0.0450 to 0.0798
		Aluminum heatsink	1.5	0.0169
		System motherboard	1	0.011245
			Total	2.83 to 2.90

Table 1: The material description of the prototype.



Figure 3: One plane of the Preshower prototype. From left to right it is shown: the absorber sandwich, the baseplate, the micromodules with the silicon sensors, the aluminium heatsinks and the system motherboard. The micromodules were connected to the system motherboard via polyimide cables.

2.1 System control and data acquisition

On the system motherboards the voltage samples coming from the PACE3 chips are digitized with 12-bit precision by AD41240 ADCs. One ADC count is equivalent to 0.435 mV. PACE3 provides three samples per event per channel. With these three samples, the energy deposited by the incident particle(s) can be calculated. The digitized data from a group of up to four micromodules are collected via a digital front-end ASIC called the K-chip [9], and transmitted through gigabit optical links to the counting room. The system motherboards also incorporate a group of chips for distributing fast timing, trigger and control signals to the front-end readout ASICs, as well as for providing system monitoring and control capabilities.

Two PCs and the Control & Readout Emulator for the Preshower Electronics (CREPE [10]) were placed in the control room and used to control and read-out the prototype through 100 m long optical fibres. An asynchronous trigger was produced from the coincidence of signals from two beam scintillators. In order to improve the efficiency of the system, this asynchronous trigger was placed in coincidence with a short (~5 ns) gate synchronous with the 40 MHz clock of the Preshower electronics. The accepted triggers, after being encoded by the CREPE, were transmitted to the prototype through a special PCI card hosted in the Control PC. For each trigger received by the prototype, one data packet per motherboard was generated. The data packets were transmitted via two optical fibres at 800 Mbps to the control room, where the CREPE deserialized and forwarded them to the DAQ PC via a USB interface. The slow control signals for the two SMBs were generated by the Control PC.

2.2 Data taken

The PACE3 can operate in two modes of pre-amplification: the first mode called Low Gain (LG), covers a dynamic range of -50 to 400 mips and is the mode of operation during normal data taking. The second mode, called High Gain (HG), covers a dynamic range of -10 to 50 mips and is used for calibration purposes. The ratio of the gains of the two modes, measured in the laboratory, was found to be HG/LG=6.7.

The Preshower prototype was operated for a total of six days. During these days the following data samples were collected:

- Muon data at 150 GeV/c collected in HG
- Electron data at several energies: 20, 35, 50, 80 and 120 GeV/c. All data collected in LG
- Pion data at energies: 20, 30, 50, 80 and 120 GeV/c. All data collected in LG
- Electron data at 120 GeV/c collected in HG
- Several pedestal runs with and without beam in both LG and HG

3 Data Analysis and results

For this work the muon data and also pedestal runs collected in High Gain were used.

3.1 Pedestal Subtraction

In order to extract the total signal per sensor, the first step in our analysis is the pedestal subtraction for each channel for each time sample. The evaluation of the pedestals was done by using data from dedicated runs. These data were collected by triggering the system with an external pulse generator, without the presence of the beam. For every channel the raw values were fitted to a Gaussian distribution and the central value with its sigma were evaluated. Figure 4 shows typical pedestal distributions for one strip in X and one strip in Y, together with the results of the fit. Figure 5 shows the pedestal values and sigmas for all channels of the X and Y sensors. The average sigma was found to be 6.6 ADC counts (2.9 mV) for the X sensor and 8.5 ADC counts (3.7 mV) for the Y sensor, with a very good channel-to-channel uniformity. The sigma as evaluated above is the pedestal sigma convoluted with the common mode sigma, which is discussed in the next section. Indeed the common-mode is different for the two planes, due to a synchronization problem observed in the second plane, and is the reason why the two planes are significantly different.

Figure 4: Typical pedestal distributions for one strip in the X and one strip in the Y sensor.

Figure 5: The pedestal values and the noise (pedestal sigma convoluted with the common-mode noise) values for all strips of the X and Y sensors.

3.2 Common Mode correction

After pedestal subtraction, the signal in a channel should correspond to the total charge deposited in the given strip. In fact this is not true because a small displacement of the baseline was observed, differing on an event by event basis. This is due to external sources of noise that affect a number of strips in parallel. This type of noise is called "common mode" (CM) and requires a correction on an event by event basis.

The method of CM rejection¹ is based on histogramming the measured amplitude in all channels of a single detector. Since the occupancy of the Preshower sensors is low, a peak corresponding to the common mode will be seen, together with some "hits". The CM value was obtained by fitting this peak to a Gaussian distribution. Figure 6 shows a single event (solid line, left) and the projection of the event on the y axis (right), the fitting of the peak and the

¹ An alternative algorithm, with similar performance, was also examined [11].

extraction of the common mode value. Then again on the left it is shown the common mode corrected event (dashed line) by shifting the baseline according to the estimated common mode value.

Figure 6: On the left a typical event (solid line) and the common mode corrected event (dashed line). On the right the projection of the event on the *y* axis, the fitting of the peak and the extraction of the common mode value.

