Operation and Performance of the CMS Silicon Tracker

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Abstract. The CMS silicon tracker is the largest silicon detector ever built. It consists of a pixel detector with 66 million channels and a 200 m^2 area silicon strip detector with 10 million read out channels. The presentation describes the operation of this detector in 2010 and 2011 at the LHC during proton-proton as well as heavy ion collisions. Reconstructed photon conversions and nuclear interactions are used to evaluate the material description of the tracker. The resolution and efficiency of the track and vertex reconstruction are measured with data and compared to the results from simulation. Finally, an outlook is given to the considerations towards an upgrade of the CMS silicon strip tracker for the operation at the high luminosity upgrade of the LHC. Beside the challenges to develop sensors withstanding the high radiation field, CMS is exploring options and developing solutions that would allow to include tracking information into the Level-1 trigger of CMS.

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LAYOUT OF THE CMS SILICON TRACKER

At CERN, the European Laboratory for Particle Physics in Switzerland, the Large Hadron Collider LHC started operation in 2009. In the first years, the LHC produces proton-proton collisions at a centre of mass energy of 7 TeV with an envisaged luminosity of up to $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. A running period colliding lead ions took place at the end of 2010 and is also foreseen for the end of 2011. To exploit this machine several experiments went into operation to analyze the collisions, among them the multi-purpose experiment CMS.

The CMS detector [1] consists of several shells of different detector elements. Particles created in the collisions in the very centre of the detector will first traverse the 'Tracker', a system of silicon sensors designed to provide a precise and efficient measurement of the trajectories of charged particles.

This Tracker is geometrically divided into several substructures (see figure 1): the pixel detector very close to the interaction point and the Silicon Strip Tracker (SST) consisting of the inner barrel detector (TIB), the inner discs (TID), the outer barrel (TOB) and the two end cap detector systems (TEC). The overall length of the Tracker is 5.4 m with an outer diameter of 2.4 m.

The pixel detector consists of three cylindrical layers of hybrid pixel modules surrounding the interaction point at radii of 4.4, 7.3 and 10.2 cm. Two discs of pixel modules on each side complement the pixel detector. Figure 2 shows a graphical view of the

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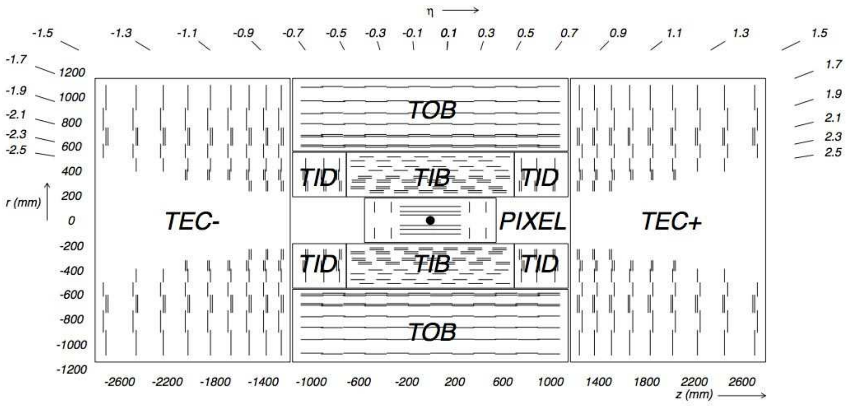

FIGURE 1. Schematic cross section through the CMS tracker. Each line represents a detector module. Double lines indicate back-to-back modules which deliver stereo hits.

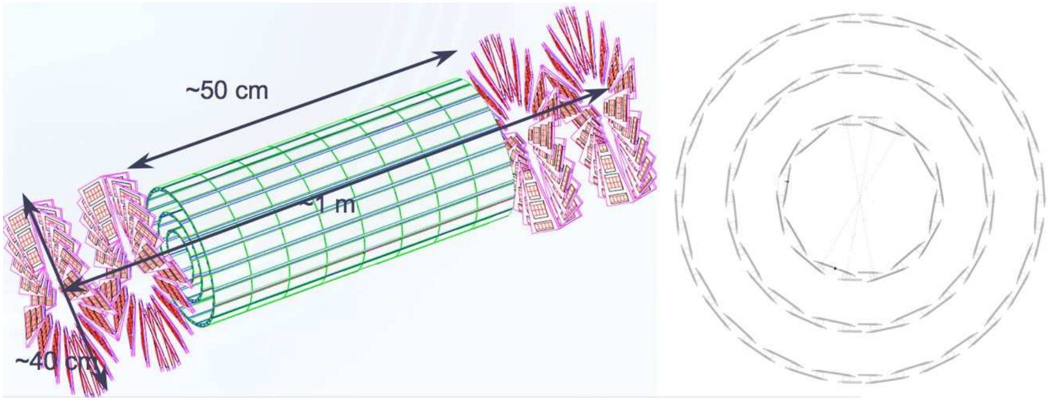

FIGURE 2. View of the pixel detector (left) and cut through the central part (right).

pixel detector and a cut through the central part.

