Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 37 (2012) 119 – 127

Physics Procedia

TIPP 2011 – Technology and Instrumentation in Particle Physics 2011

Status of the CMS Detector

Ettore Focardi[1]

University and INFN Florence, Via G. Sansone 1,
50019, Sesto Fiorentino, Italy

Abstract

The Compact Muon Solenoid (CMS) detector is one of the two largest and most powerful particle physics detectors ever built. CMS is installed in P5 at CERN's Large Hadron Collider (LHC) and as of early 2011 has completed nearly a year of operation in which it recorded products of interactions produced in proton-proton collisions at a center of mass energy of 7 TeV. The proton-proton run 2010 lasted 7 months and was followed by Pb-Pb ion collisions in November. During the first few months of 2011 the LHC has delivered higher luminosity.

The LHC machine is performing extremely well, allowing CMS to record enough data to perform a large number of studies of the Standard Model (SM) of particle physics in this new energy domain for the first time and to search for evidence of new physics in regions of phase space that have never before been entered. The CMS detector components, the operational experience and the performance with colliding beams will be described.

Keywords: Detector;Tracker; calorimeters

---

[1] On behalf of CMS collaboration.
Email: ettore.focardi@cern.ch. Tel: +41227676412; fax::+41227669160.

doi:10.1016/j.phpro.2012.02.363

1. Introduction

The Compact Muon Solenoid (CMS) is a general purpose detector [1] installed in the experimental area P5 at the Large Hadron Collider (LHC) at Cern. CMS aims to cleanly detect the different signatures of new physics at LHC by identifying and precisely measuring muons, electrons, photons and jets over a large energy range. The CMS detector has been designed to record and reconstruct pp collisions at $\sqrt{s}$ = 14 TeV with an instantaneous luminosity of about 10^{34} cm^{-2} s^{-1}. The key element of the CMS detector (fig.1) is the superconducting solenoid operated to produce a magnetic field of 3.8 T within its volume. Inside the solenoid, from outside to inside, there is a fully hermetic brass-scintillator hadron calorimeter, a highly granular crystal electromagnetic calorimeter and an all-silicon tracking detector. Outside the solenoid, embedded in the iron yoke, there are gaseous detectors to identify muons and reconstruct their trajectories and momenta together with the inner tracker. The detector has been built thanks to the effort of the all CMS collaboration consisting of more than 3200 scientists and engineers from 189 Institutes distributed in 41 countries all over the world.

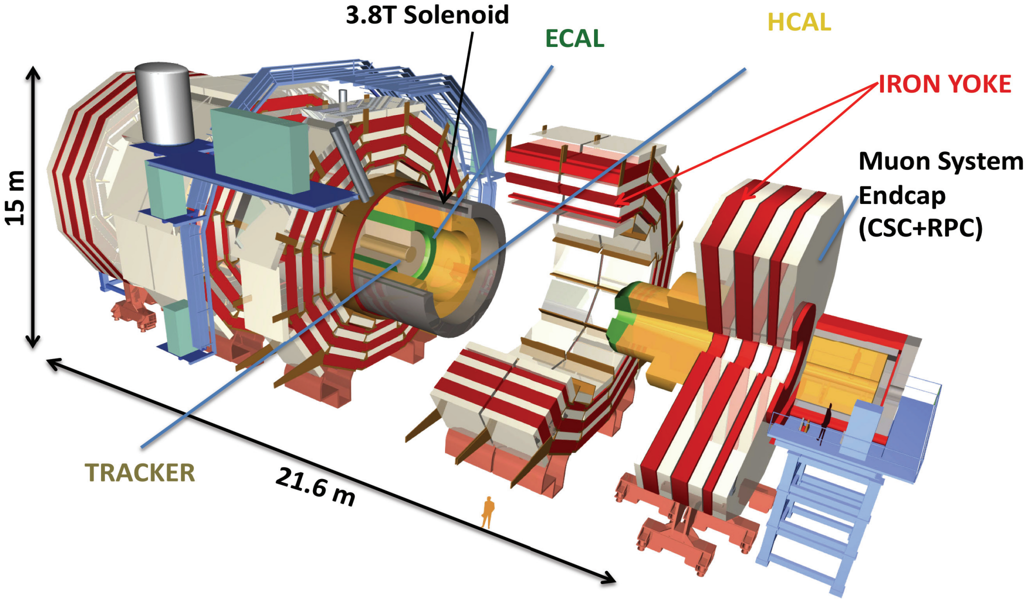

Fig. 1- Schematic view of the CMS detector.

