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The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Readiness of the CMS Detector for First Data

E. Meschi for the CMS Collaboration

Abstract

The Compact Muon Solenoid Detector (CMS) completed the first phase of commissioning in September 2008. The detector, data acquisition and distribution, reconstruction and analysis chains were successfully commissioned in a first phase with cosmic ray triggers. On September 10, 2008 CMS captured the first events from the LHC beam. In the following few days, the experiment accumulated many beam-splash and beam halo events from circulating beams. After the LHC setback on September 19th, CMS went back to cosmics operation. Continuous running with full magnetic field and the tracker detectors in full swing allowed the collection of large samples of muon tracks to be used for alignment and calibration, and improved the overall stability and efficiency of data taking. We present results of the analysis of data from the three phases, which have enabled establishing good starting points for time and space alignment, and accuracy of detector measurements. The status of the detector, and prospects for the collider run in 2009-2010 are subsequently discussed.

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READINESS OF THE CMS DETECTOR FOR FIRST DATA

E. MESCHI
for the CMS Collaboration
CERN - CH1211 Geneva 23 - Switzerland

The Compact Muon Solenoid Detector (CMS) completed the first phase of commissioning in September 2008. The detector, data acquisition and distribution, reconstruction and analysis chains were successfully commissioned in a first phase with cosmic ray triggers. On September 10, 2008 CMS captured the first events from the LHC beam. In the following few days, the experiment accumulated many beam-splash and beam halo events from circulating beams. After the LHC setback on September 19th, CMS went back to cosmics operation. Continuous running with full magnetic field and the tracker detectors in full swing allowed the collection of large samples of muon tracks to be used for alignment and calibration, and improved the overall stability and efficiency of data taking. We present results of the analysis of data from the three phases, which have enabled establishing good starting points for time and space alignment, and accuracy of detector measurements. The status of the detector, and prospects for the collider run in 2009-2010 are subsequently discussed.

1 The CMS Detector

The CMS detector is a multi-purpose experiment at the CERN Large Hadron Collider (LHC).

The design of CMS is discussed in detail elsewhere[1]. The overall layout of CMS is shown in Fig. 1. The distinguishing features of CMS are a 4 T superconducting solenoid, whose large bore accommodates the inner tracker and the calorimetry, a full-silicon-based inner tracking system, consisting of 10 layers of silicon microstrips and 3 layers of silicon pixel detectors close to the interaction region, and a homogeneous electromagnetic calorimeter consisting of lead tungstate ($PbWO_4$) crystals with coverage in pseudorapidity up to $|\eta| < 3.0$. Four muon *stations* are integrated in the iron yoke of the magnet, to ensure robustness and full geometric coverage. Each muon station consists of several layers of drift tubes (DT) in the barrel region and cathode strip chambers (CSC) in the endcap region, complemented by resistive plate chambers (RPC).

The detector main characteristics are:

- Good muon identification and momentum resolution over a wide range of momenta and angles, and the ability to determine unambiguously the charge of muons with $p < 1\,\mathrm{TeV}$;
- Good charged particle momentum resolution and reconstruction efficiency in the inner tracker.
- Efficient tagging of τ's and b-jets, thanks to the pixel detectors close to the interaction region;
- Good electromagnetic energy resolution over a wide geometric range;
- Good missing-transverse-energy and dijet-mass resolution

