CMS Conference Report

13 December 2005

The CMS Silicon Strip Tracker

P. Azzurri, on behalf of the CMS Tracker Collaboration

Scuola Normale Superiore, piazza dei Cavalieri 7, 56100 Pisa, Italy

Abstract

With over 200 square meters of sensitive Silicon and almost 10 million readout channels, the Silicon Strip Tracker of the CMS experiment at the LHC will be the largest Silicon strip detector ever built. The design, construction and expected performance of the CMS Tracker is reviewed in the following.

Presented at EPS 19th Nuclear Physics Divisional Conference
New Trends in Nuclear Physics Applications and Technology,
Pavia (Italy) September 5-9, 2005

1 The CMS experiment at the LHC

The Compact Muon Solenoid (CMS) experiment is scheduled to start data taking in summer 2007 at the Large Hadron Collider (LHC) at CERN where 7 TeV proton beams will collide head on at a center-of-mass energy of 14 TeV. The LHC is projected to reach a peak luminosity of 10^{34} cm^{-2} sec^{-1}. The LHC will operate with a bunch crossing rate of 40 MHz (25 ns) and at peak luminosity about 20 interactions are expected per crossing, producing on average 2000 charged particles per crossing. Severe radiation conditions are expected, corresponding to a flux of 10^{18} hadrons per year from interaction points.

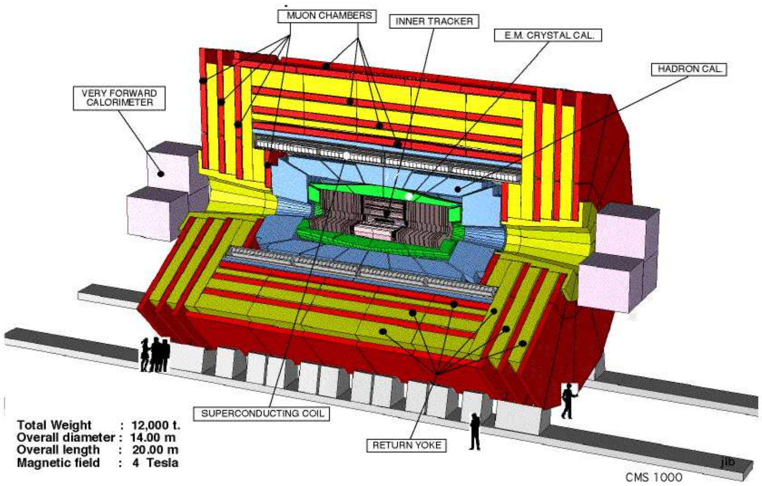

Figure 1: A three-dimensional view of the CMS experiment and it's various subdetectors. The Silicon Strip Tracker will be placed in the inner part of the experiment, around the beam line and the interaction point, immersed in the 4 Tesla solenoidal magnetic field.

The complete CMS experiment will be a cylinder 20 m long and 14 m in diameter, with 12,000 tons of total weight. CMS will be composed of an external high precision muon spectrometer in the return yoke of a 4 Tesla superconducting solenoidal coil cylinder 12.5 m long and 6 m in diameter. The coil will contain a sampling brass hadron calorimeter, a lead-tungstate scintillating electromagnetic calorimeter, and, closest to the beam line, an internal Silicon Tracker, as shown in figure 1.

2 The CMS Inner Tracker

The CMS Silicon tracker [1] is composed of different substructures. Closest to the Interaction Point (IP) is a Silicon Pixel detector, with about 66 million 100×150 μm^2 pixels arranged at distance of 4 to 11 cm from the beam line on a cylindrical barrel and end-caps structure with total length of 92 cm, this detector will not be further described in this paper. The Silicon Strip detectors are divided in the inner barrel part (TIB), the inner disks (TID), the outer barrel (TOB) and outer end-caps (TEC). The layout of the Tracker substructures is sketched in figure 2.

