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Performance of the CMS Silicon Tracker at LHC

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Abstract

After nearly two years of operation at the Large Hadron Collider with proton-proton collisions at a center of mass energy of 7 TeV, the performance of the CMS silicon tracker is reviewed. Both the status and basic properties of the pixel and the strip detector, as well as the performance of the tracking such as vertex reconstruction and b-tagging are discussed.

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Performance of the CMS Silicon Tracker at LHC

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After nearly two years of operation at the Large Hadron Collider with proton-proton collisions at a center of mass energy of 7 TeV, the performance of the CMS silicon tracker is reviewed. Both the status and basic properties of the pixel and the strip detector, as well as the performance of the tracking such as vertex reconstruction and b-tagging are discussed.

Keywords: LHC; CMS; Detector; Silicon Tracker; Performance.

1. Introduction

The Compact Muon Solenoid (CMS) experiment is one of the four large detectors operated at the Large Hadron Collider (LHC) at the CERN laboratory in Switzerland. It is a multipurpose high energy physics experiment composed of (from inside-out) a silicon pixel tracker, a silicon strip tracker, an electromagnetic calorimeter, a hadronic calorimeter, a superconducting magnet and a muon system embedded in the iron return yoke of the magnet.

The tracking detector, which is subject to this article, consists of two major parts. The first one is the pixel detector comprising about 66 million pixels arranged in three barrel layers and two endcap disks on either side. The rectangular pixels with a cell size of $100\,\mu\text{m} \times 150\,\mu\text{m}$ cover an area of about $1\,\text{m}^2$ ranging from a radius of $r = 4.4\,\text{cm}$ to $r = 10.2\,\text{cm}$ with respect to the beam pipe. The second one is the strip tracker containing about 10 million strips subdivided into about 15,000 silicon modules. The strip tracker surrounds the pixel detector, adding 10 layers in the barrel and 12 disks on either side of the endcaps to the tracking system. It ranges from $r = 25.5\,\text{cm}$ to $r = 110\,\text{cm}$ and covers a surface of about $198\,\text{m}^2$. Both rectangular (in the barrel) and trapezoidal modules (in the endcaps) are used with a typical strip cell size of the order $100\,\mu\text{m} \times 10\,\text{cm}$.

The data used in this article were collected in proton-proton collisions at

Fig. 1. Integrated luminosity vs. time delivered to (red) and recorded by (blue) CMS during stable beams at 7 TeV center of mass energy¹ (status as of October 9th, 2011).

Fig. 2. Occupancy map of reconstructed clusters attached to a particle track in the strip tracker. The white areas are modules that are not in data acquisition.

the LHC at a center of mass energy of 7 TeV. Although the total integrated luminosity recorded by CMS is about 4.17 fb^{-1} as of October 9th 2011, see Fig. 1, the presented results are based only on a subset of the whole data sample, as indicated in the dedicated plots. Nevertheless, the analyses are representative also for the current detector operation since the performance of the tracking system has not changed with time.

2. Performance of the Pixel and Strip Tracker

In the following sections, some basic properties of both the pixel and strip tracker are highlighted. If the analysis/calibration techniques are the same or comparable for the two detector parts, they will be explained only for one exemplarily.

2.1. Operational Status

The first proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ occurred in spring 2010, which means that the detector has been running for nearly two years now. During this time, few issues resulted in a permanent removal of some tracker parts from the data acquisition. The main reasons are the loss of control rings disabling the configuration of the modules, faulty front-end drivers disabling the data acquisition, closed cooling loops disabling the active cooling of the sensors and the readout electronics and thus a proper operation of the modules, and faulty power groups disabling the low or high voltage. A detailed description of the tracker layout can be found in Ref. 2.

Figure 2 shows the occupancy of reconstructed clusters which could be matched to a trajectory in a nominal collision run for the different layers of the strip tracker. The barrel region is unrolled in the $z - \phi$ plane, while the endcap disks are displayed in $x - y$ (In CMS, x is pointing to the LHC center, y is pointing to the surface and z along the beam pipe completing a right-handed frame. ϕ is the azimuthal and θ the polar angle). The white areas correspond to silicon modules not in the DAQ. Since the tracker has several redundant layers and the track reconstruction algorithms are robust enough to treat missing layers properly, these holes are not serious for the event reconstruction. In the strip tracker, a total of 97.8% of all readout channels is operational. A similar result holds for the pixel detector, where a total of 97.1% operational readout channels is achieved.