The pixel detector modules are built as hybrid pixel assemblies containing the components described in the following. The active silicon sensors are realized on high-resistance n-substrate, with an implanted pn-junction and a pixel cell size of 100x150 μm^2. Indium bumps are deposited onto the sensors for subsequent connection to the readout electronics. The readout electronics consists of custom ASICs fabricated in a commercial 0.25 μm process. Each chip processes the signals from 4160 pixels. Up to 16 chips are bump bonded onto one sensor wafer. On top of the sensor and chip assembly is a low mass multilayer printed circuit board holding an additional control chip and other components. Further details of the technology used for the pixel detector can be found in [2].

The SST surrounds the pixel detector and adds 10 layers of strip detectors in the central region (4 TIB, 6 TOB). In addition, 3 small and 9 large detector discs (TID and TEC) are located on either side [3]. The basic construction element of the silicon strip tracker is a module. The supporting frame of a module is made of carbon fibre or graphite. Glued onto the frame is a Kapton layer to electrically isolate the frame from

TABLE 1. Some key parameters of the SST construction.

Area of active silicon	$\approx 200\ \text{m}^2$
Number of silicon sensors	24,244
Different sensor designs	15
Number of modules	15,148
Mechanically different module designs	27
Number of strips	$\approx$ 9,300,000
Number of electronics channels	$\approx$ 9,300,000
Number of readout chips	$\approx$ 73,000
Number of wire bonds	$\approx$ 25,000,000

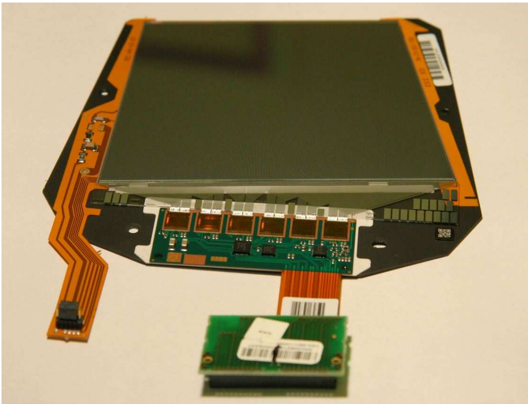

FIGURE 3. A module for the TEC subdetector of the CMS silicon tracker.

the silicon and to provide the electrical connection to the silicon backplane. Depending on the module type, silicon strip sensors with different strip pitches, sensor thicknesses (320 μm and 500 μm) and material resistivities are used [4]. A ceramic multilayer circuit holds the readout chips and the auxiliary chips. A glass pitch adapter is mounted between the hybrid and the first silicon sensor to match the different pitches of the sensor strips to the chips' input pads. Wire bond connections between the individual channels of the readout chips and the pitch adapter, between the pitch adapter and the first sensor, and where applicable, between the two sensors provide the electrical connections. The modules of the TIB, the TID and the four inner rings of TEC consist of only one silicon sensor, whereas the modules of the TOB and the three outer rings of TEC hold two sensors. All barrel modules are of rectangular shape. The modules of the discs have a wedge shape in order to form rings. Figure 3 shows a production module of the second ring of the TEC. The first two layers in TIB and TOB, the first two rings in TID and the rings 1, 2, and 5 in TEC are instrumented with double-sided modules. These are made of two independent single-sided modules, mounted back to back and rotated by 100 mrad with respect to each other. Table 1 lists some numbers illustrating the overall dimensions of the SST.

The SST was completed at CERN using the tracker integration facility - a clean room with facilities to assemble, connect and operate parts of the tracker in turn. The sealed SST was finally transported to the experimental area and lifted down into the cavern.

On December 15, 2007 the tracker was inserted into its final place inside the experiment CMS. The pixel detector was completed independently and, after the installation of the LHC beam pipe in CMS, the pixel detector was inserted into the tracker in April 2008.