As it can be seen in figure 2, the TIB and TOB systems are composed respectively of four and six concentric layer barrel shell structures. The TID system is made of three disk structures on each side, each divided in three concentric rings, while the TEC is made of nine disk structures on each side, each made of four to seven rings. The whole inner tracker will be housed in a cylindrical support structure with a diameter of 2.4 m and a total length of 5.6 m. An active thermal screen will keep the tracker volume at at temperature of -10°C and at 30% relative humidity, to avoid the reverse annealing of the silicon sensors, and to protect the silicon detectors from the increased leakage current coming from radiation damage. A cooling system will extract the 60 kW power that the front-end electronics dissipate.

3 Tracker Modules

The Tracker will be composed of 15,148 detector modules distributed among the four sub-systems (TIB, TID, TOB, TEC) described above. Each module has one or two silicon sensors, for a total of 24,244 sensors. Modules are supported by a carbon-fiber or graphite frame, with a kapton layer to isolate the silicon and provide the electrical connections to the sensor backplane. The readout and auxiliary chips are housed on a ceramic multiplayer hybrid, and a glass pitch adapter between the hybrid and the sensor, brings the signals from the sensor strips to the readout input pads. An example of a TIB detector module is shown in figure 3.

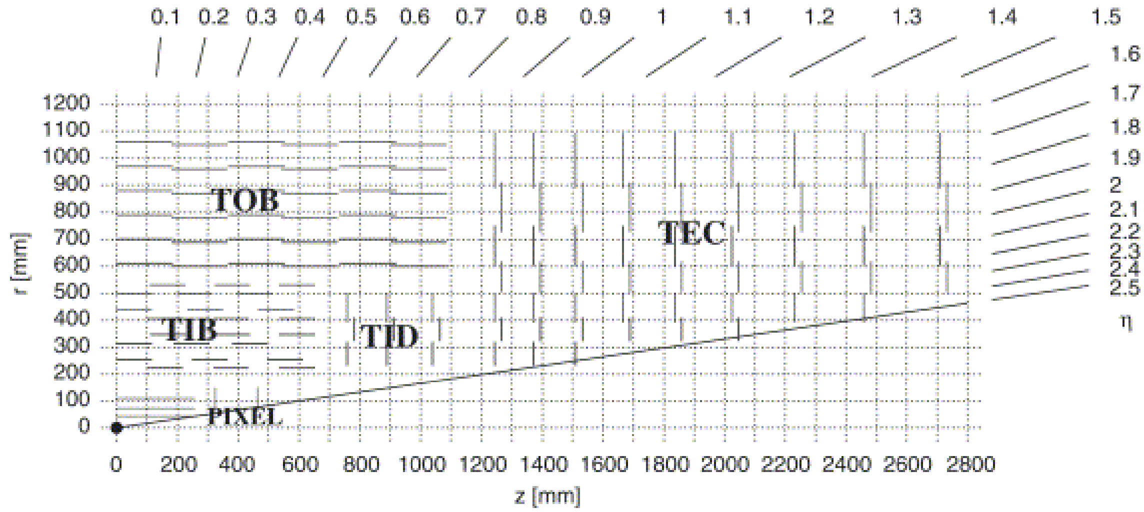

Figure 2: Projected view of one quarter of the CMS tracker layout in the $r-z$ plane, showing the pseudorapidity coverage. Segments represent detector modules, lighter ones are single sided and darker ones double-sided.