2. CMS detector.

The most important aspect of the overall CMS detector is the choice of a superconducting high magnetic field solenoid to accurately measure muon and other charged particle momenta. The field is returned through a 1.5 m of Fe structure, which houses four muon stations with wide geometric coverage. The bore of the magnetic coil accommodates the tracking detector and the calorimeters. The cylindrical tracker volume is 6 m long and 2.6 m in diameter. To deal with high track multiplicities, the Silicon Strip Tracker (SST) uses ten layers of silicon microstrips detectors with fine granularity to provide high tracking precision. Three silicon pixels layers placed close to the interaction region, improve the measurement of the impact parameter of the charged particle tracks and the position of secondary vertices. The particles then encounter the calorimeters: the electromagnetic calorimeter (ECAL), which employs lead tungstate ($PbWO_4$) crystals for the measurements of the energy of photons and electrons. The ECAL is surrounded by a brass/scintillator sampling hadron calorimeter. The forward calorimeters provide geometric coverage to $|\eta|=5$, for the measurement of the transverse energy in the event.

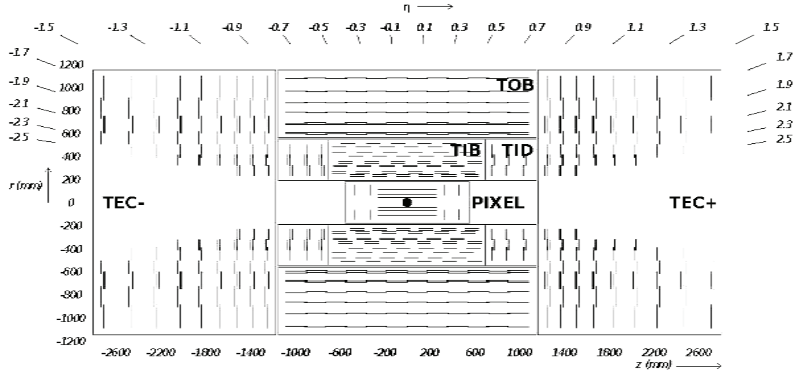

Fig. 2- Schematic overview of the CMS tracker. Each line represents a detector module. Double lines indicate double-sided modules which deliver stereo hits.

2.1 The Tracking system

Experience has shown that a robust tracking and a detailed vertex reconstruction within a strong magnetic field are powerful tools for precisely detecting charged particles. The characterization of events involving gauge bosons, W and Z and in particular, their leptonic decays provide clean experimental signals. To fully exploit these signatures, the Tracker detector has to provide good momentum measurement for energetic leptons. The tracker measurements are combined with track segments reconstructed in the muon system to extend the kinematic region of precision muon momentum measurement. One of the critical issues of the Silicon Tracker is the long-term survival after heavy irradiation. The system has been designed to guarantee stable operating conditions for about 10 years of LHC running. A schematic overview of the CMS Tracker is shown in Figure 2. The CMS tracker [2] is composed of a Pixel Silicon Detector with three barrel layers (BPIX) at radii between 4.4 cm and 10.2 cm and two endcap disks (FPIX) at each end, and a Silicon Strip Tracker (SST) with 10 barrel detection layers extending to a radius of 1.1 m and 3+9 disks on each side of the barrel to extend the overall tracker acceptance up to pseudorapidity $|\eta| < 2.5$. The Silicon Strip Tracker is arranged in four subsystems: the inner barrel (TIB), the inner disks (TID), the outer barrel (TOB) and the outer end caps [TEC]. The total active surface is about 207 m^2, the largest silicon tracker ever built. The pixel size is $100\text{x}150\ \mu m^2$ for a total of 1440 modules with 15840 readout chips and ~66M channels while the strip tracker is equipped with 24440 sensors (300) μm thick for the inner layers and 500 μm thick for the outer layers) with different pitches, from 80 to 180 μm, 15148 modules and 75000 readout chips leading to about 9.6 Mchannels. In the strip tracker 4 layers in the barrel and 3 rings in the end caps are equipped with paired sensors with a 100 mrad relative stereo angle among the strips to provide accurate 3-dimensional hits. This granularity was chosen to balance the need for a low occupancy, which is expected to be a few percent at the nominal LHC luminosity, and the requirement to keep the power density, the needed cooling power and the amount of material at the minimum. The basic performance expected for the tracking detector is a transverse momentum resolution of about 1-2% for muons of p_t ~100GeV, an impact parameter resolution of about 10-20μm for tracks with p_t 10-20 GeV and the ability to reconstruct tracks in hadronic jets with an efficiency about 85-90% and a fake rate not exceeding a few percent.

