The Compact Muon Solenoid Experiment
Conference Report

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23 September 2010 (v2, 11 October 2010)

Tracking and Vertexing Capabilities of the CMS Tracking Detector with the First LHC Data

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Presented at *Pixel2010: International Workshop on Semiconductor Pixel Detectors for Particles and Imaging*

Tracking and Vertexing Capabilities of the CMS Tracking Detector with the First LHC Data.[☆]

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Abstract

The CMS experiment relies on an all-Silicon based tracking detector for the reconstruction of charged particles in the hostile radiation environment of proton-proton collisions at the CERN LHC collider. In this article are outlined measurements of the tracking, vertexing and b-jet identification performance recently estimated from data measured by CMS at the center of mass energy of 7 TeV. The excellent tracking performance rely, in particular, on the great pixel detector tracking capabilities, which are exploited in many contexts such as seeding, b-jet identification, beam-spot monitor, etc... The pixel stand-alone tracking and vertexing capabilities are here shown for a particular application: the beam-spot monitor.

Keywords: Pixel detector, strip detector, tracking, vertexing, b-jet identification, beam-spot, resolution, efficiency.

1. Introduction

CMS [1] is one of the two general purpose experiments at the CERN LHC collider [2]. The p-p collisions at LHC, at the unprecedented luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and center of mass energy of 14 TeV, will produce in the order of 20 superimposed events at a rate of 40 MHz, resulting in thousands of tracks in the acceptance of the tracking system per bunch crossing. In order to ensure full functionality after exposure to 10 years of LHC operation, the CMS tracking system relies on radiation-hard Silicon sensors and front-end electronics. To facilitate the measurement of the curvature of high momentum particles, the tracking system is embedded in a solenoidal magnetic field of 3.8 T and the high granularity of the sensors results in a low occupancy even for the extremely high flux of charged particles expected. Despite the care that has been taken throughout the design of the tracker, the final material of the CMS Silicon tracking system exceeds the originally expected value. A drawback of the current detector material is that electrons lose energy from hard bremsstrahlung radiation and charged hadrons suffer elastic and inelastic nuclear interactions with the tracker material (up to $\sim 10\%$ of charged pions experience destructive inelastic interactions before crossing the minimum number of sensitive layers necessary to measure the curvature), representing a very challenging task for pattern recognition and track reconstruction. To meet the physics requirements of CMS in the innermost, radiation hostile region, the high-precision and low-background tracking is based on a Silicon pixel detector (see Fig. 1 for the tracker layout). The Silicon pixel detector has $\sim 66 \text{ M}$ channels, it covers $\sim 1.1 \text{ m}^2$ of sensor area and it's

divided in three barrel layers, whose the innermost is at $\sim 4.3 \text{ cm}$ of radius, and four endcap disks (two on each side). The Silicon strip detector has $\sim 9.3 \text{ M}$ channels, it covers $\sim 200 \text{ m}^2$ of sensor area and it's divided in ten barrel layers and twenty-four endcap disks (twelve on each side). Currently the operation fraction of the tracking detector is: 98.3% of the Silicon pixels and 98.1% of the Silicon strips.

Figure 1: Layout of 1/4 of the CMS tracking detector. In the central region the tracking is performed by a Silicon pixel detector, the rest of the tracker is based on Silicon strips. The whole system provides full coverage up to $|\eta| \leq 2.5$. In red (blue) are shown the single (double, i.e. stereo) modules.

2. The tracking algorithm

The core of the CMS software for reconstruction of charged particles is divided in four stages [3].

Seeding: the first stage provides the seeds based on pairs or triplets of hits which are selected to be compatible with the interaction region and a lower p_T limit. Due to the

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low occupancy and the unambiguous 3-dimensional position information, the pixel layers provide generally the best seeding. In the region of the tracker at high $|\eta|$, pixel and strip measurements are combined together to extend the geometrical acceptance of the pixel detector and provide an efficient seeding up to $|\eta| \sim 2.5$.

Pattern recognition: the second reconstruction stage, based on the combinatorial Kalman filter, uses a first estimate of the track parameters, calculated from the seed, to collect the full set of measurements associated to the same charged particle. Starting from the current parameters, the trajectory is extrapolated to the next layer of the tracker and compatible hits are selected based on the χ^2 between the predicted and the measured positions. The Kalman update of the predicted parameters with each of the compatible hits provides a new set of trajectory candidates. Many candidates are built in parallel until the hits on the last layer of the tracker are added. Eventually, ambiguities are resolved between tracks sharing a substantial number of points.

Outlier rejection and final fit: the third stage consists of a tool to remove outlier measurements that are associated to a track candidate during the trajectory building, and a least-squares fit in the form of a Kalman filter for the final estimation of the track parameters and errors. A “forward” fit proceeding outwards from the interaction region removes the approximations used in the track finding stage and provides an optimal estimate of the track parameters at the outside of the tracker. A “backward” fit in the opposite direction yields the estimate of the track parameters in the interaction region and in combination with the forward fit at each of the intermediate layers.