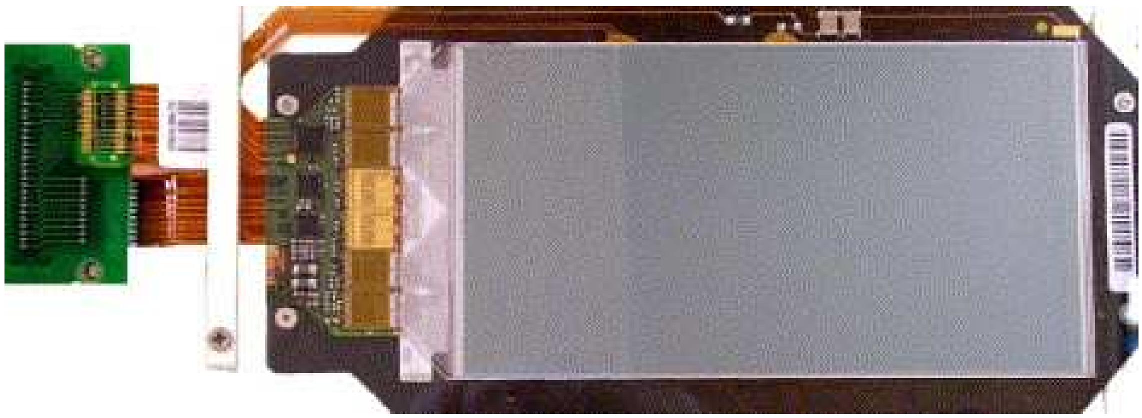

Figure 3: A module for the CMS tracker inner barrel (TIB). The external black structure is the carbon fiber frame. The larger rectangular central grey area is the silicon sensor, surrounded by the kapton circuit for insulation and bias. At the left edge of the sensor, in light grey, is the glass pitch adapter, bringing the signal to the front-end hybrid and chips, on the far left of the frame, and to the cable out of the module on the left.

The front-end hybrid hosts four or six APV25 readout chips. The APV25 chip has 128 amplifying channels and is designed in 0.25 μm CMOS technology to be radiation hard with low noise and a fast signal readout [2]. The signal shaping with a de-convolution filter has a shaping time of 25 ns. Further a pipeline buffer of 192 columns can store LHC bunch crossings over 4.8 μs, to allow a decision from the CMS first level trigger system.

In each module large number of micro-bond wire connections are necessary to bring signals between (i) the sensors, if two are present, (ii) the sensor and the pitch adapter, and (iii) the pitch adapter and the readout hybrid. For all modules, a total of approximately 25 million wire bonds are necessary, and are made with the help of programmable automatic micro-bonding stations.

The CMS tracker modules come in a variety of shapes and dimensions. The outer modules of the TOB structure and of the three outer TEC rings, hold two sensors, all the other TIB, TID and four inner TEC rings, have a single sensor. As for the modules shapes, the TIB and TOB barrel modules are rectangular, while the TID and TEC disc modules have a wedge shape, in order to form rings. A sketch with the different shapes and dimensions of the tracker modules is shown in figure 4

Roughly half of the modules in the tracker layout are in fact double-sided modules, made of two independent single-sided modules glued together back-to-back with a relative rotation of 100 mrad respect to each other. This allows a determination of the ionization in the z coordinate in the barrel modules, and in the r coordinate in the disks, i.e. the determination of a full space point where the double sided modules are present. These double-sided