3.3 Single strip signal extraction

To evaluate the signal amplitude for every event, the three time samples were combined. After pedestal subtraction and common mode correction, the signal distributions per channel are plotted. Figure 7 shows the total signal for one typical channel in the X and Y sensors. In these plots, the pedestal peak around zero and the true signal coming from muons around 40-50 ADC counts (17.4 - 21.8 mV) are shown. By fitting the pedestal region to a Gaussian distribution the width, which is the noise N in the plots, is extracted. It is expected the signal to follow a Landau distribution, which describes the energy deposition of a minimum ionizing charged particle in a thin material, convoluted with a Gaussian, which describes the electronic noise per channel. Fitting the signal region the most probable energy (MPE) of the Landau distribution is extracted, which is noted as S in our plots. From these distributions the signal-to-noise ratios (S/N) were found to be S/N≈9 for the X and S/N≈7 for the Y sensor. The average pedestal sigma, after common mode correction, was found to be 5.4 ADC counts (2.3 mV) for the X sensor and 5.9 ADC counts (2.6 mV) for the Y sensor.

Figure 7: The total signal for one typical strip in the X and Y sensors and the evaluation of signal over noise ratios.

3.4 Total signal extraction

In some events the signal is spread amongst multiple strips, due to particles incident at strip boundaries and the inclination of the sensors with respect to the beam. The total signal per sensor, in ADC counts, is evaluated by summing the signals in all channels after applying a 5σ cut. Figure 8 shows the total charge distributions, in ADC counts, for the X and Y sensors. The data were fitted to a Landau distribution convoluted with a Gaussian one as described before. The parameters of the fit are the following:

- σ_L : Width parameter of Landau density.
- MPE: Most Probable Value of Landau density (in our case the Most Probable Energy).
- Integral: Total Area (normalization constant).
- σ_G : Width of convoluted Gaussian distribution.

The results of the fit give the MPE per sensor:

- Sensor X: 49.0±0.1 ADC counts
- Sensor Y: 43.7±0.1 ADC counts

where the above errors are purely statistical. The most probable energy deposit in the X sensor is larger by almost 10% than in Y. This difference is due to the different gains of the PACE3 chips that equipped the two sensors. The gain of the PACE3 chip on the Y sensor is smaller by about 10% than that on the X sensor.

Figure 8: The total charge distributions, in ADC counts, for X and Y sensors.

4 The GEANT-4 Simulation

In order to evaluate the true energy deposition of muons in the Preshower silicon strip sensors, a GEANT-4 simulation of the prototype was developed. Figure 9 shows a sketch of the prototype produced by the simulation program. For the material description in the simulation the data of Table 1 were used. The 150 GeV/c muon beam was incident uniformly over an area of 2.3x1.9 cm² similar to the beam test. In the simulation as secondary particles were accepted all those that were able to travel at least 0.05 mm from their production point.

Figure 9: The sketch of the prototype produced by GEANT-4.

The first step of the simulation was the evaluation of the true energy deposition per strip and per sensor. Figure 10 shows the results of the simulation on the total true energy deposition for X and Y sensors, after summing all strips. A large peak around 90 keV, a small bump around ~180 keV and a long Landau tail are observed. The bump comes mainly from secondary particles (e.g. delta rays) produced by the passage of muons through the materials around the silicon sensor.

Figure 10: The simulated total true energy distributions, for X and Y sensors with the result of our fit.

In order to evaluate precisely the most probable energy that corresponds to the large peak in the above distributions, the simulated data were fitted to a Landau distribution. In Table 2 the results of the fits on the data and

simulation are presented, where all errors are statistical. These values give the absolute energy calibration for our sensors.

	Simulation	Data	
	(keV)	(ADC Counts)	
Sensor X (MPE)	89.0±0.1	49.0±0.1	
Sensor Y (MPE)	89.3±0.1	43.7±0.1	

Table 2: Energy Calibration.

As already mentioned, in section 2, the effective thicknesses of our sensors were 313 μ m for X and 314 μ m for Y. For these thicknesses the expected [5] most probable energy deposits are 89 keV for X and 89.3 keV for Y, in perfect agreement with our simulation.

To make the simulation more realistic, electronic noise was added to every channel in the form of a Gaussian distribution with widths 5.4 ADC counts for the X and 5.9 ADC counts for the Y sensors. Using the energy calibration of Table 2 the widths correspond to energy as:

- X sensor average noise width 5.4 ADC counts corresponds to 9.8 keV.
- Y sensor average noise width 5.9 ADC counts corresponds to 12.1 keV.

The total energy deposition on every sensor was recalculated by applying a 5σ cut (the above sigmas) as was done with the real data. Figure 11 shows the data distributions of figure 8, in solid line, the simulated true energy distributions of figure 10, in dashed line, and the simulated true energy distributions with electronic noise added, with circles. An excellent agreement between data and simulation is observed. Figure 11 also shows that by including the noise in the simulation the effect of the delta rays is smeared-out. The tail in the simulation follows precisely that of the data distribution.

Figure 11: The muon total charge data distributions, in solid line, the simulated true energy distributions, in dashed line, and the simulated true energy distributions with electronic noise added, with circles.

5 Summary and Conclusions

In this work the results of the analysis of muon data collected at the energy of 150 GeV is presented. These data were collected during the test of the CMS Preshower prototype, which took place in 2004 in the H4 beam at CERN. The muon signal per silicon sensor is extracted, after pedestal subtraction and common mode correction. A GEANT-4 based simulation program for the Preshower beam test prototype was also developed. The results of the simulation are

in excellent agreement with the results of the data analysis. This demonstrates a very good understanding of our apparatus and accurate settings for the simulation.

The principle of performing an absolute calibration of the Preshower system, in terms of converting ADC counts to keV is also demonstrated. This absolute calibration will be performed at regular intervals in-situ in CMS, as described in [12].

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