Quality filter: in the fourth stage a quality selection is applied to the set of reconstructed trajectories in order to reject candidates that are likely to be ghost tracks. In addition to requirements on the number of hits, the χ^2 of the fit and the energy, tracks are selected also according to their compatibility with the reconstructed vertices.

In order to loosen as much as possible the selection criterion while maintaining a reasonable fake rate, the sequence of four track-reconstruction stages is run iteratively six times. During the first two iterations the seeding is based on pixels and tracks with relatively high momentum are reconstructed. All tracker measurements that are fully compatible with, and only with, the tracks reconstructed in the iteration are “locked” and they are not used to identify additional trajectories. During the third step, again based on pixel seeds, tracks with relatively low momentum (short tracks) are reconstructed. During the last three steps mixed pixel-strip and strip-only seeds are used to reconstruct tracks which are not found by pixel-only seeding (i.e. coming from long-living particles). The iterative tracking allows to measure the momentum of charged particles across a five order of magnitude range: 100 MeV/c - 1 TeV/c and the fake-track rate is 2-3% (5%) for Monte Carlo simulated $t\bar{t}$ events reconstructed in the barrel (endcap).

Figure 2: Distributions of di-muon invariant mass (data points) for tag muons paired with passing (first plot) and failing (second plot) probes in collision data at $|\eta| \leq 1.1$. The mass is calculated using only the muon detector information for all probe muons.

3. Tracking efficiency

The method used for measuring the tracking efficiency in data is the so-called *tag-and-probe* technique, in which the J/ψ di-muon resonance is reconstructed requiring stringent quality requirements on one muon, referred to as the *tag*, and then comparing the relative efficiency of two different selection criteria on the second muon, referred to as the *probe*. The probe muons are reconstructed using information only from the muon detector system, and then passing and failing probe muons are defined as those that are or are not matched to tracks in the Silicon tracker, respectively. The measured efficiency (ϵ) is computed from the spectra in Fig. 2 in the following way: $\epsilon = (\# \text{ passing probes}) / (\# \text{ passing probes} + \# \text{ failing probes})$. The measured efficiency determined in this way can be expressed in terms of the true tracking efficiency ϵ_T , the track-muon matching efficiency (i.e. the capability of matching a Silicon track to a probe muon) ϵ_M , and the probability of fake (random) matches ϵ_F as:

Figure 3: The first plot shows the p_T resolution measured on data and Monte Carlo. The gray band in data represents the error on the fitted function for data computed from the errors on the parameters. The second plot shows the p_T spectrum of the muons and of the di-muons from the J/ψ decay.

$$\epsilon = \epsilon_T \epsilon_M + (1 - \epsilon_T \epsilon_M) \epsilon_F \quad (1)$$

The probability of fake matches can be measured directly in data using the following technique. Before applying the track-matching selection to the probe muon, all Silicon tracks that, when combined with the tag muon, give an invariant mass near the J/ψ mass, are removed. The rate of probe muons passing the matching criteria after removing such tracks is then a measurement of the probability of getting a fake match between probe and track. Inverting Eq. 1 one can obtain the combined probability of reconstructing a track and matching it to a probe muon, see Eq. 2.

$$\epsilon_T \epsilon_M = \frac{\epsilon - \epsilon_F}{1 - \epsilon_F} \quad (2)$$

ϵ_M has been estimated to be 100% while ϵ_F has been evaluated from data to be $\sim 10\%$. Given that the track-muon matching criteria has been defined to be fully efficient, Eq. 2 can be interpreted as the tracking efficiency for muons. For $|\eta| \leq 2.4$ the tracking efficiency for muons on data is $98.8 \pm 0.5\%$ and on Monte Carlo is $99.2 \pm 0.1\%$. For more details on the analysis see Ref. [4].

4. Tracking p_T resolution

Thanks to the relatively small width of the J/ψ mass resonance $\Gamma(J/\psi) \sim 90$ keV (with respect to its invariant mass $M(J/\psi) \sim 3097$ MeV), the p_T resolution is estimated from the decay $J/\psi \rightarrow \mu^+ \mu^-$ by expressing the width as a function of the kinematics of the two muon tracks. The results for the transverse momentum resolution are shown in Fig. 3, for more details on the analysis see Ref. [5].

Figure 4: The first (second) plot shows the measured resolution of the track transverse impact parameter as a function of p_T (η). Black and red symbols correspond to results from data and simulation, respectively. Filled and open symbols correspond to results from data and simulation, respectively.

5. Track impact parameter resolution

The resolution on the track impact parameters is extracted from data evaluating the impact parameter with respect to the primary vertex position. The width of the distribution of the track impact parameters (transverse and longitudinal) depends on the track impact parameter resolution and on the vertex position resolution. The vertex position uncertainty is estimated

from simulation and it can be de-convolved in order to extract the actual impact parameter resolution of the tracks. Figure 4 reports the results on the transverse impact parameter resolution as a function of p_T and η , showing good agreement between data and simulation for a wide range of p_T and η . For more details on the analysis see Ref. [6].

Figure 5: Primary vertex resolution as a function of the number of tracks in the vertex.