DETECTOR OPERATION 2010 AND 2011

Pixel Detector Operation

The pixel detector was operated in 2010 and 2011 with a coolant temperature of +7.4°C. With increasing irradiation of the sensors the temperature will have to be decreased for future runs. In the winter stop of 2010, a test with a coolant temperature of -10°C was performed and the calibration of the temperature dependent digital-to-analog converters was demonstrated successfully.

The pixel detector has to withstand the highest particle rate densities and is therefore also exposed to the heaviest radiation damage of all CMS subdetector systems. During p-p collision, on average 3000 pixels are hit per bunch crossing and read out with a Level-1 trigger rate close to 100 kHz. During the Pb-Pb run of the LHC in 2010, the trigger rate was only about 150 Hz whereas the number of pixels hit per event was up to 30,000 for central collisions. These condition changes made it necessary to update the firmware of the pixel Front End Driver (FED) several times to cope for example with the different event sizes.

During the 2010 and 2011 operation, 96.9% of the Read Out Chips (ROCs) were fully functional. Some problems, e.g. with slow analogue outputs, could also be fixed by firmware updates. Other problems, such as bad modules, were repaired during the winter shutdown end of 2010. The fact that the pixel system can be accessed for maintenance independently from the SST has paid off in this respect.

The CMS data-taking efficiency was about 92% with the pixel detector contributing only about 6% to the inefficiency.

The pixel hit efficiency was calculated as the ratio of found pixel hits to the number of expected hits. The expected hits were determined from the extrapolation of charged tracks to the pixel modules and from a search for a hit within a defined area around the impact point. Excluding known defect pixels, the hit efficiency in both the barrel and the end caps is above 99%. The spatial resolution of the pixel modules is shown in figure 4 for both the transverse and the longitudinal coordinate. The result as a function of the cluster size is in very good agreement with Monte Carlo simulations as can be seen in the figure.

Strip Detector Operation

The SST is a very large system and hence the operation is very complex. The cooling of the SST uses C_6F_{14} which is forced by two cooling plants through 180 lines. The temperature in 2010 and 2011 was set to 4°C which is sufficiently low taking into account the low radiation load accumulated so far. During the 2010 operation, two lines were leaky and had to be closed. Nevertheless, the leakage rate increased over

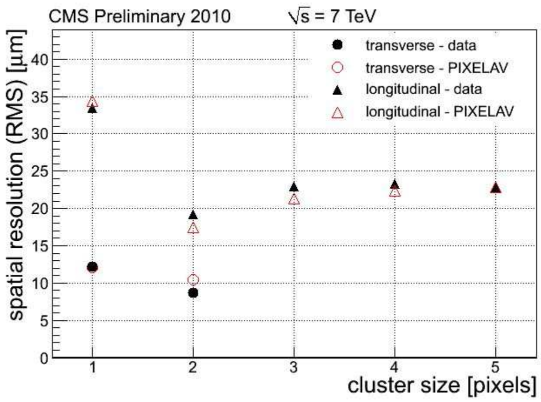

FIGURE 4. Transverse and longitudinal pixel spatial resolution as a function of the cluster size. Full dots and triangles are measurements, open symbols are simulations.

time reaching unacceptable levels. In the 2010 winter stop, an intervention took place resulting in the closure of three additional lines. The present low leak rate of 0.7 kg/day is acceptable and stable over months. The modules connected to the closed cooling loops show slightly higher temperatures but can be operated safely.

The power supply system for the SST has to provide up to 60 kW electrical power. 2000 power supply units provide the low and high voltages needed by the detector modules. The location of the power supplies is within the LHC cavern and, as a consequence, the access is limited to periods when the LHC machine is stopped. The failure rate in 2010 was about 1% and is decreasing during 2011.

The status of the functionality of the SST channels at the end of August 2011 shows 97.7% of fully working channels, stable over time. The SST has been designed with high redundancy, and therefore the low number of malfunctioning channels has no influence on the physics performance of the detector.

The data aquisition of the SST has been running very stably and it has collected high-quality physics data with an uptime of greater than 98.5% during the p-p runs in 2010 and 2011.

