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Commissioning of the Muon, Electron and Tau Identification at CMS with Cosmics Rays

R. Bellan[*] **on behalf of the CMS Collaboration**
European Organization for Nuclear Research (CERN)
E-mail: `riccardo.bellan@cern.ch`

The cosmic data collected in 2008 and 2009 have been invaluable to study the performance of the CMS detector, to commission the alignment and calibration techniques, test the muon identification algorithms and to make several cosmic ray measurements. This contribution focuses on the commissioning of the lepton reconstruction and identification algorithms, mainly showing the muon reconstruction performance evaluated using the large cosmic data sample. Although direct tests of the tau and electron identification algorithms were not possible using cosmic rays, indirect information on their commissiong status can be inferred looking at the detector performance, of which a summary is given here.

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[*] Speaker.

1. Introduction

The CMS Collaboration conducted two month-long data-taking exercises known as the Cosmic Run At Four Tesla in late 2008 [1] and in 2009, in order to complete the commissioning of the experiment for extended operation. The cosmic data collected have been used to study the performance of the detectors up to make several cosmic ray measurements.

A detailed description of the CMS experiment, can be found elsewhere [2], here only a short description is given. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, 13 m length, and designed to operate at up to a field of 4 T. The magnetic flux generated by the solenoid is returned via the surrounding steel return yoke approximately 1.5 m thick, 22 m long, and 14 m in diameter arranged as a 12-sided cylinder closed at each end by endcaps. Within the field volume are the silicon pixel and strip trackers, the lead tungstate crystal electromagnetic calorimeter (ECAL), and the brass-scintillator hadronic calorimeter (HCAL). Muons emerging from the calorimeter system are measured in gas-ionisation detectors embedded in the return yoke. Three technologies are used for the detection of muons: drift-tubes (DT) in the central region ($|\eta| < 1.2$), cathode strip chambers (CSC) in the endcaps ($0.9 < |\eta| < 2.4$), and resistive plate chambers (RPC) throughout barrel and endcap ($|\eta| < 1.6$). The CMS experiment has a two-level trigger system consisting of the hardware-based Level-1 Trigger and the software-based High-Level Trigger (HLT).

Commissioning of lepton reconstruction (the identification strategies are briefly described in Section 2) strongly relies on the detector performance. In Section 3 a summary of the performance of the detectors is shown. The results there presented should be considered as the first step for the commissioning of the lepton identification. While for the electron and tau identification commissioning we can only draw indirect conclusion through the detector performance results, the muon reconstruction and identification algorithms have been extensively studied with more than 200 million of good cosmic events [3]. The results are corresponding to the 2008 data summarised in Section 4.

2. Lepton Identification at CMS

The muon identification and reconstruction uses two complementary approaches for a unique collection of muons: stand-alone muon based (outside-in strategy) and tracker based (inside-out approach). The outside-in approach consists of a complete track fit of the hits in the muon chambers and a subsequent searching of a compatible track in the tracker to build a global muon. The inside-out strategy, instead, tries to match the tracks in the tracker with the muon segments and on compatibility basis identify the tracker tracks that are muons. The two algorithms are integrated such that they complete each other after they have individually performed their choices.

The electron reconstruction starts from clusters in ECAL followed by a matching with the tracker track seeds. Then to extend the track, the electron hypothesis for energy loss is used (together with relaxed cuts on the inclusion of new hits in the trajectory). The final fit is done with the Gaussian Sum Filter method [4]. There are ongoing studies on the development on a complementary approach, which starts from the tracks in the tracker and search for compatible clusters in ECAL. The final identification is performed cutting on variables such as isolation, cluster shape and the compatibility of the track parameters with the cluster in the electromagnetic calorimeter.

Tau leptons are reconstructed in hadronic channels, therefore the main particles searched by the algorithms are photons and charged pions. In CMS, the tau reconstruction is based on the Particle Flow technique [5], which combines the information from the calorimeters with the track particles precisely measured in the tracker. All reconstructed particle in the event from any possible hadronic tau decay products, are then clustered into jets using a simple cone algorithm of radius 0.5. Using particle flow, the tau parameters are given by the tracker and ECAL.

3. CMS Detector Readiness before 2009 LHC Collisions

The availability of all CMS sub-detectors, before the 2009 LHC data taking, has been evaluated to be well above 95% of the total read-out channels. In this section, the highlights for the different sub-systems are presented.

Hit efficiency study of the pixel detector using cosmic rays shows efficiencies greater than 96% for most pixel detector modules [1]. Using tracks that intersect overlapping barrel modules, hit resolutions of 19 μm ($r\phi$) and 31 μm (z) were extracted from the small event sample available. The transverse (longitudinal) impact parameter resolution was found to be 18 μm (35 μm) for high momentum tracks.

The efficiency of hit and track reconstruction in the silicon strip tracker were measured to be higher than 99% and consistent with expectations from Monte Carlo simulation. The positions of the modules were determined with respect to cosmic ray trajectories to an average precision of 3–4 microns RMS in the barrel and 3–14 microns RMS in the endcap in the most sensitive coordinate [1].

