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Track Reconstruction and Experience with Cosmic Ray Data in CMS

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Abstract

The CMS tracking system, comprised of silicon pixel and micro-strip detectors, is designed to provide a precise and efficient measurement of the trajectories of charged particles emerging from the LHC collisions. With over 70 million electronic channels and an active area of about $200\,\mathrm{m}^2$ it is the largest silicon tracker ever built. After a short introduction to the CMS tracker and to the track reconstruction algorithms, results from tracking with cosmic ray data are presented. First experience with cosmic ray tracking was gained in a vertical slice test involving various CMS sub-detectors. Additional understanding was obtained during the final assembly and surface commissioning of the silicon micro-strip tracker. Both data sets have been extensively studied, and a concise summary focussing on track reconstruction is given.

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1 Introduction

CMS is one of the two general purpose experiments in construction at the LHC at CERN. Its prime goals are to explore physics at the TeV scale and to study the mechanism of electroweak symmetry breaking [1]. The LHC is designed to provide proton-proton collisions with a luminosity of up to $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and a center-of-mass energy of 14 TeV. At the design luminosity there will be on average about 1000 particles from more than 20 overlapping proton-proton interactions traversing the tracker for each bunch crossing, i.e., every 25 ns. In order to cope with these challenging conditions, track and vertex reconstruction rely on a system of silicon pixel and micro-strip sensors, embedded in a solenoidal magnetic field of 4 T. The high granularity of the sensors results in a low occupancy even for the expected high flux of charged particles. A high single point resolution translates into excellent momentum resolution and precise extrapolation of charged particle trajectories.

2 CMS Tracker

The CMS tracker occupies a cylindrical volume around the interaction point with a length of 5.8 m and a diameter of 2.5 m. The region closest to the interaction point is equipped with a pixel system while the major part of the tracker consists of layers of silicon strip detectors. A schematic overview of the CMS tracker is shown in Figure 1. The CMS reference system has its origin in the center of the detector, the z-axis is along the beam line in the anti-clockwise direction for an observer standing in the middle of the LHC ring. The x-axis points to the LHC center and the y-axis points upward. The azimuthal angle ϕ is measured starting from the x-axis toward the y-axis. The polar radius r is defined as the distance from the z axis in the transverse x-y plane.

The pixel detector is the innermost part of the tracking system. Three cylindrical layers of pixel detector modules are complemented by two disks of pixel modules on each end. The strip detector surrounds the pixel detector and is composed of four subsystems. The central region up to a pseudo-rapidity of $|\eta| \approx 1$ is covered by the Tracker Inner Barrel (TIB) and the Tracker Outer Barrel (TOB). At each end of the TIB the remaining volume inside the TOB is filled by the Tracker Inner Disks (TID). The silicon strip system is completed by two Tracker End Caps (TEC), extending the acceptance of the tracker up to a pseudo-rapidity of $|\eta| < 2.5$.

The TIB is composed of four layers using $320\,\mu\mathrm{m}$ thick silicon micro-strip sensors. The strip pitch is $80\,\mu\mathrm{m}$ on layers 1 and 2 and $120\,\mu\mathrm{m}$ on layers 3 and 4. The TID consists of three disks on each side, also employing $320\,\mu\mathrm{m}$ thick silicon micro-strip sensors. Its mean pitch varies between $100\,\mu\mathrm{m}$ and $141\,\mu\mathrm{m}$. The TOB surrounds TIB/TID and consists of six layers of $500\,\mu\mathrm{m}$ thick sensors with strip pitches of $183\,\mu\mathrm{m}$ on the first four layers and $122\,\mu\mathrm{m}$ on layers 5 and 6. The TEC is composed of nine disks on each end, carrying up to seven rings of silicon micro-strip detectors. The sensor width is $320\,\mu\mathrm{m}$ on the inner four rings and $500\,\mu\mathrm{m}$ on the outer three rings, the mean pitch varies from $97\,\mu\mathrm{m}$ to $184\,\mu\mathrm{m}$.