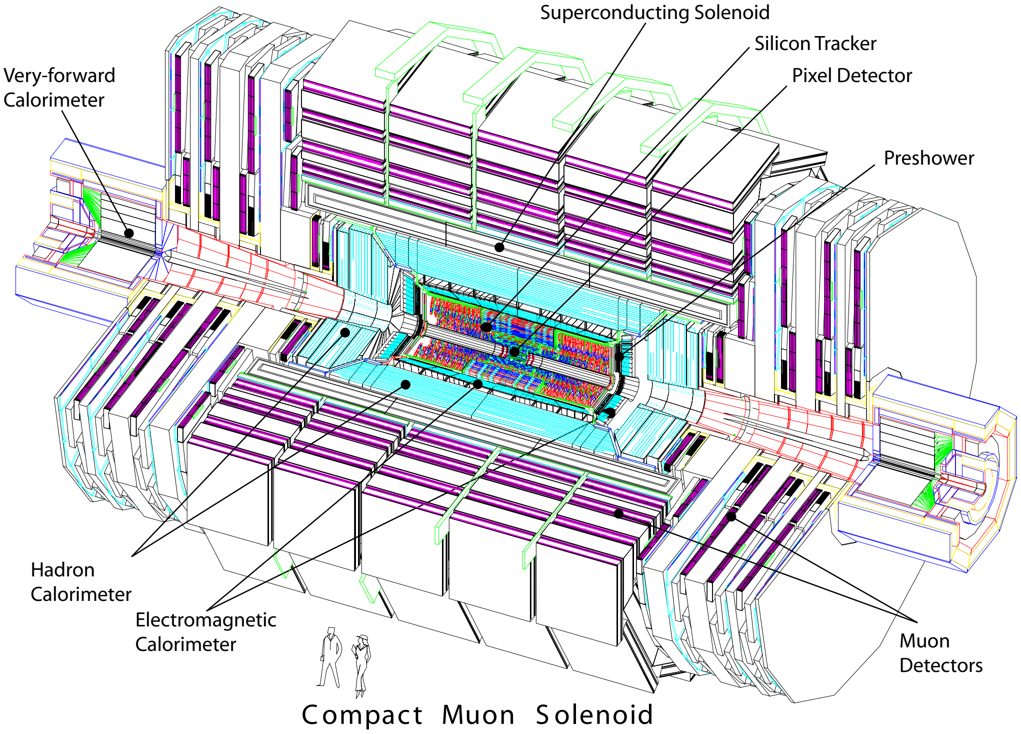

Figure 1: A perspective view of the CMS detector.

2 Commissioning Without Beam

A first system test of the CMS detector as an integrated set of sub-detectors was carried out in the CMS surface assembly hall in the summer of 2006. The Magnet Test and Cosmic Challenge, MTCC for short [2], profited of the surface test of the superconducting magnet and the mapping of the magnetic field to test the integration of a slice of the complete detector with a scaled-down infrastructure (DAQ, Level-1 Trigger, services). Nearly all final components were tested and several millions of cosmic ray events, producing signals in the detector, were collected.

During the subsequent period of heavy lowering, to bring all the components of the detector in the experimental hall 100 m below, the final infrastructure was completed and commissioned, while the heavy components were assembled again, and connected to the services in the collision hall. This phase was completed in spring 2007, when integration tests restarted in the underground experimental and service cavern.

In a series of short "Global Runs" starting in May '07, the muons systems were gradually integrated together as they completed commissioning. First cosmic muons were observed in the collision hall in June '07. At the end of the year, the final DAQ system (readout and data-to-surface) was commissioned, as well as the final services for the detector (detector control system, voltages, cooling). The various phases of the commissioning are illustrated in Fig. 2