The electromagnetic calorimeter showed to have a very stable behaviour in presence of the 3.8 T magnetic field [1]. A energy pedestal of 40 MeV/channel, in complete agreement to what was found in a dedicated test beam held in 2006 [6], has been found for the barrel modules. In the barrel, the relative energy scale between super-modules was verified with a precision of $\approx$ 1%.

The performance of the CMS hadron calorimeter has been studied using cosmic ray and beam splash events [1], providing improved calibrations with respect to those obtained in test beam data and with radioactive sources. The barrel portion is inter-calibrated to the level of 5%, for 85% of the channels, while the endcap channels are inter-calibrated to better than 10%. Noise studies have been performed, showing that noise will contribute a trigger rate of around 100 Hz.

The magnetic flux density in the steel plates of the CMS barrel return yoke was measured precisely using cosmic ray muons [1]. In the CMS yoke, the new map is estimated to be accurate to better than 3% in the steel of the three central barrel wheels, and to about 8% in the steel of the two outermost barrel wheels.

The Level-1 trigger was operated stably during the LHC single beam operation, and during the cosmic ray data-taking periods [1]. All muon sub-detector triggers have been synchronised and shown to provide good efficiency and muon parameter assignment. The e/γ and jet triggers were commissioned during CRAFT and shown to be fully efficient.

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4. Muons Reconstruction Performance in Cosmic Rays Events

Efficiencies of various high-level trigger, identification, and reconstruction algorithms have been measured for a broad range of muon momenta, and were found to be in good agreement with expectations from Monte Carlo simulation. Studies of the performance of the individual muon subsystems carried out on CRAFT data are described in Refs. [1]. This section focuses on the results related to the tasks of muon identification and reconstruction for high-level trigger and physics analysis. Depending on the information used, muon reconstruction and identification algorithms can roughly be divided into three groups: standalone muon fits using only information from the muon system, global muon reconstruction algorithms based on combined fits of the hits in the muon and the silicon tracker system, and muon identification algorithms, which check whether the tracks reconstructed in the tracker have signatures compatible with that of a muon in the calorimeters and in the muon system. Only the results for the reconstruction optimised for the LHC runs are presented here.

The efficiency of the muon reconstruction and identification algorithms was measured by selecting events with a good-quality global muon in one hemisphere of the detector (top or bottom) and examining whether there is a corresponding track in the opposite one. To ensure that the muon traversed the whole detector a p_T larger than 10 GeV/c is applied to the reference global-muon track. Figure 1(a) shows the efficiencies to reconstruct a global muons and their constituents as a function of the pseudorapidity of the reference tracks. Figure 1 also shows the efficiency for the global muons with an additional requirement applied to the normalised χ^2 of the fit, χ^2 / ndf <10 (*GlobalMuonPromptTight*); this cut is expected to strongly suppress hadronic punch-through and muons from decays of π- and K-mesons in collision events, leaving the efficiency for prompt muons almost intact. In Fig. 1(b) the muon reconstruction and identification efficiencies are shown as a function of p_T. *CompatibilityLoose* refers to a compatibility-based selection of the tracker tracks, where two "compatibility" variables (based on calorimeter and muon system information) are constructed. A tracker track is considered to be a muon if the value of a linear combination of these variables is larger than a pre-defined threshold. *LastStationLoose*, instead, is a cut-based selection, where cuts are applied on the number of matched muon segments and on their proximity

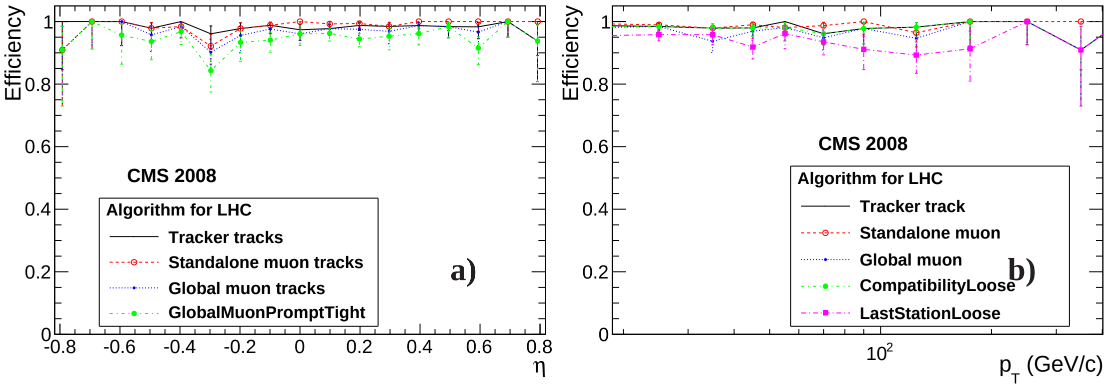

Figure 1: Muon reconstruction efficiencies as a function of η and p_T of the reference track, for algorithms developed for muons produced in beam collisions at the LHC.

to the extrapolated position of the tracker track. In this method, one makes use of the fact that the penetration depth of muons is larger than that of hadrons by requiring that there be well-matched segments in at least two muon stations, one of them being in the outermost station.