All silicon strip subsystems are equipped with $r\phi$ modules. These modules have their strips parallel to the beam

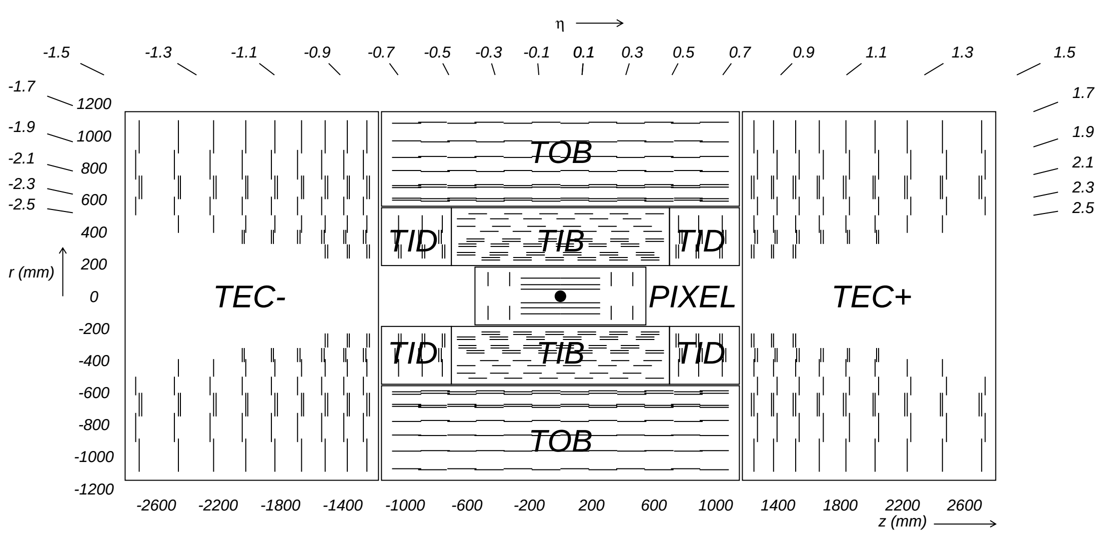


Figure 1: Schematic layout of the CMS tracker. Each line represents a detector module.

axis in the barrel and radial on the disks. In addition, the modules in the first two layers and rings of TIB, TID and TOB as well as rings 1, 2 and 5 in the TEC carry a second micro-strip detector module, generally referred to as stereo module. The stereo modules are mounted back-to-back to the $r\phi$ modules with a stereo angle of 100 mrad. The combination of $r\phi$ and stereo results in a measurement of z in the barrel and r on the disks.

A detailed description of the CMS tracker can be found in Ref. [2].

3 Track Reconstruction and Algorithms at CMS

There are three tracking algorithms available for cosmic track reconstruction: the two standard algorithms designed for the reconstruction of proton-proton collisions and adapted for cosmic tracking ("Combinatorial Track Finder" [1] and "Road Search") and one specialized algorithm for the reconstruction of single-track cosmic events ("Cosmic Track Finder"). They use reconstructed hits, i.e., position estimates based on clusters found in the modules of the tracker. These position estimates may depend on the local track angles.

All three algorithms decompose the task of track reconstruction into three stages:

1. seed finding, which provides a selection of initial hits and a first estimate of parameters,
2. pattern recognition, which associates hits to a track, and
3. track fitting, which determines the best estimate of the track parameters.

The first two items are specific to each of the algorithms while the track fit is always performed by a Kalman filter and smoother [3]. All these software modules use some common services. In the absence of a magnetic field the tracks are extrapolated as straight lines. Material effects – energy loss and multiple Coulomb scattering – are estimated each time a track crosses a detector layer. The amount of material at normal incidence is obtained via the reconstruction geometry, and the same constants as for the reconstruction of proton-proton collisions are used.

3.1 Cosmic Track Finder

The Cosmic Track Finder is designed as a simple and robust algorithm, tailored to the specific task of reconstructing single tracks without imposing a region of origin, but assuming a preferred direction. It assumes that cosmic events yield a considerably lower number of hits in the tracker than proton-proton collisions. Hence, any combination of two hits that are compatible with the geometric acceptance from different layers is used to build the initial track seed. Geometrical compatibility is motivated by the small incident angles of cosmic tracks and restricts the distance between the two seed hits in all three global coordinates.

The pattern recognition starts by ordering the hits with respect to the global y coordinate. Subsequently the algorithm attempts to add the hits to the candidate tracks in the order defined by the previous sorting procedure. The compatibility of the hit with the propagated trajectory is evaluated using a χ^2 estimator. The uncertainty from multiple scattering is considered when the track is propagated. All hits in the given layer are tested for compatibility.

At the end of the pattern recognition step several trajectories are reported, but only one is retained since only one track per event is expected. The best trajectory is chosen based on the following criteria: largest number of layers with hits in the trajectory, largest number of hits in the trajectory and smallest χ^2 value.