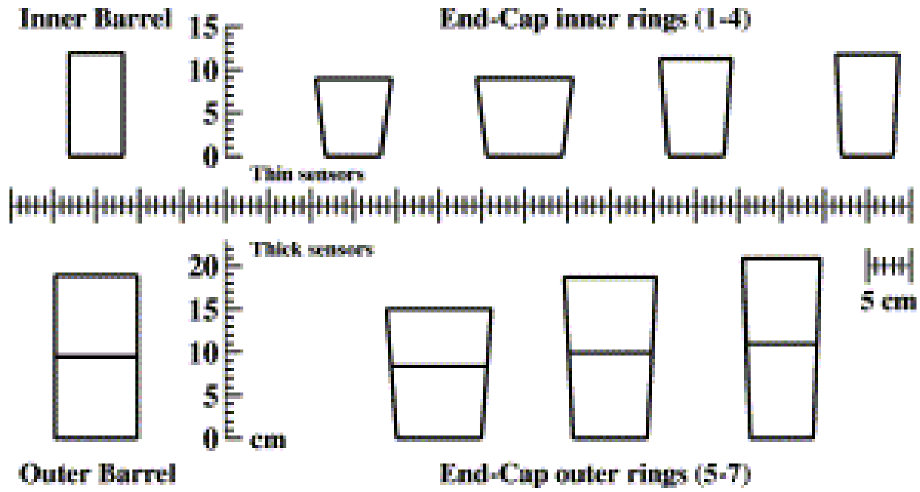

Figure 4: Shapes and dimensions of the CMS tracker modules mounted on the Inner Barrel (TIB, upper left), Outer Barrel (lower left) and End-Caps inner (upper right) and outer (lower right) rings .

modules are mounted in the first two layers of the TIB and TOB, in the first two TID rings, and in rings 1, 2 and 5 of the TEC structure.

4 Tracker Sensors

The design of the CMS tracker sensors is rather simple, and has been studied in collaboration with industry to ease the mass production needed to build such a large silicon system. This is why only single-sided sensors are produced. Also the 15 different sensor types finally designed for the tracker make use of the maximum area available on the 6 inch wafers commonly used in sensor production lines.

The choice of the material is of n-type silicon with 512 or 768 p^+ single sided strips, of resistivity in the 1.25-7.5 KΩ cm range, with thickness of 320 μm or 500 μm, and $<100>$ crystal orientation. Design choices have been driven by many factors, and most of all radiation hardness.

Silicon is inherently radiation hard and the most important macroscopic effects of irradiation are the increase of the leakage current, that is linear with the radiation fluence, and the conversion of the n-type bulk into p-type bulk with the increase of the carrier concentration. As a consequence the bias voltage needed for depletion increases with the radiation damage, and this can lead to the detector current breakdown. For these reasons the inner parts of the tracker (TIB, TID and the four innermost TEC rings) have been instrumented with sensors of lower resistivity (1.25-3.25 KΩ cm) and standard 320 μm thickness, while the outer parts of the tracker have higher resistivity (3.5-7.5 KΩ cm) and thicker 500 μm sensor wafers.

The lower resistivity of the inner sensors will require higher operational voltages at startup (300V) but this will give more margin for the bulk type inversion caused by the damage from higher radiation levels closer to the interaction point. In this way even at the end of 10 years of operation, even the sensors that are most exposed to irradiation will require maximum operational voltages, after the bulk inversion, similar to the startup ones. The choice of the lattice orientation $<100>$ is also driven by radiation hardness considerations as it minimizes the surface damage and thus the increase of inter-strip capacitance after irradiation [3].

The inter-strip distance (strip pitch) in different sensors varies from 80 μm to 205 μm, but the ratio of the strip pitch to the strip width is 0.25 for all types. The strips width, pitch and length are chosen in order to minimize inter-strip capacitance, optimize the resolution and occupancy, and assure high voltage operational stability. The evolution of strip length and pitch with the radius of the detector position to the beam line is shown in figure 5. In the inner 320 μm thick sensors the strip lines cover a surface of 0.1 cm^2 per channel, in the outer 500 μm thick sensors strip lines cover 0.4 cm^2, this leads to an expected occupancy around 1% with the expected LHC track densities at high luminosity.

Strips are AC coupled to aluminum readout lines of 1.2 μm minimum thickness, and the coupling insulation is achieved with two layers of dielectric SiO_2 and Si_3N_4. The high voltage operational stability of the module is enhanced by the metal overhanging of the aluminum readout strips over the p^+ implants, and by introducing a