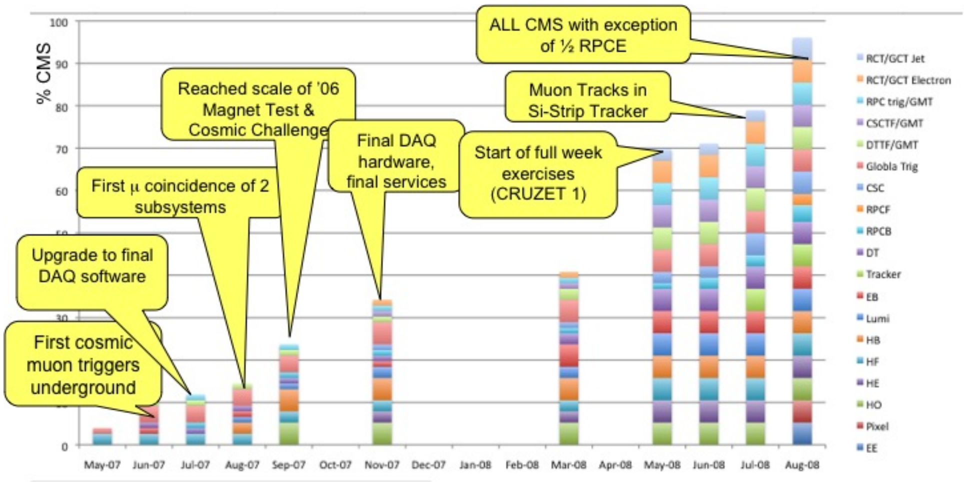

Figure 2: Percentage of sub-detectors integrated as a function of time. Trigger is considered separately from the corresponding sub-detector. The size of the boxes represents approximate fraction included (25%, 50%, 75%, 100%) With exception of the endcap Preshower detector, and some parts of the RPC, all CMS detector and trigger systems were ready for the LHC startup at the end of August 2008.

The goal of the cosmic runs with no magnetic field was to commission CMS as a single detector. In coordination with the installation schedule, the various sub-detectors were successively integrated in the global run and large sample of cosmic ray events collected (Fig. 3).

A total of 350M events were collected with magnet off and the detector fully operational.

It was quickly realized that the samples of muon tracks collected were large enough to provide a better initial alignment than the simple surveys. The final long cosmic run with full magnetic field, which was planned to provide a sample sufficient for a first complete alignment, was postponed due to the imminent startup of LHC [a].

3 The First LHC Beam

The first LHC protons were delivered to CMS starting on September 7, 2008. Single beam shots of 2×10^9 protons at injection energy were sent onto the closed collimators about 150 m upstream of CMS (beam 1, cw). Hundreds of thousand of scattered muons passing through the detector deposited several hundred TeV of energy in the calorimeters (Fig. 4). These events represented a challenging environment for the detector, producing measurable hits in virtually all of the detector channels. Recording splash events, analyzing them, and producing useful measurements represents an important step in establishing the reliability of the detector readout and data acquisition chain. The first beam shots allowed the correct synchronization of triggers previously synchronized with cosmic muons, thus removing the random phase error with respect to the machine clock. They also made a first synchronization of the end-cap muon chambers and the beam pick-ups possible.

Beam splash events were also used to verify the correct correlation of the energy measurements in the calorimeters with respect to each other and to the beam loss monitors (Fig. 5).

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[a] The alignment of the muon chambers and the tracker are discussed in more detail in a following section