2.2 The Calorimeters

The Electromagnetic Calorimeter (ECAL) [3] is a hermetic homogeneous calorimeter made of 75848 lead tungstate (PbWO4) scintillating crystals. It consists of a central barrel region (EB) organized in 36 super modules, each containing 1700 crystals, and two end caps (EE) of 7324 crystals each. The scintillation light is readout by avalanche photodiodes (APDs) in the barrel and with vacuum photo triodes (VPTs) in the end caps. Silicon preshower detectors (ES) are installed in front of the ECAL end caps.

The EB provides the coverage of pseudo rapidity $|\eta| < 1.48$ with EE extending to $|\eta| = 3.0$. The ES covers $1.65 < \eta < 2.6$. The ECAL energy resolution measured in electron beam tests is parameterized for electrons incident on the center of crystals and shows three contributions that correspond to the stochastic, noise and constant terms. In the environment of CMS, for unconverted photons with energies above 100 GeV, the energy resolution is dominated by the constant term of ~0.5%, by the stability of the system and by the precision to which the intercalibration constants can be established. Since the cosmic runs taken by CMS before the pp runs, the required level of stability has been reached for temperature, low voltage and high voltage. The calorimeter is equipped with a laser monitoring system to monitor crystal stability in time, particularly under irradiation. During stable running, the monitoring system has been shown to follow the crystal response to a precision of 0.1% for 99.6% of the channels and 0.2% for 99.9% of the channels.

The hadronic calorimeter (HCAL) [4] is a sampling calorimeter that covers the pseudo rapidity region $|\eta| < 5.2$. It is completed outside the solenoid by a tail catcher in the barrel region ($|\eta| <3$), which uses the solenoid coil as absorber. The $3 < |\eta| < 5.2$ region is covered by a forward calorimeter, located 11.2 m from the interaction point. The part in the solenoid (barrel and end cap) uses brass as absorber and BiCron BC408 scintillator as active material. Light is collected with wavelength shifting fibres. The total absorber thickness at 90^o is 5.82 interaction lengths. The readout granularity is $\eta = 0.087x0.087$ for $|\eta| < 1.6$ and $\eta = 0.17x0.17$ for $|\eta| > 1.6$. The calorimeter in the forward region uses steel as absorber. The active part is made of quartz fibres, where light is produced by Cerenkov effect. The usage of two fibre lengths allows separation of electrons and photons from hadrons based on their shower profile. More than 99.75% of the channels of the hadronic calorimeter are operational.

2.3 The magnet

The CMS detector is equipped with a 12.5 m long and 6.3 m diameter 3.8 T superconducting Solenoid. The coil design is sectioned in 5 modules each of 2.5 m length. The magnetic flux is returned through a 12000 ton yoke consisting of 5 wheels and two end caps, the latter composed of three disks each. A distinctive feature is the 4-layer winding of Nb-Ti superconductor through which 20 KA of current flows.

2.4 The muon system

Due to the shape of the solenoid magnet, the muon system [5] is naturally divided into a cylindrical barrel section, completed by two planar end cap regions. The barrel muon spectrometer is segmented in five wheels divided in 12 sectors, each made of four drift tubes chambers (DT). Each chamber is made of 3 groups of four layers of tubes, called a super-layer (two groups oriented in r - ϕ and one in r - z). In total there are more than 170000 tubes. Cosmic muons recorded by CMS during the cosmic runs in 2008-2009 (CRAFT runs) were analyzed to assess the DT efficiency: track segments were reconstructed and for each drift tube traversed by a track, the expected position was compared with the effective hit position. For each super-layer the efficiency is calculated as the average efficiency of its tubes and is found above 98.5%. The DT hit resolution with cosmic rays is found to be between 200 and 260 μm. The magnetic field degrades the resolution of the innermost muon chambers in the external wheels due to the presence of a radial component of the field that affects the drift velocity. Muon barrel and end caps are equipped with Resistive Plate Chambers (RPCs). The RPC efficiency is evaluated by extrapolating the DT track segments to the RPC layer and checking for the presence of hits. There are, in each chamber, a few regions of lower efficiency corresponding to the RPC gap spacers and to regions where the chambers are operated by construction in single gap mode. Overall the efficiency is around 90%. In the end caps Cathode Strip Chambers have simultaneous readout of x - y coordinates.