The signal-to-noise ratio (S/N) measured in the strips after correcting for the track incidence angle with respect to the module surface results in a Landau distribution as expected for thin absorbers. The $320\ \mu\text{m}$ modules have a most probable S/N of about 18, while the $500\ \mu\text{m}$ modules have $S/N \approx 22$. The numbers quoted belong to the so-called deconvolution readout mode,² which is the nominal operation and provides a weighted sum of three consecutive signal samples. In peak mode, these values are about 1.7 times larger for the sake of a worse time resolution.

2.2. Hit Efficiency and Resolution

To measure the hit reconstruction efficiency, a particle trajectory is extrapolated to the layer under investigation and a reconstructed hit compatible with the expected position is searched for. It is required that the trajectory has a valid hit on either side of this layer and that the track extrapolation does not cross the border of a silicon module but that it is well within the sensitive area of the silicon. The layer efficiency is then calculated by the number of found hits divided by the number of expected hits. In this study, known bad components such as disconnected modules are excluded in order to measure the efficiency only for the operational part of the tracker. Figure 3 shows the efficiency of all pixel layers in the barrel and endcap regions. It is well above 99%. The same measurement was done for the strip tracker, also resulting in a hit efficiency of $> 99\%$ for all layers.

The spatial hit resolution is obtained using overlapping modules in the same layer. This reduces the effects of multiple scattering and track extrapolation uncertainties, since the overlapping modules are close to each other with only little material in between. In addition, the impact of misalignment is negligible for those module pairs. Since the hit resolution depends on the

Fig. 3. Hit reconstruction efficiency³ as measured for all layers of the pixel tracker.

Fig. 4. Spatial hit resolution³ as measured for the different pitches in the strip tracker barrel. The results are shown for different cluster widths and track incidence angles.

strip or pixel cell size, the cluster width (charge sharing) and the track incidence angle, the results can be determined in different ways, binning the data for example in strip pitch and cluster width or track angle, as shown in Fig. 4. As expected, a linear dependance on the strip pitch is observed with a resolution in the barrel between $\sim 15 \mu\text{m}$ and $45 \mu\text{m}$. In the pixel detector, the resolution is about $10 \mu\text{m}$ in the transverse and $20 \mu\text{m}$ in the longitudinal direction.

2.3. Timing and Gain Calibration

The correct timing between the tracker readout and the bunch crossing is vital to achieve the best detector performance. In dedicated commissioning runs the timing of each single strip module was randomly varied around the nominal operation point so that the reconstructed signal could be studied at several delays putting the information of all modules together. In Fig. 5 such a time profile is shown for the different strip tracker parts. The signal amplitude is displayed as a function of the readout delay with respect to the nominal working point. From these measurements, a signal width of 12 ns , as expected from the deconvolution pulse shape, is obtained. The maximum should peak at zero if the nominal working point is the best. Otherwise, each deviation can be used to optimize the readout timing. Both for the strip and the pixel detector the best sampling time could be adjusted with a precision of about 1 ns .

Fig. 5. Time profile of the signal³ in different parts of the strip tracker.

Fig. 6. Energy loss dE/dx measured in the strip tracker versus track momentum.³ Kaons, Protons, Deuterons and Tritium are visible.

Another important ingredient after the adjustment of the timing is the gain calibration of the readout chains. First, a synchronization pulse of the readout chips, called tickmark, is used as measure for the electronics gain and the signals of all strip modules are normalized to a default tickmark height. Then, minimum ionizing particles are used to equalize the response of all silicon sensors by applying a particle gain calibration factor to the measured signals. Afterwards, all sensors and readout chains have equal behaviour and the measured charge can be used for particle identification exploiting the energy loss (dE/dx). Figure 6 shows the measured energy loss for kaons, protons, deuterons and tritium as a function of track momentum. The red lines correspond to Bethe-Bloch distributions, where the theoretical prediction was fitted to the proton data and then extrapolated to the other particles. The deviations at large dE/dx are due to saturation effects in the readout.

3. Performance of the Tracking

3.1. Nuclear Interactions

A way to investigate the material inside the tracker volume is the use of nuclear interactions. Either neutral or charged hadrons like pions or kaons emerging from the primary vertex can interact with the tracker material leading to secondary vertices. The abundance of such vertices is proportional to the amount of material in the respective place. Thus, their re-

Fig. 7. $x - y$ view of reconstructed nuclear interaction vertices³ for $-20 \text{ cm} < z < 20 \text{ cm}$.

