The Compact Muon Solenoid Experiment
Conference Report

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26 November 2014 (v2, 01 December 2014)

The CMS tracker and vertexing before and after the upgrade

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Abstract

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Presented at *IEEE-NSS-MIC-2014 2014 IEEE Nuclear Science Symposium and Medical Imaging Conference*

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Abstract—The CMS detector’s core is composed of the largest silicon detector ever built. This tracker consists of a hybrid pixel detector with 66 million channels and a 200 m silicon strip detector with 10 million read out channels. Thanks to its fine granularity, it can perform excellent tracks and vertices reconstruction, essential objects in physics analyses. However, the next LHC upgrades will expose CMS to a higher number of simultaneous inelastic collisions per crossing (pile-up events). In order to maintain such performances, the pixel detector will be upgraded. In this contribution, we describe the current tracker performances, driven by the resolution and efficiency of the tracks and vertices reconstruction. We will then highlight the significant role of secondary vertices in physics analyses, especially for the identification of jets coming from the hadronization of a b quark, fundamental in new particles and new physics searches. Finally, we will describe the foreseen upgrades of the tracker and emphasize the expected performance improvements in a high luminosity and high pile-up environment.

I. INTRODUCTION

The Compact Muon Solenoid (CMS) detector is one of the four detectors located around the Large Hadron Collider (LHC). CMS records the products of proton-proton collisions since 2010, where it started at an energy $\sqrt{s} = 7$ TeV and then run at $\sqrt{s} = 8$ TeV. During the early run, $\sim 23 \text{ fb}^{-1}$ of data have been taken, with an average of twenty-one interactions per crossing (Pile-Up events, PU). In 2013, the first long shutdown (LS1) is occurring, in order to qualify the LHC for collisions at $\sqrt{s} = 13$ TeV (and even 14 TeV, if possible). A second LS is programmed in 2018, and in between, the Phase 1 upgrade will be held. On one hand, the LHC upgrade foresees to increase the interaction rate, and on the other hand the goal of the CMS upgrade is to improve the on-line event selection to increase the amount of available data for physics analyses. To prevent technical failures due to the aging material, repairs and improvements will also be done. The second run of data taking (Run II) is planned to start in Summer 2015 and stop in 2017. During this period, the LHC is expected to provide around $75 - 100 \text{ fb}^{-1}$. In this conference note, we describe the CMS tracker, the tracking and vertexing procedures, and their related performances in Sect. II. In Sect. III, we develop the theoretical background for the identification of secondary vertices, a technique called “ b -tagging”. The upgrade of the tracker, along with its consequences on the b -tagging performance, is presented in Sect. IV. Conclusions are finally drawn in Sect. V.

Fig. 1. Layout of the pixel and the SiStrip detectors in the CMS tracker.

II. THE CMS TRACKER

The innermost component of the CMS detector consists of a silicon pixel tracker made of three barrel layers (BPIX) and two forward/backward disks (FPIX) [1]. Thanks to the 3-dimensional capability brought by these pixelated detectors, it is feasible to measure the properties of charged particles crossing the detector with single hit resolution between $10 - 20 \mu\text{m}$. To achieve optimal vertex position resolution, the detector is paved with $285 \mu\text{m}$ thick, almost square-shaped, silicon sensors with a pixel cell size of $100 \times 150 \mu\text{m}^2$. The pixel detector is composed of 66 million pixels, clustered into 1440 modules, in order to cover a pseudo-rapidity range up to $|\eta| < 2.5$. The resulting signal is recorded using ~ 16000 read-out chips (ROC), bump-bonded to the detector modules. Around the pixel detector is the SiStrip detector, the largest silicon tracker ever built: it has an active area of 200 m^2 and its dimensions are of 5 meters long with a diameter of 2.5 meters. It is the first ‘all silicon’ central tracker with around 9.6 million electronic channels. There are ten layers in the barrel region, four Inner Barrel (TIB), six Outer Barrel (TOB) and ten+three discs in the inner disks (TID) and end caps (TEC). The entire design of the CMS tracker can be seen in Fig. 1.