During the first beam runs a few chambers showed hardware occupancy problems. They were mostly repaired during the shutdown. Although, for forward chambers, the statistics of cosmic rays traversing the apparatus is small, for some chambers it was possible to evaluate the efficiency to obtain a single hit in a layer and the efficiency to obtain a track segment in a chamber and both were found above 99%.

A preliminary alignment was made with beam halo muons.

2.5 Event Selection and Acquisition

LHC provides pp collisions at a frequency of 40 MHz. Since it is impossible to store and process the large amount of data associated with the resulting high number of events, a drastic selection has to be achieved. This task is performed by the trigger system. The rate is reduced in two steps: level 1 Trigger that is designed to select high-energy deposits in the calorimeters and track segments in the muon spectrometer. This system is made with electronic modules, partly integrated in the detector front-end electronics and partly in the service cavern. The level-1 trigger can sustain the 40 MHz LHC bunch crossing rate in input and the system is designed to handle a maximum rate of 100 KHz of accepted events. After the level-1, the events are directly sent to the high-level trigger system (HLT), consisting of a farm of 720 PCs, which execute the full event reconstruction to search for specific physics signature and to send events at 100 Hz to the storage manager. The raw event size depends on the event and which varies between 1 and 2 MB. Cosmics events are typically much smaller in size. A fraction of the events are also sent in parallel to the data quality monitoring process (DQM), which monitors online the detector data quality from a fraction of the events (efficiency, noise, average signal levels) and produces plots for the shifters. An offline version of the DQM runs on all events during offline event reconstruction. The offline DQM plots are monitored in remote control rooms a few hours after data taking.

3. Detector Operation

The CMS detector installation was completed during summer 2008. Since then, a set of cosmic runs provided calibration constants (alignment etc.) and allowed the commissioning of the subdetectors. After the test run with pp collisions at an injection energy of 450 GeV and after at 2.36 TeV at the end of 2009, the pp collision run at 7 TeV started on March 2010. LHC delivered 47 pb^{-1} and 43 pb^{-1} were recorded by CMS. There was a high efficiency and great flexibility of the trigger system and an overall data taking efficiency of 92%. This pp run was followed by Heavy ions run in November 2010 with a delivered integrated luminosity of 8.4 μb^{-1}with similar data taking efficiency.

LHC started again with pp collisions in March 2011 with a real jump in the delivered luminosity thanks to the bunch trains operation. To date (June 2011) LHC delivered 830 pb^{-1} with 763 pb^{-1} recorded by CMS with daily-integrated luminosities reaching over 40 pb^{-1} as shown in fig.3.

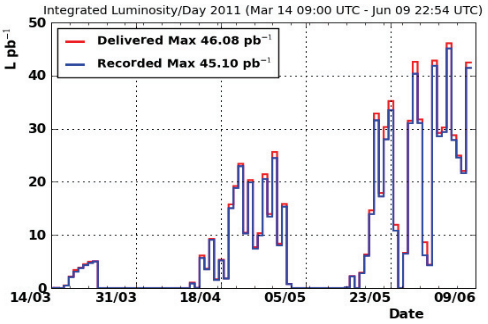

Fig.3- Integrated luminosity /Day 2011

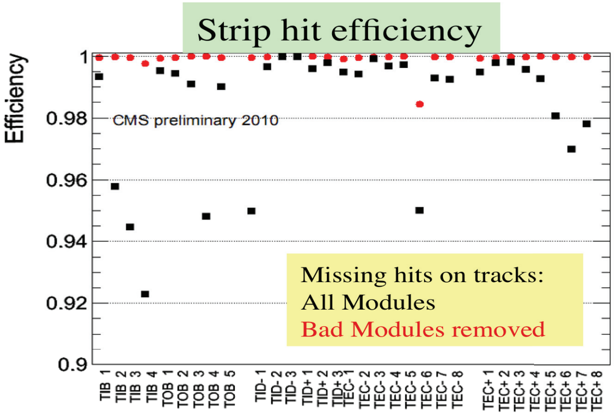

Fig. 4- Strip Tracker hit efficiencies

4. Detector performance

During the last data taking periods (2010-2011) no major problems occurred to the detector showing very good performance. The Fraction of alive Tracker detector channels was: Pixel 97.3%, Strips: 97.8% with very high hit efficiency >99.9%, fig. 4.