Fig. 8. Primary vertex resolution in x as a function of the number of tracks in the vertex⁴ for different average track momenta $\bar{p}_T$.

construction with a slightly modified tracking procedure relaxing the track quality criteria (the tracks have usually low momentum and are not pointing to the primary vertex) can provide a picture of the material distribution similar to radiography. Such a result is shown in Fig. 7, where the position of nuclear interaction vertices is displayed in the $x - y$ plane for the innermost part of the pixel detector (the white region is an artifact of the event selection). Both the first pixel layer and the beam pipe (dark black circle) are clearly visible. A fit of these data shows on the one hand that the beam pipe is displaced with respect to the pixel layer, and on the other hand that the average beam spot position (the "x" in the picture) and the fitted beam pipe center (the "+" in the picture) are close to each other.

Another study of the beam pipe position along z for two different magnetic fields has shown that the variation of its position is very small, less than 0.5 mm in both x and y direction. This is important for a future upgrade of the pixel tracker, where the innermost layer will be even closer to the beam pipe compared to the current layout. Further details about nuclear interaction reconstruction in CMS can be found in Ref. 5.

3.2. Vertex Reconstruction

A crucial ingredient for a proper event reconstruction and interpretation is the vertex reconstruction. Its performance can be measured in terms of primary vertex resolution and efficiency. The resolution is obtained using a

split method where all tracks belonging to a reconstructed vertex are split in two sets. To do so, the tracks are first ordered in descending momentum and afterwards they are assigned alternately and randomly to one or the other set. Finally, two vertices are reconstructed independently for the two track collections and their distance in both x , y and z is measured. The gaussian width of the respective distribution is quoted as primary vertex resolution, as shown in Fig. 8 for the x coordinate. It can be seen that the resolution strongly depends on the number of tracks attached to the vertex and on the average track momentum $\bar{p}_T$. A vertex with 30 tracks and $\bar{p}_T > 1.2$ GeV has a resolution of about $20 \mu\text{m}$. The vertex reconstruction efficiency is computed with a similar splitting method and performing a tag and probe analysis afterwards. As for the resolution, the efficiency depends on the number of tracks and is close to 100 % if more than two tracks with $p_T > 0.5$ GeV are contained in the vertex.

In addition to the vertex itself, the track impact parameter (IP), which is the point of closest approach of a track with respect to the vertex, is an important measure used for example in b-tagging algorithms. The impact parameter resolution can be obtained by removing the track under investigation from the vertex fit and calculating afterwards its distance from the vertex in the three space dimensions. This measurement is a convolution of the IP resolution, the vertex resolution and the contamination with gen-

Fig. 9. Transverse impact parameter resolution⁴ as a function of the track ϕ for different track momenta p_T .

Fig. 10. b tagging efficiency⁶ for a specific b identification algorithm as a function of the jet p_T . The lower panel shows the Data/MC scale factors.

uinely displaced particle tracks. The plain IP resolution, which depends on the track momentum and direction (different material budget in different $\eta - \phi$ regions) was measured to be about $20\,\mu\text{m}$ in the transverse and $40\,\mu\text{m}$ in the longitudinal direction for tracks with $p_T > 10\,\text{GeV}$. In Fig. 9 the transverse IP resolution is shown for different momenta as a function of the track azimuthal angle ϕ . For low track momenta, 18 peaks corresponding to 18 cooling pipes in the first pixel layer are clearly visible. In addition, a slight $\sin\phi$ modulation can be observed, which is due to the displacement of the beams with respect to the innermost tracking layer (compare Fig. 7). A detailed description of vertex and IP reconstruction can be found in Ref. 4.

3.3. *b*-Tagging

Different algorithms and working points are in place to identify jets originating from *b* quarks in CMS (see Ref. 6 for details). Their performance strongly depends on the ability to reconstruct secondary vertices and track impact parameters. The track counting algorithm for example counts the number of tracks in a jet that have an IP significance above a certain threshold. This provides a discriminator to tag *b* jets with either high efficiency or high purity. In Fig. 10 the *b* tag efficiency for a specific algorithm (Track Counting High Efficiency Loose) and two different measurement methods ("PtRel" and "System8") is shown as a function of the jet p_T . An efficiency of roughly 85 % is achieved for jets with $p_T > 80\,\text{GeV}$. The mistag rate for light flavour jets is for the same tagger measured to be about 15 % for $p_T \approx 80\,\text{GeV}$ jets.

4. Conclusions

After nearly two years of operation, the CMS silicon tracker has an operational fraction of about 97 % of the readout channels. The recorded luminosity of $\sim 4.17\,\text{fb}^{-1}$ is high quality data with the tracker fulfilling both the performance and the physics requirements. Local hit and global track reconstruction provide excellent precision needed for vertex and *b* jet identification.

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