The signal-to-noise ratio of the different strip modules depends on the strip geometry, the thickness of the sensors, and on the module design (single- or two-sensor modules). The signal-to-noise values for tracks perpendicular to the silicon plane (most probable value of the distributions) have been measured to be 18.5, 19.4, 23.9, 18.4 and 22.4 for TID, TEC (thin sensors), TEC (thick sensors), TIB and TOB modules, respectively. The hit efficiency of the SST was measured to be 99.9% in an analysis excluding known defect modules. The strip sensor hit resolutions were measured using tracks passing through regions with sensor overlaps. The results are shown in figure 5 for tracks perpendicular to the sensor surface as a function of the strip pitch for various sensor types. All measured spatial resolutions are well below the binary resolution given by the strip pitch.

More details on the operational performance of the pixel detector and of the SST can be found in references [5] and [6].

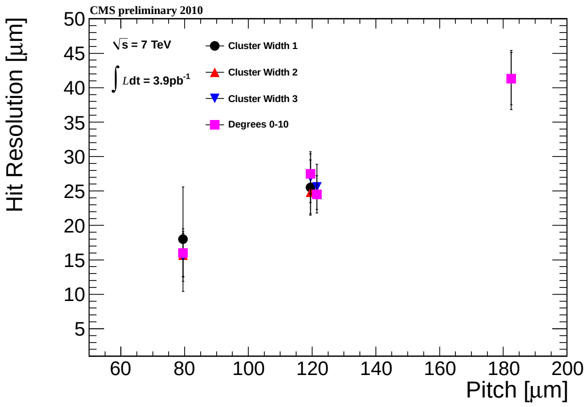

FIGURE 5. Measured spatial resolution for strip sensors of TIB (strip pitches 80 μm and 120 μm) and TOB (strip pitches 122 μm and 183 μm).

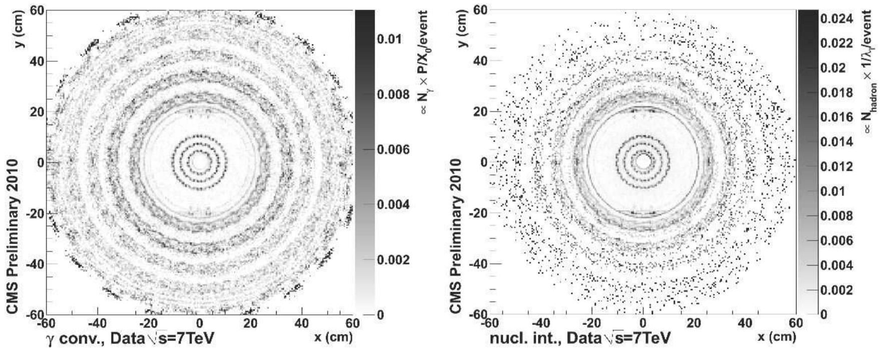

FIGURE 6. Maps of the x-y cross section of the reconstructed material distribution for photon conversions (left) and for nuclear interactions (right) in data (x-y bin size 0.5 x 0.5 cm^2).

TRACKER PERFORMANCE

The overall tracker performance is largely affected by the material of the tracker itself. The tracker material modifies the trajectories of charged tracks through bremsstrahlung, photon conversion, nuclear interactions, multiple scattering, and energy loss. It is therefore of utmost importance to have a precise description of the material distribution in order to correctly treat all these effects in the detector simulation. To check the consistency of the tracker simulation with the material distribution of the real detector the vertices of photon conversions and nuclear interactions are reconstructed using data (see figure 6) [7]. A quantitative comparison of data and simulation is shown in figure 7 for several radial bins corresponding to specific substructures. Overall, the observed relative agreement is about 10%, except for a localized larger discrepancy in one area.

As an example for the tracker performance the measured impact parameter resolution is shown in figure 8 as a function of the track p_T [8]. The resolution is better for higher track momenta as expected, as these particles are less deflected by multiple scattering