In the Silicon Strip tracker a S/N ~19 (thin sensors) and ~23 (thick sensors) was measured. The hit resolutions measured match the expected values: 17 to 39 μm for the strips and 12.7 μm (rϕ) and 28.2 μm for the Pixel.

The Tracker alignment of 15148 (strips)+1440 (Pixel) modules was carried out to a precision of a few microns. Alignment algorithms based on the track reconstruction are used for the final determination of the sensor positions and orientations. The core of the track-based alignment is the minimization of the χ^2 of the hit-track residuals with respect to the parameters describing the sensor positions. The alignment parameters have been determined with cosmic muon tracks in 2008, 2009 and, finally, in 2010 with about 1.5 million cosmic tracks (p>4 GeV) and about 1.7 million collision tracks (p>3 GeV). The complementariness of the cosmic and collision track samples enabled both the barrel and the end cap sections of the tracker to be accurately aligned.

In figure 5 the distributions of the median of the residuals (DMR) for sensors with at least 200 hits from tracks are shown. The RMS of these distributions is a useful figure to quantify the accuracy of the alignment.

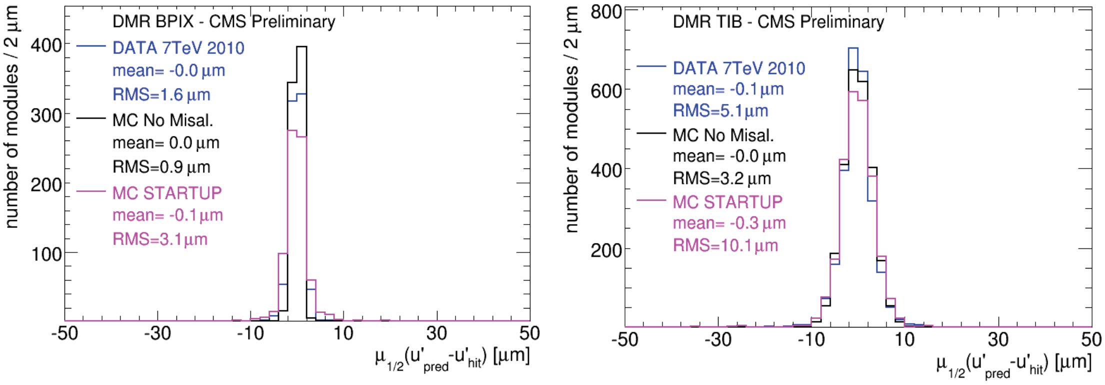

Fig. 5 Distributions of the hit residual medians for sensors with >200 hits in barrel pixel (left), and strip inner barrel (right). Results from real data are compared to simulations with no or realistic misalignment.

The muon momentum resolution, extracted from the decay of resonances, agrees well with Monte Carlo expectations as shown in fig. 6.

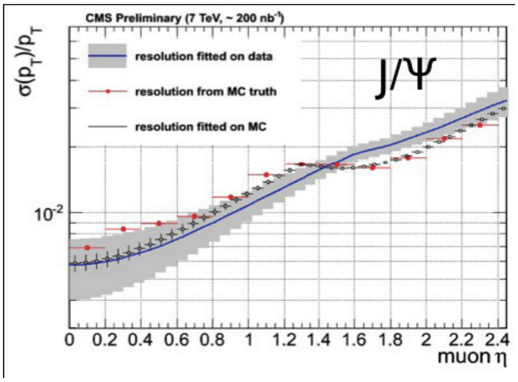

Fig.6- muon momentum resolution vs. η from J/Ψ.

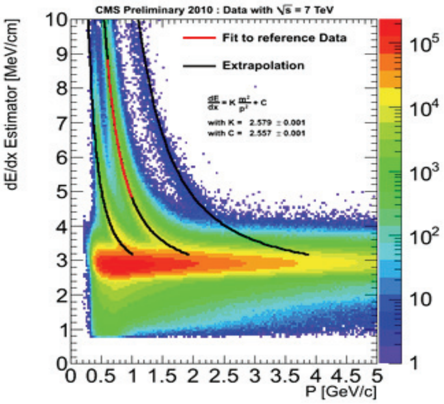

Fig.7. Energy loss in Si strips with clear separation of K, p, d particles.