3.2 Combinatorial Track Finder (CTF)

In standard track reconstruction, i.e., for particles coming from the interaction point, the CTF builds a seed out of either a hit pair in the inner layers and a loose beam spot constraint or out of a hit triplet in the inner layers. The starting parameters of the trajectory are calculated from a helix passing through the three points. The selected hits must be pointing towards the interaction point and a minimum p_T cut is applied.

In the pattern recognition step, each trajectory determined in the seeding step is propagated to the next surface. Hits are looked for in a window whose width is related to the precision of the track parameters. If a hit is found inside this window it is added to the candidate trajectory and the track parameters are updated. If several compatible hits are found a new candidate is created for each of them. Candidates are sorted according to quality (based on the χ^2 and the number of hits) and the five best are retained for further propagation. As hits are added to the candidate trajectory the knowledge of the track parameters improves and the size of the search window decreases. Propagation of a candidate ends if configurable cuts on the number of layers or the number of consecutive layers without a hit are exceeded.

To allow cosmic track reconstruction various modifications were implemented. In the seeding the beam spot requirement is not applied anymore, and the seeds are created in the outer layers of the tracker. The pattern recognition has been adapted to allow for propagation between the upper and lower hemispheres of the tracker and to allow for missing hits due to non-hermetic coverage of the tracker for cosmic tracks.

3.3 Road Search

The Road Search algorithm treats the CMS tracker in terms of *rings*, where a ring contains all tracker modules at a given r-z position, spanning 360° in ϕ. A track will be a line in r-z, and the algorithm uses pre-defined sets of rings consistent with a line in r-z in which it will search for a track. These pre-defined sets of rings are referred to as *roads*.

For seed finding, the Road Search algorithm uses pairs of hits in seed rings. A cut is imposed on the maximal difference in the azimuthal angles of the seed hits ($\Delta\phi$), translating to a requirement on the minimum transverse momentum of the track. The set of rings that composes the road will be those consistent with the linear extrapolation between the seed rings in the r-z plane.

In the first part of the pattern recognition step, an expected trajectory is determined using the two seed hits and the beamspot. The trajectory is extrapolated through the other rings of the road, and hits are collected inside a narrow window around the expected trajectory. This collection should contain all the hits of a track, along with other hits that happen to overlap and lie close to the track. In the second part of pattern recognition, the collection of hits is turned into a trajectory. A trajectory is first built in low occupancy layers, extrapolating inside-out. With the trajectory well-defined from the low occupancy layers, hits from the higher occupancy layers are added to the trajectory. The final track will contain at most one hit per detector module, though potentially more than one hit per layer due to detector overlaps.

The standard Road Search algorithm had to be slightly modified in order to reconstruct cosmic muons. In the standard algorithm roads are constrained to point back to the luminous region of the beam, centered at $z = 0$. Cosmic rays will not point back to $z = 0$, so for cosmic track reconstruction specific roads were generated, where the constraint on the extrapolation of the roads was loosened to include any pair of seed rings within the acceptance of the read-out detector. In addition, hits are sorted in y, rather than inside out.

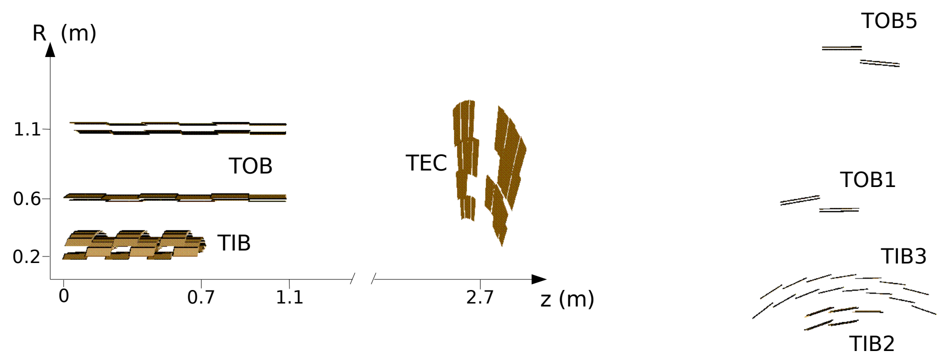
4 Tracking Performance at the Magnet Test and Cosmic Challenge (MTCC)

First experience with tracker operations and track reconstruction was gained during summer 2006, when a small fraction of the silicon strip tracker was operated at room temperature in a comprehensive slice test involving various CMS sub-detectors (with the exception of the pixel system). Cosmic rays detected in the muon chambers were used to trigger the readout of all CMS sub-detectors in the presence of a magnetic field (B) of up to 4 T. Although the tracker setup was limited and represented only 1% of the total electronic channels and an active area of $0.75\,\mathrm{m}^2$, most of the selected hardware and software systems were advanced prototypes of the final versions. The MTCC tracker layout is shown in Figure 2.