6. Primary vertex resolution

The primary vertex algorithm is based on an adaptive Kalman filter: after a first coarse approximation of the vertex location, the Kalman filter updates the position track-by-track (tracks are weighed according to their longitudinal distance to the vertex). The primary vertex efficiency and resolution are measured with the data-driven method based on vertex-splitting: the tracks used in the vertex are split into two different sets, which are then fit independently with the adaptive vertex fitter. In the computation of the efficiency the two vertices are identified as *tag* and *probe*. The efficiency is calculated by how often the probe vertex is matched to the original vertex given that the tag vertex is

reconstructed and matched to the original vertex. The primary vertex efficiency is hence estimated to be $\sim 100\%$ for vertices made out of at least 5 tracks. To calculate the resolution the distribution of the position difference of the two vertices is fitted with a Gaussian function, whose sigma is $\sigma = \sqrt{2} \cdot \sigma_{vtx}$, σ_{vtx} being the actual vertex resolution (see Fig. 5). For more details on the analysis see Ref. [6].

Figure 6: Fits of the muon p_T^{rel} distributions to b and light-flavour templates for muon jets that (first plot) pass or (second plot) fail the b-jet identification algorithm (the results shown concern the “Simple Secondary Vertex” algorithm).

7. b-jet identification efficiency

The b-jet identification efficiency is estimated from data by fitting the p_T^{rel} (p_T with respect to the jet axes) distribution of muons in semi-leptonic jets ($p_T \geq 31$ GeV/c; $|\eta| \leq 2$). The b-jet fraction is then extracted from the fit using distribution templates based on Monte Carlo. For the “Simple Secondary Vertex” b-jet identification algorithm set to “High-Purity” (i.e. requiring a secondary vertex made out of at least 3 tracks) and choosing the value of the discriminant (i.e. three-dimensional flight distance) in such a way that the acceptance of light-flavoured jets estimated from Monte Carlo is 0.1%, the b-jet

identification efficiency on data is estimated to be $20.3 \pm 1.5\%$ and on Monte Carlo $20.7 \pm 0.2\%$ (see Fig. 6). For more details on the analysis see Ref. [7].

8. Pixel stand-alone tracking

Up to now it has been presented the performance of the CMS tracking system as a whole. On the other hand, the pixel detector on itself is already able to provide very good information on tracks and vertices which are extremely useful to elaborate a fast high-level trigger (b-jet identification, τ -reconstruction, etc. . .), indeed pixel stand-alone tracking is simpler and faster than the general tracking. Pixel tracks are made out of triplets of pixel hits. The track parameters are obtained by: a fast circle fit with the conformal mapping method; solving analytically the straight line equation in the Z-azimuthal angle plane. Pixel vertices are made out of pixel tracks using the adaptive Kalman filter algorithm. Preliminary results on the studies of the pixel stand-alone tracking and vertexing are very promising, in this article will be shown the performance of the beam-spot monitor application which is entirely based on the pixel information.

Figure 7: Beam-spot (BS) coordinate distribution as a function of time during an LHC fill where a luminosity scan was performed. No points are plotted when an insufficient number of tracks or vertices were reconstructed. A comparison between the pixel (red circles) and the general tracking (blue triangles) based beam-spot monitors shows they provide very consistent results.

8.1. Beam-spot monitor

The beam-spot parameters are measured by using a log-likelihood estimator based on the unbinned 3D Gaussian fit to the pixel vertex positions. The beam-spot measured quantities

Figure 8: Beam-spot (BS) widths as a function of time during an LHC fill. A comparison between the pixel (red circles) and the general tracking (blue triangles) based beam-spot monitors shows they provide very consistent results.

are: 3 coordinate position; 3 widths; 2 tilt angles (in the X-Z and Y-Z planes), for more details on the analysis see Ref. [6]. The plots in Fig. 7 and Fig. 8 shows that the pixel and the general tracking based methods give consistent results and are able to track well the movements of the beam. Collecting ~ 200 vertices the pixel based beam-spot monitor gives the following resolutions on the beam-spot parameters:

- X and Y position error: $\sim 4 \mu\text{m}$;
- Z position error: $\sim 3 \text{ mm}$;
- X and Y width error: $\sim 6 \mu\text{m}$;
- Z width error: $\sim 2 \text{ mm}$;
- tilt angles error: $\sim 10^4 \text{ rad}$.

The timing performance of such application were tested on minimum bias data at center of mass energy of 2.3 TeV. The High-Level Trigger menu without the beam-spot monitor application takes in average 23.62 ms. The pixel beam-spot monitor adds just $\sim 0.54 \text{ ms}$, therefore it's well suited to be used in the High-Level Trigger environment which gives access to the whole statistics without a pre-filter of the events.

9. Conclusions

After collecting $\sim 100 \text{ nb}^{-1}$, a good understanding of tracking efficiency, momentum and impact parameter resolutions and

vertex reconstruction performance has been acquired. The great CMS tracking performance is strictly related to the great pixel detector tracking capabilities, which are exploited in many contexts: seeding, b-jet identification, beam-spot monitor, etc. . . As the integrated luminosity collected by CMS increases, tracking performance is estimated from data with increasing detail.

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