The Compact Muon Solenoid Experiment
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Operational Experience with the CMS Pixel Detectors

Willard Johns for the CMS Collaboration

Abstract

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Operational Experience with the CMS Pixel Detectors

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Key words: Solid state detectors; Particle tracking detectors; Large detector systems for particle and astroparticle physics

1. Introduction

The CMS pixel detector consists of a central barrel (Fig. 1) and pairs of forward disks (Fig. 2). The three 53 cm long barrel layers (BPIX) are located at mean radii of 4.3 cm, 7.2 cm and 11.0 cm from the beamline. The two pairs of forward disks (FPIX) are placed 34.5 cm and 46.5 cm from the barrel center. To achieve optimal vertex position resolution in both the ($r\phi$) and the z coordinates an almost square pixel shape was adopted. To enhance the spatial resolution by analog signal interpolation, the effect of charge sharing induced by the large Lorentz drift in the 4 T ($\hat{z}$) magnetic field is used in the barrel. The charge sharing is also working in the FPIX using the turbine shapes of the blades. More details of the CMS detector layout and geometry can be found in reference [1].

In the fall of 2009, collisions in the CMS detector at CERN provided the data necessary to produce detailed studies of the performance of the pixel detectors. In all, proton-proton collisions at the LHC produced about $10 \mu b^{-1}$ at 900 GeV $\sqrt{s}$ and $400 mb^{-1}$ at 2.36 TeV $\sqrt{s}$. In this note we will mention preparations for proton-proton running, the current status of the pixel detectors, and some physics benchmarks determined using information from the pixel detectors.

2. Pixel Preparation and Status

During the long shutdown period from December 2008 to May 2009, we were able to remove the FPIX to repair and address issues that were discovered during the commissioning period after detector installation in the Summer of 2008. Shorted high voltage connections and bad low voltage crimps, corresponding to 2.2 % and 3.1 % respectively of FPIX channels, were fixed. Additionally, we added cooling to our analog optical laser driver, solving a temperature stability issue. After reinstallation of the FPIX in early April 2009 and recommissioning of the pixel detectors in August 2009, we determined that 99.0 % of the BPIX and 96.9 % of the FPIX were operational.

Figure 1: Half of the Barrel Pixel Detector. The three radii are clearly visible, and one gets a sense of the size of the detector from the hands in the lower portion of the photograph

The majority of the loss in the FPIX is due to a variable bandwidth loss traced to channels which share common PC board infrastructure. Another large source of lost channels is due to missing readout chips (ROCs) in the analog pulse train coming from the detector (see Fig. 3). Currently, the problem with missing ROCs has been addressed in readout firmware by the Vienna group, and we are gathering more data find a firmware solution for the lost bandwidth channels.

3. Results from Beam in the LHC

3.1. Pixel Timing

One of the first operations done with safe circulating beams in the LHC was to set the timing for the pixel detector. This was performed with information available on a short time scale in order to get good physics as soon as possible. Finding the

Figure 2: A Service Cylinder (1/4) of the Forward Pixel Detector. The plaquette (petal) visible contain 21 pixel readout chips with sensors while a reflection of the other side, which contains 24 chips, can be seen in some of the plaquettes at the top.

Figure 3: Example of a detector pathology that is being addressed in the readout. The picture contains a space where a marker for an individual Readout Chip (ROC) should be in the pulse train coming from the detector. When the pulse train is read, the read out firmware can be set to skip over the problematic spot, successfully incorporating good ROC's into the data stream for later analysis.

correct timing is important since the latch for pixel charge and time-stamp information is done with a non-zero crossing scheme, and it is only possible to save information from one beam crossing (25 ns) in the CMS pixel detector. In Fig. 4 c), one can see that small deposited pixel charge will latch at later times (T3 on the figure) than large deposited pixel charge (T1 on the figure). It is not enough though, to examine the largest charge deposited in a single pixel by a charged particle (4 b)), one should consider other pixels (a cluster) associated with the particle (4 d)) and finally, the number of pixels associated with a cluster (4 a)). The timing choice was made quickly using on-line Data Quality Monitoring (DQM) tools [2] and checked offline. In the offline analysis, it was determined that the choice made using DQM, +6 ns from the putative choice made with cosmic tracks labeled 0 in Fig. 4 a), was in the high efficiency (well above 90 %) plateau. A more sophisticated timing scan, designed to adjust the smaller module to module timing differences, will be performed in 2010.

Figure 4: Since the pixel detector samples the latched charge every 25ns, setting the threshold for the latching is critical to be efficient during the triggered time slice. The chosen time setting, labeled T2 (+6 ns), was determined by considering a multidimensional approach (see text).

3.2. Lorentz Angle Determination

By using tracks which impinge at a shallow angle to the detector plane, one can determine the average distance traveled by deposited charge vs. the average depth at which the charge was deposited [3]. In Fig. 5 b), one can imagine a track going from bottom to top in the plot, passing through a detector plane at points representing zero and 300 microns of depth, traveling nearly along the direction of the B field. Since the drift due to the electric field is perpendicular to the page, the magnetic field produces a lateral drift in the figure with a resolution of the pixel dimension. A fit in the region where the drift is a linear function of the depth is shown in 5 a). The value is in agreement with the Lorentz angle determined with cosmic muon data for the BPIX. The Lorentz angle is small for the FPIX and not nearly as interesting.