A. Hit and track reconstruction

The regularly used pattern recognition and track reconstruction for charged particles follows an iterative method [2]. First, the seeding starts from the pixel layers: from hit triplets or pairs compatibles with the beam-spot, seeds are created while those which are not compatible are discarded. Then, the estimation of the trajectory is performed: each seed is propagated to the successive layers, using a Kalman filter technique. It allows the reconstruction of the trajectory even if there is a missing hit in a layer. The propagation continues

until there are no more layers or there is more than one missing hit. Finally, the track is fitted: further hits are added and the track parameters estimation is updated for each new hit obtained. A final fit is performed to obtain the track parameters at the interaction point. It is an iterative tracking: the higher quality tracks are reconstructed first, allowing to remove their associated hits with great precision. Then the procedure is repeated so that lower quality tracks are evaluated from the cleaned pack of hits, until there are no more hits.

B. Vertexing

Afterward, vertex reconstruction can be achieved [2]. It is essential to properly determine the primary vertex, where tracks from the main interaction originate. The candidates are selected by clustering reconstructed tracks, based on the z -coordinate of their closest approach to the beam line. An adaptive vertex fit is then used to estimate the vertex position with a sample of tracks that are compatible with an origin close to the interaction region. Among the primary vertices found, the one with the highest p_T is selected as a candidate for the origin of the hard interaction. The primary vertex reconstruction efficiency is close to 100%. The vertex resolution measurement is performed with a data driven method: the vertex is split in two, then an independent fit is done on the two resulting vertices and their difference in position gives the resolution. This resolution strongly depends on the number of tracks, as it is shown in Fig. 2.

C. Performance

Since its start-up in 2009, more than 95 % of the pixel channels of the CMS detector are active during the data taking, allowing good detector performances [2][3]. Thanks to its fine granularity, the pixel detector can provide high quality seeds for off-line track reconstruction algorithms. The hit efficiency is determined by the quantification of missing hits on reconstructed tracks during LHC runs. It is estimated to be above 99 %, as it is shown on Fig. 3. The pixel thresholds increase with the integrated luminosity, reducing the cluster size and affecting the resolution. Recalibrations are then performed during LHC technical stops to partially recover from this degradation (see Fig. 4).

III. B-TAGGING

Long lived particles, such as b quarks, fly into the beam pipe before decaying, forming a secondary vertex (see Fig. 5, left panel). These particles are very challenging to properly identify, but they remain of a main interest for physical analyses [4]. Several algorithms have been developed to identify jets arising from the hadronization of a b quark, called b -jets. Tracking-dependent variables may be used to identify them, such as the impact parameter (IP), defined as the closest distance between a track and the primary vertex. The geometric definition of the IP can be found in Fig. 5 (right panel). More sophisticated algorithms are also available, but they rely on secondary vertex reconstruction, which is a rather challenging and less reliable process in comparison with primary vertex reconstruction. Besides, since most vertex finders

Fig. 2. Primary vertex resolution along the z -axis (top) and the x -axis (bottom) as a function of the number of tracks coming from the vertex for jet-enriched data and for minimum bias data events.

Fig. 3. Hit finding efficiency as a function of the integrated luminosity, for every component of the pixel detector.

Fig. 4. Pixel resolution in the r - Φ plane as a function of the integrated delivered luminosity. The recalibration phases are indicated in green.

Fig. 5. Left: diagram of the main properties of a b-jet. Right: geometric construction of the track impact parameter.

are sensitive to both primary and secondary vertices, a vertex filter is necessary to ensure the selection of, and uniquely, secondary vertex candidates. The discrimination between the two vertex orders is based on the distance between a vertex and the beam line (or a primary vertex if one has already been reconstructed).

During the earliest LHC run, excellent b-tagging performances have been achieved [4] [5]. For 70 % chances of tagging a b-jet, there is only a chance of 1 % to misidentify a non b-jet as a real b-jet. An example is shown on Fig. 6 and such performances is a lower limit to be also achieved for the upcoming Run II. Indeed, the b quarks identification will ultimately help to characterize the final state of LHC events, and will potentially reveal new physics. Since one of the main goal of CMS during the Run II period is to identify the coupling mechanism between the newly discovered boson and the b quark, the highest b-tagging performance have to be reached. However, as it was stated before, b-tagging is highly tracker dependent, meaning that the tracker upgrade will be decisive.