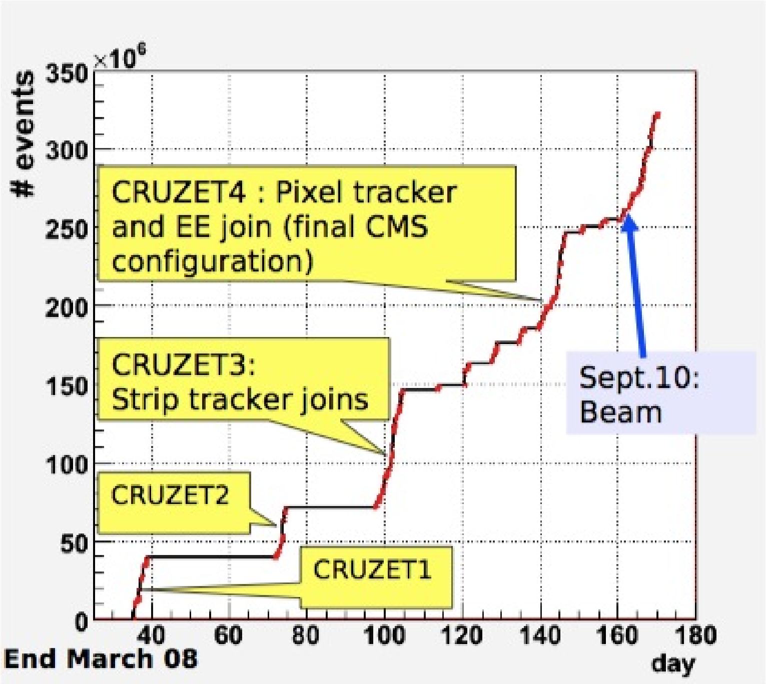

Figure 3: Number of events collected in the various cosmic ray runs prior to Sep. 10 (Cosmic RUn at ZEro Tesla - CRUZET for short). New sub-detectors were progressively commissioned and integrated in the general readout, while infrastructure was being completed

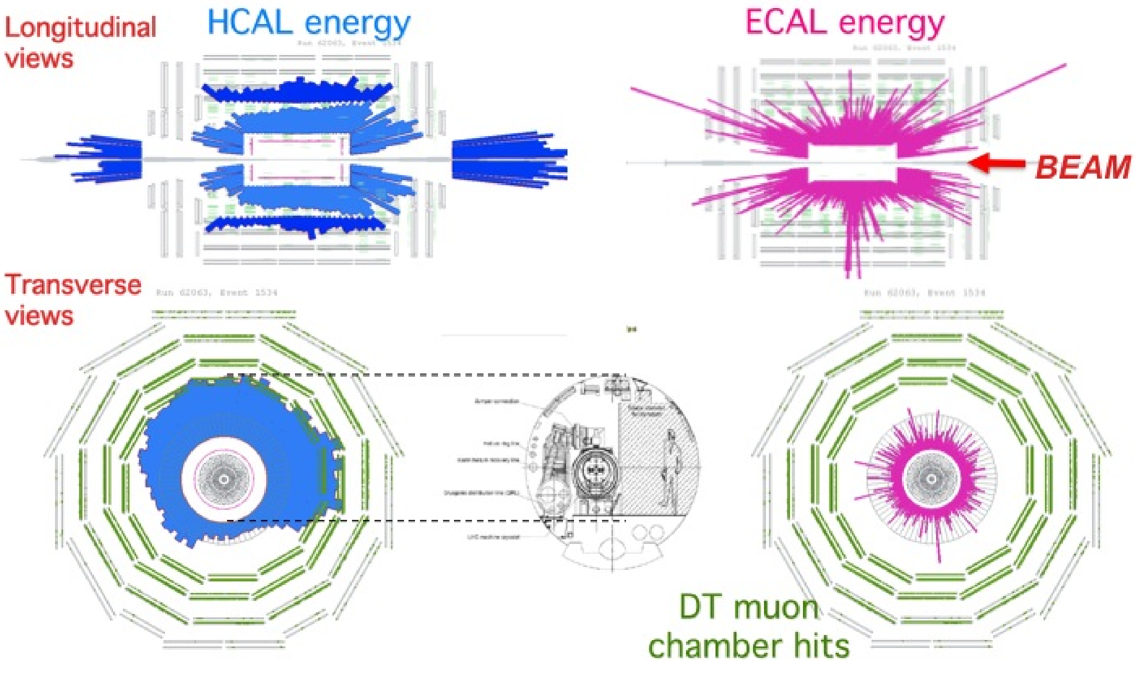

Figure 4: Display of the energy deposited in the calorimeters by a beam-splash event (top). The Energy profile in the endcap calorimeter matches the tunnel profile (bottom left). Virtually all of the channels of the three innermost layers of the barrel muon chambers fired (bottm right).