Figure 5: For tracks which graze the BPIX at a shallow angle, the drift of deposited charge vs. the depth at which the charge is deposited is shown on average in a) and for an ensemble of events in b). Notice in b), that this technique reproduces the pixel size in the drift dimension.

As seen in Fig. 5 b), tracks which graze the silicon detectors tend to leave charge in many adjacent pixels. A powerful check for the simulation is to see if the total charge in this cluster of pixels is reproduced by the simulation. In Fig. 6, the total cluster charge has been corrected in the data and the simulation to represent the cluster charge expected for a track at 90 degrees to the detector plane.

Figure 6: In a), the variation with cluster size vs η ($-\ln \tan \theta/2$) is shown for tracks in the BPIX. Points below the red line come from interactions that occur away from the nominal beam spot and are not considered for the cluster charge study [4]. In b), we show the total cluster charge from the data (histogram) and the simulation (line) for the BPIX corrected for angle. A similar agreement is seen with the FPIX (not shown).

3.3. Beam Spot and Primary Vertex Reconstruction

The width associated with the beam spot is a convolution of the resolution available with the detectors and software as well as variations in the actual location at which the protons interact (a reconstructed proton interaction point is commonly referred to as a primary vertex). In Fig. 7 we show the results of an analysis done to test the event by event primary vertex resolution. Briefly, the tracks used in finding a primary vertex are split into two equal groups (as much as possible) and a vertex is determined for each group. The two resultant vertices are compared as a function of the number of tracks in each group and compared to the simulation. The asymptotic difference seen is a factor of $\sqrt{2}$ higher than resolution expected for a primary vertex containing the number of tracks shown. It is interesting to contrast the resolution seen event by event with the beam spot widths in Fig. 7. The beam spot size is dominated by the spread in the locations where the protons interact.

3.4. Long-lived Neutral Particle (V^0) Reconstruction

A stringent test for the performance of a particle detector is the reconstruction of particle decays. In particular, long-lived particles such as the K_S^0 and the Λ^0 (V^0 's) can occur at locations other than the primary vertex, testing the ability of the reconstruction to compensate for different hit topologies, and this is especially true for the decay of a compound object such as the Ξ^- . In reconstructing the K_S^0 and the Λ^0 , fairly loose requirements are employed. For consideration, an event must have a reconstructed primary vertex, and to reduce backgrounds from beam induced splashes and halo, we require there be less than 150 tracks reconstructed in a single event. Tracks used to form candidate V^0 's must have a χ^2/DOF less than 5, must have 6 or more hits (a track moving along R through the barrel region

Figure 7: Primary interaction vertex reconstruction. In a) and b) a comparison is made to identical primary vertices fit with independent tracks for both the data and the simulation. In c) and d) we show the reconstructed beam spot in data for 900 GeV collisions. The different colored broad regions in c) and d) roughly represent one sigma. Notice that the transverse spot (x,y) is much sharper than the beam spot determination in z and that the worst primary vertex resolution suggested by a) and b) (see text) is smaller than the beam spot resolution.

could have 13 or more hits), and an impact parameter significance with respect to the primary vertex location exceeding 0.5. Oppositely charged tracks are required to have a distance of closest approach less than 1 cm, and, assuming pion masses, an invariant mass less than $1 \text{ GeV}/c^2$. This is done to remove unlikely V^0 candidates from consideration and to reduce the number of calls to the vertex fitter. After the fitter is applied, V^0 candidates must have a vertex χ^2/DOF less than 7 and a significance of separation from the primary vertex in the radial direction exceeding 15. The results of the V^0 analysis on the 900 GeV data are shown in Figures 8 and 9 for the K_S^0 and the Λ^0 respectively. Note that for the Λ^0 , we have assigned a proton mass to the higher momentum particle when forming the invariant mass. Agreement between the data and the simulation as well as between data and the Particle Data Group (PDG) [5] is fairly promising for these early results.

Figure 8: Invariant mass of the $K_S^0 \rightarrow \pi^+\pi^-$ from the 900 GeV data and simulation (Monte Carlo). The invariant mass is fit with a double Gaussian.

We combine the Λ^0 's that occur within $8 \text{ MeV}/c^2$ of the PDG mass with a charged pion having the same charge as the pion from the Λ^0 to look for charged Ξ 's. In addition to track requirements listed above, all the tracks used for the Ξ 's must

Figure 9: Invariant mass of the $\Lambda \rightarrow p\pi^- + c.c.$ from 900 GeV data and simulation (Monte Carlo). The invariant mass is fit with a single Gaussian.

have an impact parameter significance with respect to the primary vertex greater than 3, and form a $\Lambda^0\pi$ vertex with a fit probability exceeding 1 %. The mass of candidate Ξ^- 's is determined with a kinematic fit. The result of the reconstruction is shown in Fig. 10. Though in the V0 plots the relative level of background and signal seems reasonable, the amount of signal for the Ξ is underestimated in the simulation (not shown). Agreement is decent for this more complex reconstruction.

Figure 10: Invariant mass of the $\Xi^- \rightarrow \Lambda\pi^- + c.c.$ from data with fit parameters included from the simulation (MC). The invariant mass is fit with a single Gaussian.

4. Conclusions

The CMS pixel detectors are in good shape for more beam to arrive in 2010. Detector parameters and performance are in good agreement with expectations from our simulations and the PDG, and most of our lost readout channels appear to be recoverable. Fine tuning remains, but good physics results are already present due to the hard work of many people. Having mass plots that show agreement with expectations at this early stage is very encouraging and speaks well for the future.

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