IV. TRACKER UPGRADE

In its original design, the LHC was planned to operate at $1 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$ with 25 ns bunch spacing, where approximately 25 PU events would occur. Such goal should be achieved soon after the first of the three long shutdown

Fig. 6. B-tagging efficiency as a function of the misidentification rate for several b-tagging algorithms used in CMS at $\sqrt{s} = 7 \text{ TeV}$.

foreseen by the current LHC calendar. The CMS experiment was designed to run under this operating scenario but must be prepared to operate with an average pile-up events of, at least, 50 (with a non-null possibility of significantly higher values). The detector performances must be maintained in order not to impact resulting detections; it is the aim of the forthcoming CMS upgrade [4]. If the current tracker is not upgraded, as the luminosity will increase, the buffer size and readout speed of the current pixel ROC will lead to a non-tolerated dynamic inefficiency of 4 %. Another reason for upgrading the tracker is that the three hit coverage of the detector is not completely hermetic, leading to 10 – 15 % inefficiencies at $|\eta| < 1.5$, and larger inefficiencies in the region where $1.5 < |\eta| < 2.5$. It can be seen in Fig. 7 how the track fake rate (top panel) and the tracking efficiency (bottom panel) evolve, as pile-up increases with the current and with the upgraded detector, confirming the need of an upgrade.

The pixel detector will be completely removed during the technical stop foreseen in 2016/2017 [4]. It will be replaced by a new, high efficiency, low mass detector with four barrel layers (against the current three barrel layers) and three forward/backward disks (two are currently operated) to provide a four-hit pixel coverage up to $|\eta| < 2.5$ (see Fig. 8, top panel). Moreover, as it is shown in Fig. 8 (bottom panel), the first layer will be placed closer to the beam line, allowing a more precise measurement of the track IP (which is crucial for b-tagging, as previously mentioned). The addition of the fourth outer layer of the new pixel detector will play a significant role: in the case the inner layers of the inner barrel are compromised, the fourth layer would largely offset the losses, especially at high PU. Besides, this layer will be closer to the outer tracker, implying a reduction of the fake tracks rate. On top of that, it is also planned to try to reduce material costs using new cooling systems and/or new beam pipes.

A. Impact on b-tagging performance

The improvements arising from the new detector will lead to a better pattern recognition, increasing efficiencies and decreasing fake rates, lowering dead-time/data-loss and ex-

Fig. 7. Average track fake rate (top figure) and average tracking efficiency (bottom figure) as a function of the average PU, using the current detector (blue dots) or the Phase I upgrade detector (red dots).

Fig. 8. Layout of the Phase I upgrade detector compared to the current tracker.

Fig. 9. Performance of the Combined Secondary Vertex b-tagging algorithm for jets with $p_T > 30$ GeV, in a top quark pair sample of events, with an average PU of 50. In black and blue markers are performances with current detector and, in red, with the Phase I upgrade (red markers).

tending the lifetime of the detector. As a consequence, it is expected to see a significant improvement in the tracking at high PU, with direct consequences concerning b-tagging performances: an improvement of the order of 30 – 40 % in the transverse and longitudinal IP is foreseen, and the resolution on the vertices is expected to be improved by about 20 %, leading to a measurable overall gain on the b-tagging performance [4] (see Fig. 9).

V. CONCLUSION

Great performances have been achieved by the CMS tracker during Run I, allowing excellent track and vertex reconstruction. For physical analyses, it is important to consider the goodness of the reconstruction of primary vertices coupled with the capabilities to achieve secondary vertices reconstruction of the same quality. Their identification is of a prime interest for the new physics expected to be discovered during Run II, since the procedure is highly tracker dependent. So far, good performances have been reached, but to maintain similar achievements at higher energies, an upgrade of the tracker is needed. With a complete pixel detector replacement foreseen in the horizon 2016 – 2017, a significant improvement of the b-tagging method should be reached.

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