On September 10^{th} beam 1 and then beam 2 (ccw) were circulated for the first time (without radiofrequencies) for hundreds of turns. On 11 September, the firs RF capture was successfully attempted with a single bunch circulating counter-clock-wise (Fig. 6), resulting in millions of

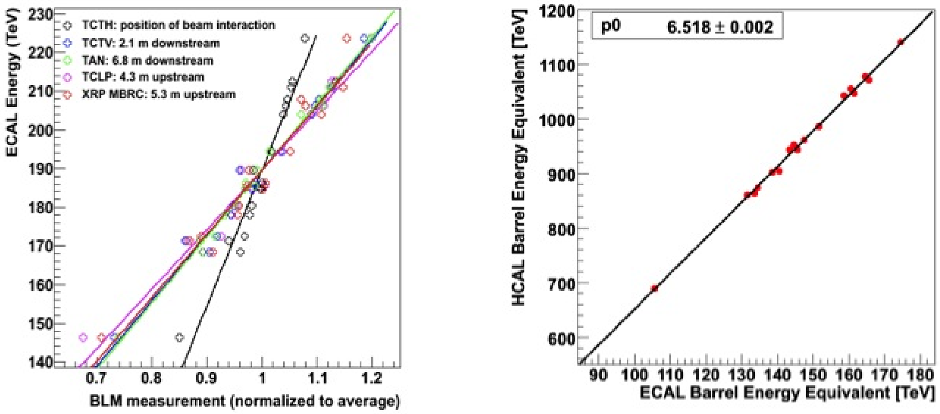

Figure 5: Linear correlation between the electromagnetic calorimeter measurement and the beam-loss monitors (left) and between the electromagnetic and hadronic calorimeter (right) for beam-splash events. The average energy deposit in ECAL for beam splash was about 150 TeV, while the average HCAL energy was about 1000 TeV.

orbits through CMS. Halo muons were detected and reconstructed in the muon endcaps. A measurement of the angular distribution of muons with respect to the longitudinal direction in the endcap chambers is shown in Fig. 7 (left). Halo muons, characterized by being collinear