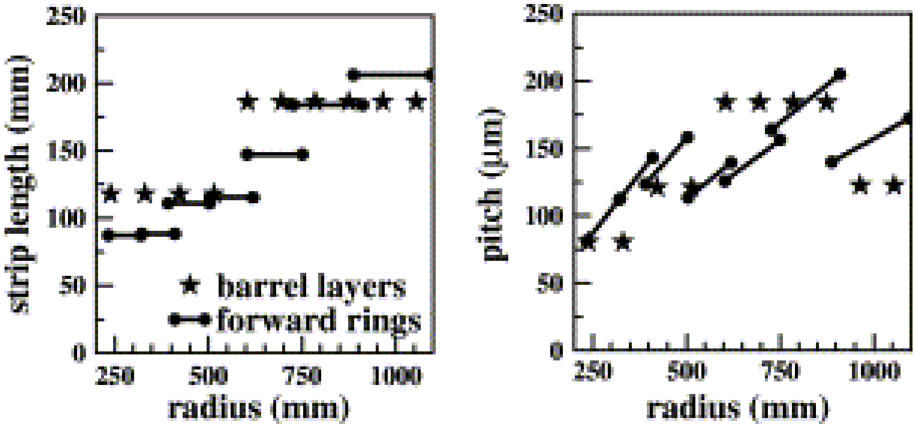

Figure 5: Silicon sensors strips length and pitch as a function of the module radius to the beam line. Markers are barrel sensors, lines are end-cap ring sensors.

floating p^+ guard ring around the p^+ bias ring, to avoid high field near cut edges. The bias ring is connected to the p^+ strips with an array of polysilicon resistors, each 1.5±0.5 MΩ. DC pads in direct contact with the p^+ strips implants are available for testing, while two series of AC pads are available for the wire micro-bonding of each strip to the readout electronics. A sketch view of a typical corner of a CMS tracker silicon sensor is shown in figure 6.

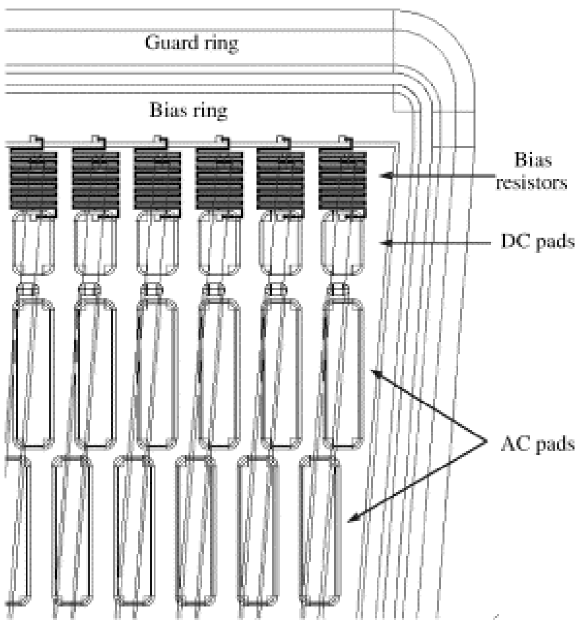

Figure 6: View of a corner region of a wedge-type silicon strip sensor for the CMS tracker. The bias ring runs around the sensor and brings the depletion voltage to the p^+ strips through the bias resistors. The floating guard ring runs around the bias ring and protects the sensor at high voltage operations. The series of DC pads are in direct contact with the p^+ strip implants, while the two series of AC pads are in contact with the superficial aluminum strips, and serve for the wire bonding connections to the readout electronics.

5 Sensor production and quality assurance

The production of the CMS silicon sensors has been awarded to two companies, Hamamatsu Photonics (Hamamatsu, Japan) for thin (320 μm) sensors and ST Microelectronics (Catania, Italy) for thick (500 μm) sensors. The acceptance test for the quality assurance of produced sensors have been performed in four stages. The first stage of measurements is done at the manufacturing centers, while the following three are done at CMS centers that perform a full sensor *quality control*, a *process control* on test structures and *irradiation test* on a small fraction of sensors.

The sensor quality control, performed at Karlsruhe, Rochester, Perugia, Pisa and Vienna, include (i) an optical inspection of possible sensor damages, (ii) a scan of the sensor capacitance and leakage current as a function of the bias voltage up to 550 V, (iii) a measurement of strip parameters with a 400 V bias. The process controls, performed at Florence, Strasbourg and Vienna, are another set of ten standard electrical measurements to be compared to the specifications and to monitor the production. The irradiation test are performed at Louvain and Karlsruhe on small samples of sensors at -10°C up to the final doses expected in CMS, and serve to confirm the expected radiation hardness of the detectors.