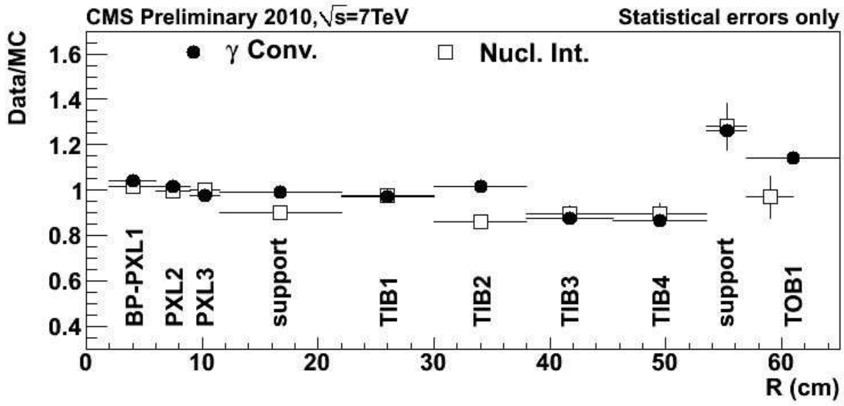

FIGURE 7. Ratio of the number of candidates in data and in simulation for photon conversion reconstruction (black circles) and for nuclear interaction reconstruction (open squares) for radius bins embracing the major Pixel barrel or Tracker substructures, only statistical errors are shown.

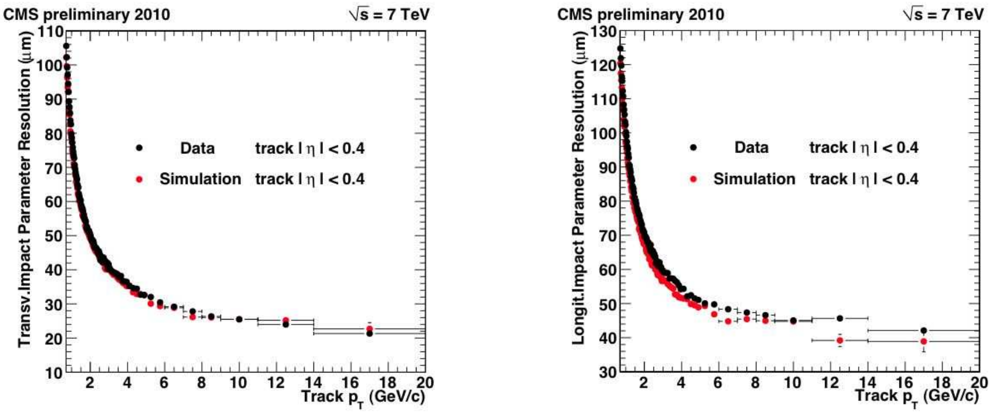

FIGURE 8. Measured resolution of the track transverse (left) and longitudinal (right) impact parameter as a function of the track p_T. Only central tracks with $|\eta| < 0.4$ are considered. Black and red symbols correspond to results from data and simulation, respectively.

while traversing the material of the beam pipe. The comparison with the simulation proves the excellent understanding of the detector.

An important figure of merit of the CMS tracker is the resolution of the muon transverse momentum. This parameter depends on the precise knowledge of the material distribution, the tracker alignment, the knowledge of the magnetic field, and on the reconstruction algorithm. Figure 9 shows the measured transverse momentum resolution for muons originating from the decay of J/ψ mesons from early collision data. These muons have on average a momentum of a few GeV/c. At this energy the reconstruction of the muons in CMS is dominated by the Tracker data and is therefore an excellent tool to study the performance of the Tracker. The muon resolution is found to be in quite good agreement with simulation, except for the transition region from the barrel to the