There is an excellent resolution for primary vertex reconstruction and transverse impact parameter. The b-tagging was operational already at 15 nb^{-1}. Detector performance is monitored using the Data Quality Monitoring System (DQM), i.e. for the Tracker the full reconstruction chain is monitored through histograms on Status of FED, occupancy, clusters, track parameters; module level histograms are further processed to create summary histograms, perform quality tests, produce DQM flags. The energy loss in Si strip sensors has been used for particle identification (Fig.7), clearly separating K, p, and d particles. This feature of the Tracking detector has been used for several Exotica particles searches.

The level of active ECAL channels was: Barrel (EB) 99.08%, End cap (EE) 98.56%, Preshower (ES) 96.08%. The performance is in agreement with the expectations. The energy scale from collision events is set by π^0 calibration (comparison with MC at 1% level, barrel), fig. 8.

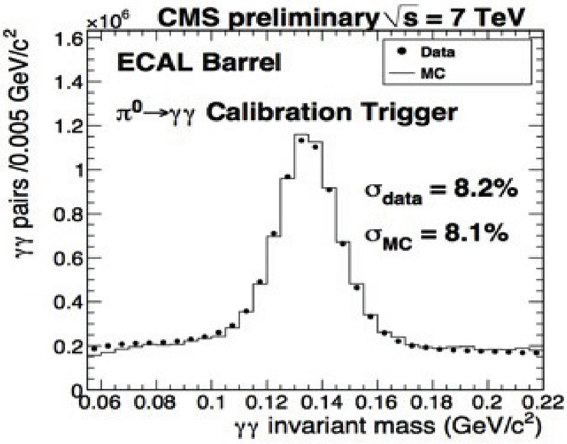

Fig.8- π^0 as from pp collision events.

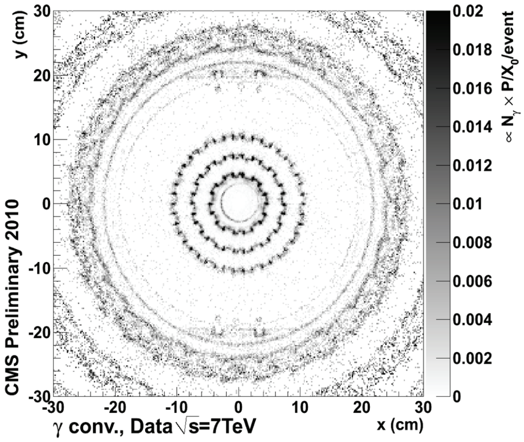

Fig.9- photon conversion, nuclear interactions in the tracker.

An initial estimate of the tracker material budget has been made, as shown in fig. 9. The radiography was carried out using tracks from photon conversion and nuclear interactions.

5. Conclusion

The status of the CMS detector at the LHC has been presented. Some highlights of the detector performance in the first 1.5 years of running with pp collisions at 7 TeV have been shown. Profiting from the cosmic rays runs taken with the CMS apparatus before the pp LHC running, the detector commissioning was very well advanced when pp collisions started at the end of 2009, allowing a quick understanding of the detector performance and of the Standard Model properties at 7 TeV. The detector has been operated very efficiently with the level of working channels above 95%, and data taking efficiency above 92%.

Acknowledgements

I would like to thank the LHC machine team for achieving an impressive performance in this running period. I am grateful to all colleagues of the CMS collaboration for their great collective effort in building and operating the detector so efficiently. Lastly I would like to thank the Organizers for making this Conference interesting and stimulating.

References

[1] CMS Collaboration, The CMS Experiment at the Cern LHC, JINST **3** (2008) S08004

[2] CMS Collaboration, Commissioning and performance of the CMS silicon strip tracker with cosmic ray muons, JINST **5** (2010) T03008

[3]CMS collaboration, Performance and operation of the CMS Electromagnetic calorimeter JINST **5** (2010)T03010

[4] CMS Collaboration, Performance of the CMS Hadron Calorimeter with Cosmic Ray Muons and LHC Beam Data, JINST **5** (2010) T03012

[5]CMS Collaboration, Performance of the CMS Drift Tube Chambers with Cosmic Rays, JINST **5** (2010) T03015