Both the quality and process control test have revealed different problems in the sensor production and feedback has been given to the manufacturing companies to correct the production faults. Just recently (2005) the full production of all fully qualified silicon sensors for the CMS tracker has been accomplished.

6 Module production and quality assurance

The assembly of the 15,232 modules of the tracker is performed in a semi-automatic way by gantry stations. Such stations can localize specific markers with a pattern recognition program and, using pickup tools, can position and glue the module components with precisions better than 10 μm in positioning and better than 5 mrad in alignment. The six CMS assembly stations operate at a rate of 90 modules per day.

After the assembly stage, the modules are sent to the bonding and testing centers, where the sensor strips are bonded to the front-end hybrid channels, and different electrical test are performed [4]. The test procedures include (i) an optical inspection of possible damages, (ii) a scan of the sensor leakage current with bias voltage up to 450 V, (iii) pedestal, noise and pulse shape measurements for each channel in four different data acquisition modes, (iv) a LED illumination test of the sensor, to spot open or pinhole channels. Channels with shorts or pinholes can cause readout problems; they are therefore disconnected and become open channels. At the end of the test each channel can be flagged as bad because it is too noisy, open, dead or has other readout problems.

Currently (December 2005) over 10,000 modules have been assembled and tested at CMS production centers, and about 3.5% of produced modules do not pass the quality requirements. A module fails the requirements on the leakage current behavior if either it has a current larger than 10 μA at 450 V, or if it shows a resistive/breakdown I-V curve at lower voltages. About 1% of produced modules fail these I-V requirements. Another 0.5% of produced modules have a number of bad channels greater that 2% of the total channels, and are classified bad for strips, while the total number of bad strips in good modules is at the level of 0.1%. Problems with the front-end hybrid electronics cause another 0.5% of produced modules to be classified as bad. The remaining bad modules (1-1.5%) have other assembly problems but a good fraction of these can probably be recovered.

After the standard full electrical tests modules go through a *long term* test where they are thermally cycled in the -20°C to +25°C range for 72 hours in a dry box and readout in operating conditions are simulated. Only 0.1% of produced modules are seen to fail at this stage of testing. All the bad modules not passing the quality requirements are collected in four specialized repair centers for further diagnosis and possible recovery.

7 Integration and test of larger structures

As qualified modules are built they are also mounted on their final structures at the integration centers. At present hundreds of modules have been assembled on their supporting mechanics and subsystems, like the one pictured in figure 7. Coming out from the modules front-end hybrids, the data are converted into optical signals, travels in optical fibers to the back-end, where they are converted back into electrical signals, digitized and processed.

Figure 7: One half of the inner barrel layer three shell assembled and cabled at the INFN Pisa integration facility. Single-sided silicon strip modules are mounted on both the internal and external surfaces of the barrel.

Substructures like the one in figure 7 are also tested inside large cold rooms, where the functioning of the cooling, controls and data acquisition of large substructures can be tested in normal operational conditions. Starting at the beginning of 2006 the substructures assembled and tested at the integration centers will be transported to the CERN Tracker Integration Facility (TIF), where finally the full tracker structure will be assembled and tested. The completed and tested silicon tracker will then be delivered at the CMS experimental area at the end of 2006. In the meanwhile a test of smaller substructures of the tracker, will also be tested inside the operating CMS magnet, with parts of other CMS detectors, with the goal of triggering and measuring cosmic rays.

8 Tracker physics performances

The CMS silicon strip tracker will be located inside the 4 Tesla solenoidal magnetic field and will provide measurements of 10 to 14 hits for charged tracks originating near the interaction point within a pseudorapidity acceptance of $|\eta| < 2.5$. Combinatorial Kalman filters are used to reconstruct charged tracks trajectories both with *inside-out* and *outside-in* seeding techniques [5].