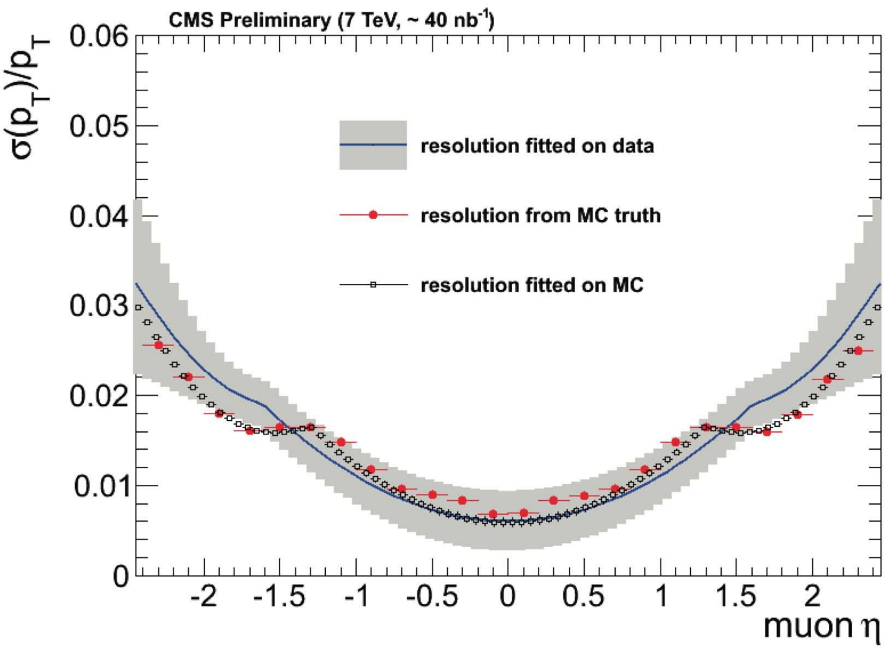

FIGURE 9. Resolution of the muon transverse momentum as measured with about 40 nb^{-1} of integrated luminosity (black line) compared to the Monte Carlo resolution computed from Monte Carlo truth (red points) and from a fit (black squares). The gray band represents the error on the fitted function for data computed from the errors on the parameters.

end caps where a difference of about 5% is observed. More details on this study can be found in reference [9].

FUTURE UPGRADE OF THE SST

The present CMS strip tracker is designed to be operated for a lifetime of 10 years at the LHC design luminosity of 10^{34} cm^{-2}s^{-1}. The lifetime of the silicon detector is limited by the radiation induced change of the doping concentration in the substrate and by the subsequent need for an increase of the operating voltage. The planning of the CERN management foresees to upgrade the LHC machine in steps towards a possible luminosity of about 5x10^{34} cm^{-2}s^{-1} at around 2020. At this luminosity the particle flux emerging from the interaction point exceeds the capabilities of the present CMS tracker and of the present CMS trigger system. As a consequence of both the predicted end of the tracker lifetime and of the need for a more performant tracker at the increased luminosity, CMS is planning to construct a new tracker [10].

The challenges for the construction of this new tracker are manifold:

- The upgraded tracker has to perform up to an integrated luminosity of about 3000 fb^{-1}. To withstand the enormous radiation doses the development of new sensor materials is required, especially for the innermost regions.
- The particle fluxes are expected to be an order of magnitude larger compared to the

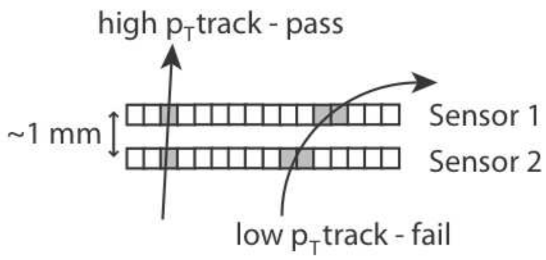

FIGURE 10. Concept of a double sensor module capable to reject low p_T tracks.

present tracker. In order to keep the channel occupancy low, smaller cell sizes are needed what leads to an increase in channel numbers.

- The new Tracker has to provide data for the Level-1 trigger decision logic. This is mandatory for CMS to maintain the overall Level-1 trigger rate within 100 kHz.
- Despite the higher number of channels the power dissipation must not be increased compared to the present tracker.
- The amount of material in the tracker volume, e.g. in the support and cooling structures, has to be significantly reduced.

On all these listed aspects research and development is ongoing within the CMS collaboration. To cope with the expected data rate and with the requirement to provide trigger Level-1 input, a hierarchical baseline strategy is followed [11]. Detector modules are being developed which are able to discriminate the particles' p_T by two closely spaced (≈1 mm) silicon modules. The strong CMS magnetic field bends the trajectories of charged particles and the angle of the through going particle is therefore a function of p_T (see the sketch in figure 10 for explanation). Rejecting particles below a p_T of 1-2 GeV/c locally reduces the amount of data to be processed significantly. Two layers of such modules ("double stacks") may then be mounted spaced by about 1-2 cm. The combined information from both layers is then used to find track elements, named "tracklets". Tracklets from several double stacks are then combined to form Level-1 tracks. The performance of various tracker geometries with different numbers of double-stack layers and of simple tracking layers is under study using simulation tools developed for this purpose.

SUMMARY

CMS has commissioned the worlds largest silicon detector. The LHC collision data collected with the CMS tracker have demonstrated the excellent performance of this scientific device. The measured performance parameters are in good agreement with simulation, proving that the detector is well understood. The reliable reconstruction of tracks and vertices provides an excellent input for the CMS physics analysis. Despite the fact that this detector has only started its operation, the development of its replacement has already started. The challenges ahead for the new tracker are huge and hence a long development time is foreseen to construct the new device in time for the LHC high-luminosity operation phase.

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