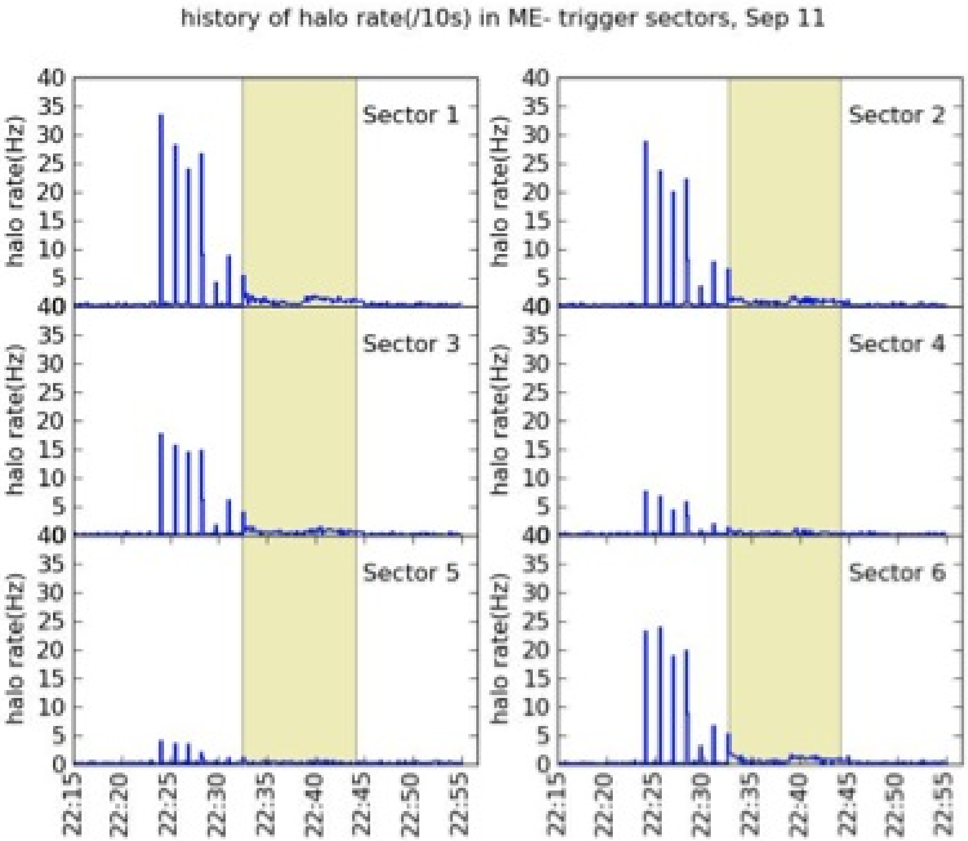

Figure 6: Trigger rate in each of the sectors of the negative-z muon endcap as a function of time. The rates are averaged over 10 s. After the beam capture (darker band) the rate of halo muons was drastically reduced. The capture lasted about 10 minutes and ended with a beam abort.

with the beam, produce a peak at small angle. An analysis of halo muon tracks is currently underway to provide a first in-situ alignment of the endcap muon chambers.

Evidence for beam-gas interaction was obtained with a detailed analysis of the energy distribution in the forward hadron calorimeter (HF), for events with circulating beam 2. These events were triggered by an energy sum over threshold in the HF itself and were further selected to have at least one energy deposit over 20 GeV in a single HF tower. A clear peak in energy deposition towards positive η is evidence for beam-gas interactions (Fig. 7, right).

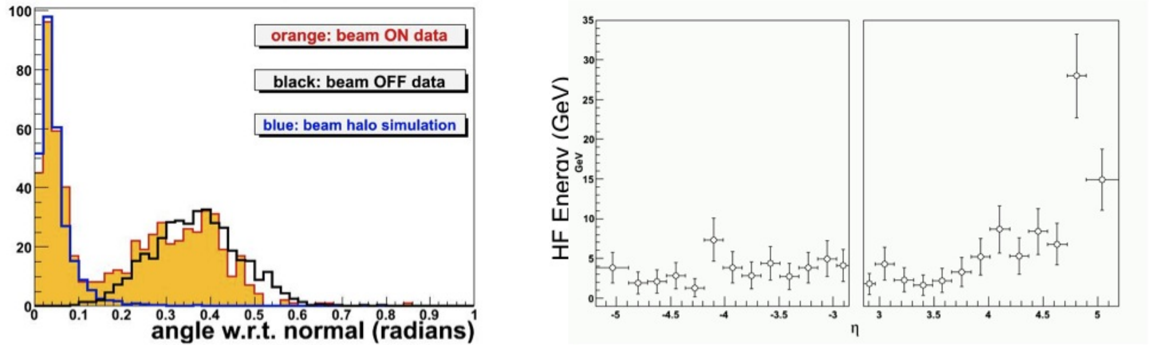

Figure 7: Left: Angular distribution with respect to the z direction of muons detected in the endcap muon chambers with circulating beam. The relative normalization of the blue and black histogram are arbitrary. Right: Energy distribution in the forward hadronic calorimeter as a function of pseudorapidity, for circulating beam 2.

4 Cosmic Ray Runs after September 10

In October 2008, CMS collected cosmic ray data for a continuous period of four weeks with the superconducting solenoid on, producing a 3.8 T magnetic field (Cosmic Run at Four Tesla - CRAFT). About 290M events were collected. This large sample of cosmic data allowed a number of problems to be identified and solved in the trigger/DAQ and detector chains. An ad-hoc cosmic-muon reconstruction was used to exercise the muon High Level Trigger (HLT) [3]. The data-transfer chain to CERN-IT and to the various GRID tiers all over the world were successfully exercised, and a number of detailed analyses carried out.

4.1 Tracking systems

The large number of cosmic events with a tracker track allowed detailed alignment studies in the silicon tracker barrel. Two alignment methods were used: a local iterative algorithm, HIP [4], and a global method called MillePede [5]. Fig. 8 illustrates the results for the tracker inner and outer barrel. The mean values of the residuals ($X_{Fit} - X_{Hit}$) are both consistent with 0, and the best resolutions obtained are 24 μm and 26 μm respectively for the inner and outer barrel.