As it can be seen in figure 8 the track reconstruction efficiency for muons is expected to be close to 100% in the acceptance range. Electrons and hadrons are expected to have slightly worse efficiencies ranging from 95% in the central region to 80% in the forward region.

The transverse momentum resolution for reconstructed tracks is 1-2% for 100 GeV/c p_T muons in the central region (figure 8). The resolution is better for lower momentum muons in the 1-10 GeV/c p_T range, but is degraded in the forward region due to the reduced level arm. The resolution for the tracks impact parameter is expected to be at the level of 20 μm for high energy tracks (p_T=100 GeV/c), but degrades at lower momenta because of multiple scattering.

The resolution on the impact parameters of reconstructed tracks will be a key factor for an efficient identification of final states with b quarks and tau leptons, crucial for measurements in the higgs sector with a light higgs decay (h$\rightarrow$ b$\bar{\rm b}$), for top physics (t$\rightarrow$bW$^+$), and for searches for new physics like supersymmetric particles.

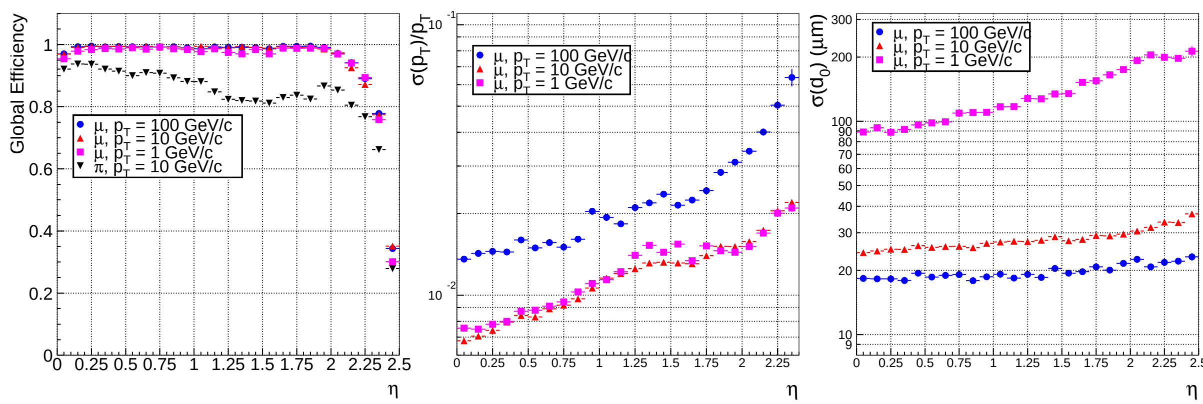

Figure 8: Performances of the CMS tracker reconstruction of charged particles. Left: track reconstruction efficiencies as a function of pseudo-rapidity $|\eta|$ for muons and pions of different tranverse momentum p_T. Center : track transverse momentum resolutions for muons as a function of $|\eta|$ and for different p_T values. Right : track impact parameter resolutions for muons as a function of $|\eta|$ and for different p_T values.

Acknowledgments

I would like to thank the EPS NPDC19 Conference organizers G. Viesti, A. Zenoni and A. Fontana for kindly inviting me to give a presentation on the CMS tracker, and for their patience for my delay in sending this contributed paper.

References

[1] The CMS Tracker Technical Design Report, CERN/LHCC **98-6** CMS TDR 5
Addendum to the CMS Tracker TDR, CERN/LHCC **2000-016**

[2] French J, et al. 2001 *Nucl. Instr. and Meth.*A**462** 359

[3] Braibant S, et al. 2002 *Nucl. Instr. and Meth.*A**485** 343

[4] Affolder A, et al. 2004 *Nucl. Instr. and Meth.*A**535** 374

[5] Speer T, et al. 2005 *CMS CR* **2005/014**