For each pair of muon tracks in the selected events, the relative q/p_T residual, $R(q/p_T)$, was calculated as

$$R(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{2}(q/p_T)^{\text{lower}}} \quad , \tag{4.1}$$

q being the charge sign of the muon. The $\sqrt{2}$ factor accounts for the fact that the upper and lower tracks are reconstructed independently and with a similar precision. The values of q/p_T were evaluated at the point of closest approach of each track to the nominal beam line. Since the momentum resolution for standalone muons is expected to be significantly worse than that obtained using the other muon reconstruction algorithms, the residuals for standalone muons were estimated by comparing q/p_T of each standalone muon reconstructed in the lower detector hemisphere with q/p_T of the global muon in the same hemisphere (and omitting $\sqrt{2}$ in Eq. (4.1)).

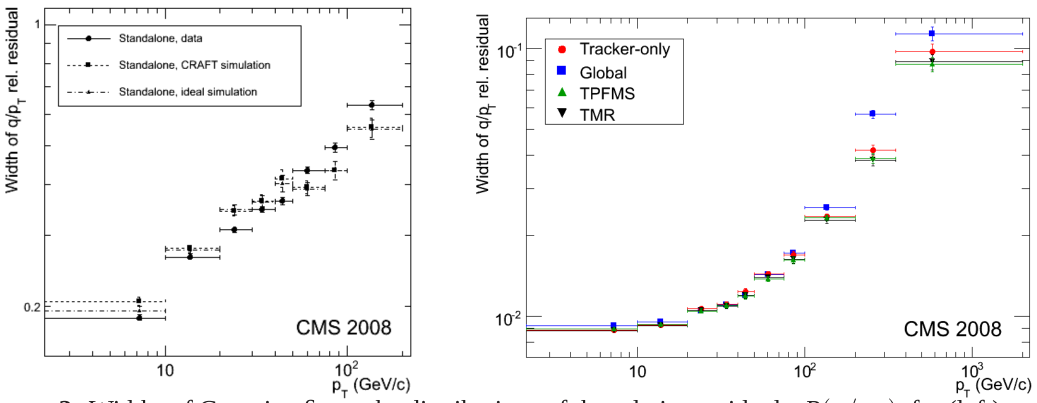

Figure 2: Widths of Gaussian fits to the distributions of the relative residuals, $R(q/p_T)$, for (left) standalone muons without the beam-spot constraint and (right) for various tracker based muon reconstruction algorithms (see text), as a function of p_T of the reference track.

Figure 2 shows the widths of the Gaussian fits to $R(q/p_T)$. These widths are a measure of the momentum resolution. In the p_T region below approximately 200 GeV/c, where the resolution is dominated by multiple-scattering effects, the inclusion of muon hits does not improve the resolution beyond that obtained with the tracker-only fits. In the high-p_T region, the resolution obtained using the fit of the tracker plus first muon station only (TPFMS) and the *truncated muon reconstructor* (TMR), whereby one chooses between the TPFMS and tracker-only fits on a track-by-track basis is better than that of global muons and of tracker-only tracks. The resolution of the global muon reconstruction algorithm at high p_T is foreseen to improve once the muon Alignment Position Errors are taken into account in the track fit.

The impact on the global muon track fit of systematic effects due to knowledge of the true magnetic field, as well as unaccounted shifts or rotations of the muon system with respect to the tracker can be estimated on a track-by-track basis, comparing the p_T value of the global muon with the p_T of the corresponding track in the tracker. It has been found that deviations from unity do not exceed 1% in the transverse momentum range up to 150 GeV/c. These results provide important constraints on the impact of any remaining unknown systematic effects on the muon reconstruction performance.

Finally, also the performance of the muon reconstruction dedicated for the High-Level Trigger has been measured with cosmic data. The muon High-Level Trigger is composed of two steps Level-2 track reconstruction, which uses the information from the muon system only and and the Level-3 track reconstruction, which also adds the information from the silicon tracker. In CRAFT data it has been found that the overall Level-2 efficiency reaches a plateau close to 100% for muons with p_T above 5 GeV/c, while the efficiency to correctly build a track in the tracker (Level-3 reconstruction), provided there is a Level-2 muon in the event, has been measured to be above 95%.

5. Conclusions

The CMS Collaboration invested a lot of resources in the detector, software and computing commissioning with cosmics, starting in August 2006 and culminating in two one-months long data taking periods in 2008 and 2009. The system was extensively and successfully stressed and tested. Over 1 billion of cosmics events were recorded and processed through the full chain designed for the LHC data. This strategy, in terms of detector, software, computing understanding, payed off, especially in the commissioning of the leptons. The improved understanding of alignment, tracking, and experience with calorimeters provides a good starting point for electron and tau commissioning with early collisions. The muon reconstruction and identification algorithms are in a fairly advanced stage of commissioning and show high performance very close to the design expectation.

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