The relatively small number of events collected with tracks traversing the pixel tracker active volume allowed nevertheless a preliminary alignment of the pixel detectors at the module level with a resolution for the best algorithm of 47 μm

Measurement of noise levels and efficiencies for the detection of cosmic muons were carried out both in the muon chambers and the tracker detectors. The hit efficiencies were consistently very close to 100%. These measurements also allowed the identification of hardware problems (voltages, readout problems, etc.). A small fraction of non functional channels (less than 1%) were identified and have been mostly fixed during the shutdown.

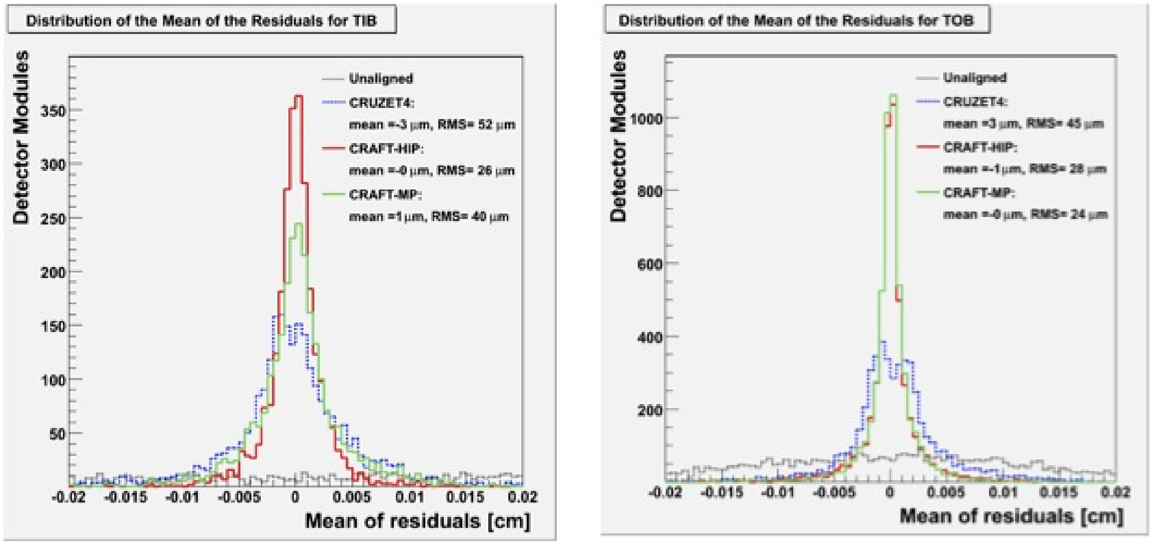

Figure 8: Residual distributions for inner (left) and outer (right) tracker barrel detectors using 4M tracks for alignment and 1M for validation from "CRAFT", compared to previous results using data with 0 magnetic field (CRUZET). Two different algorithms are shown.

4.2 Calorimetry

The response of the hadronic calorimeter barrel to muons was analyzed using muon tracks reconstructed in both the barrel muon chambers and the silicon tracker, by comparing the calibrated energy measurement to the muon momentum. The result compares well to both monte carlo simulation and previous test-beam results.

The stopping power (path-length corrected energy deposit) for cosmic muons traversing the electromagnetic calorimeter was measured as a function of the muon momentum measured in the tracker. The resulting distribution (Fig. 9) indicates the correctness of the tracker momentum scale and of the energy scale in ECAL calibrated with electrons at test beams.

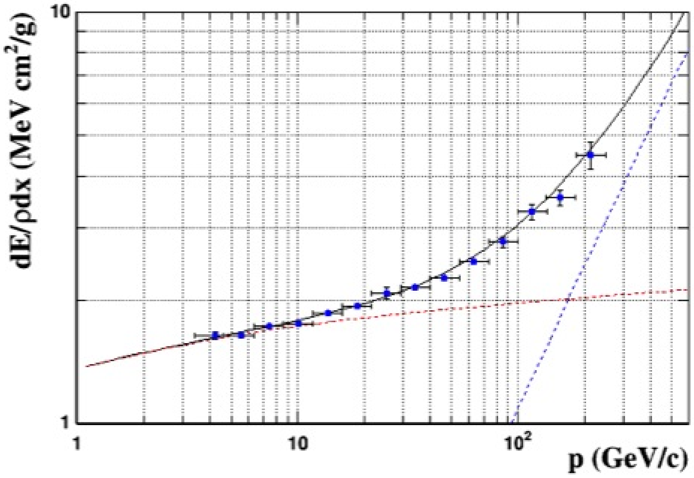

Figure 9: Stopping power of cosmic muons traversing ECAL as a function of the muon momentum . The energy deposit is measured by the energy of the cluster best matching the track. The track length is estimated from track propagation inside ECAL crystals. Experimental data (dots) are compared to the total stopping power (dE/ρdx) in PbWO$_4$ (continuous line). The dashed lines are the contributions due to collision loss and bremsstrahlung radiation. Errors on the vertical scale are statistical only. Error bars on the momentum represent the bin width.

5 Shutdown Activities, Detector Status And Plans

Since the beginning of September 2008 all installed CMS sub-detectors are read-out in global runs routinely. All the Level-1 trigger sub-systems are operational. The first stage DAQ was commissioned and high Level-1 rates tested. The stability of running with all CMS components was proven and LHC clock and orbit signals tested. The trigger and detector synchronization is now at the level of few ns or better.

Detector opening started on Nov 17, 2008 for planned interventions and repairs of problematic channels. Six % channels in the forward pixels, dead due to loss of low voltage, were repaired, and the detector re-installed. Ten out of 250 DT chambers with problems, as well as 10 out of 468 CSC chambers, were repaired. 200 ECAL lost channels ($< 1\%$) were recovered. The last missing piece of CMS, the preshower detector, was installed and commissioned. Global data-taking operations with cosmics restarted in spring 2009, and a new long run with full magnetic field is planned for the summer 2009, when the detector will be closed again in its final configuration and ready for beam in fall.

6 Prospects for 2009-2010 Collider Run

The LHC collider run 2009-2010 is expected to start in October 2009 after a short beam commissioning phase. Beam intensity, bunch spacing, and instantaneous luminosity, will be gradually increased. The run is expected to deliver $\approx 300pb^{-1}$ integrated luminosity at $\sqrt{s} \simeq 10$ TeV.

With first collision data, it will be possible to study the detector and reconstruction performance for physics objects: muons, electrons, jets, b-tags, τ, missing transverse energy.

With few pb^{-1}, hadron spectra and low-mass resonances (J/ψ, Υ, etc.) will be studied, as well as underlying event characteristics.

With 10 pb^{-1} it will be possible to verify standard model "candles", W, Z, top cross sections at $\sqrt{s} \simeq 10$ TeV. Searches using high-E$_t$ jets will be carried out.

With 100 pb^{-1} it will be possible to carry out measurements of W and Z properties, as well as searches for W', Z'. Jet Energy Scales from top events will become accessible, as well as some SUSY searches.

References

1. CMS Collaboration, JINST **3** (2008) S08004.
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3. E Meschi, in *Proceedings of the 7th International Conference on Advanced Technology and Particle Physics (ICATPP)*, World Scientific, 2002, p. 540; W Adam *et al.*, *Eur. Phys. J. C* **46**, 605 (2006); A Afaq *et al. IEEE Trans.Nucl.Sci.* **55**, 172 (2008); E Meschi *et al. J.Phys.Conf.Ser.* **119**, 022011 (2008).
4. V Karimäki *et al.*, CMS Note 2006/018.
5. P Schleper *et al.*, CMS Note 2008/029.