Over 25 million events were recorded, and the tracking performance was studied using the Cosmic Track Finder and the Road Search algorithm. In addition, tracks reconstructed in the silicon strip tracker were compared with tracks detected by the muon chambers. The tracker operation and performance results at the MTCC are described in detail in Ref. [4].

4.1 Tracking Performance

The MTCC data sample has been split into three different data samples according to the magnetic field value. About 10 million events have been recorded with zero magnetic field, and nearly 15 million events have been recorded with B $\geq 3.8\,\mathrm{T}$. Due to the small acceptance of the tracker layout, the number of reconstructed tracks is drastically reduced, and the exact numbers for both the Road Search algorithm and the Cosmic Track Finder are given in Table 1. The smaller number of reconstructed tracks of the Road Search algorithm is due to seeding, which requires an inner seed in TIB layer 2 and an outer seed in TOB layer 1 or 5, resulting in a limited geometrical acceptance. The minimum number of hits per track has been set to three for both algorithms.



(a) (b)

Figure 2: Layout of the Tracker MTCC setup: (a) 3D view (the z axis goes from left to right); (b) x-y view of the barrel part. The instrumented parts are a fraction of layer 2 and layer 3 of TIB, a fraction of layer 1 and layer 5 of TOB, and a fraction of disk 9 of TEC.

The distributions of relevant quantities of reconstructed cosmic muon tracks in the $\mathrm{B} = 3.8\,\mathrm{T}$ data sample are shown in Figure 3. Apart from the different number of reconstructed tracks, the two tracking algorithms lead to similar results. Both ϕ and η distributions of the two tracking algorithms are compatible with the trigger layout.

Table 1: Number of reconstructed tracks for the Cosmic Track Finder and the Road Search algorithm in the different data samples defined by the magnetic field value.

	$\mathrm{B} = 0.0\,\mathrm{T}$	$\mathrm{B} = 3.8\,\mathrm{T}$	$\mathrm{B} = 4.0\,\mathrm{T}$
Road Search	4737	2343	267
Cosmic Track Finder	5108	3588	583

4.2 Comparison to Tracks Reconstructed in the Muon Chambers

Since the muon system was an integral part of the MTCC it is possible to compare the tracks reconstructed in the tracking system with tracks reconstructed in the muon chambers. This allows a verification of the track reconstruction results. In order to obtain a pure reference sample, tracks reconstructed locally in the muon system are required to have at least 10 hits. Additionally, tracks in both the tracking system and the muon system have to be geometrically compatible. Using the tracks reconstructed in the muon system as a reference, the difference and resolution of the transverse momentum and of the pseudo-rapidity η have been studied for both the Cosmic Track Finder and the Road Search algorithm. Figure 4 shows the corresponding distributions for single track events in the $\mathrm{B} = 3.8\,\mathrm{T}$ sample. A gaussian fit was applied to the central region of these histograms, and both track reconstruction algorithms give similar results.

5 Tracker Commissioning at the Tracker Integration Facility (TIF)

In the period from November 2006 to July 2007 the different sub-systems of the silicon micro-strip tracker were integrated and commissioned in a dedicated area at CERN, called the Tracker Integration Facility (TIF) [5]. As part of the commissioning large samples of cosmic ray data were recorded under different running conditions. No magnetic field was present, and the tracker setup consisted of up to 15 % of the total electronic channels. Cosmic muon triggering was provided by scintillation counters mounted on the top and bottom of the tracker. A schematic view of the layout is shown in Figure 5. A lead plate with a thickness of 5 cm was located on top of the lower scintillation counter to avoid triggering on very low momentum tracks, translating into a minimal cosmic momentum of 200 MeV. Over 4.5 million events were recorded while operating the detector at five different temperature points, and about 2.2 million muon tracks have been reconstructed. The data were used to verify the reconstruction and calibration algorithms for low- and high-level objects and to compare to simulated events. The tracking performance was studied using all three algorithms described in Section 3.

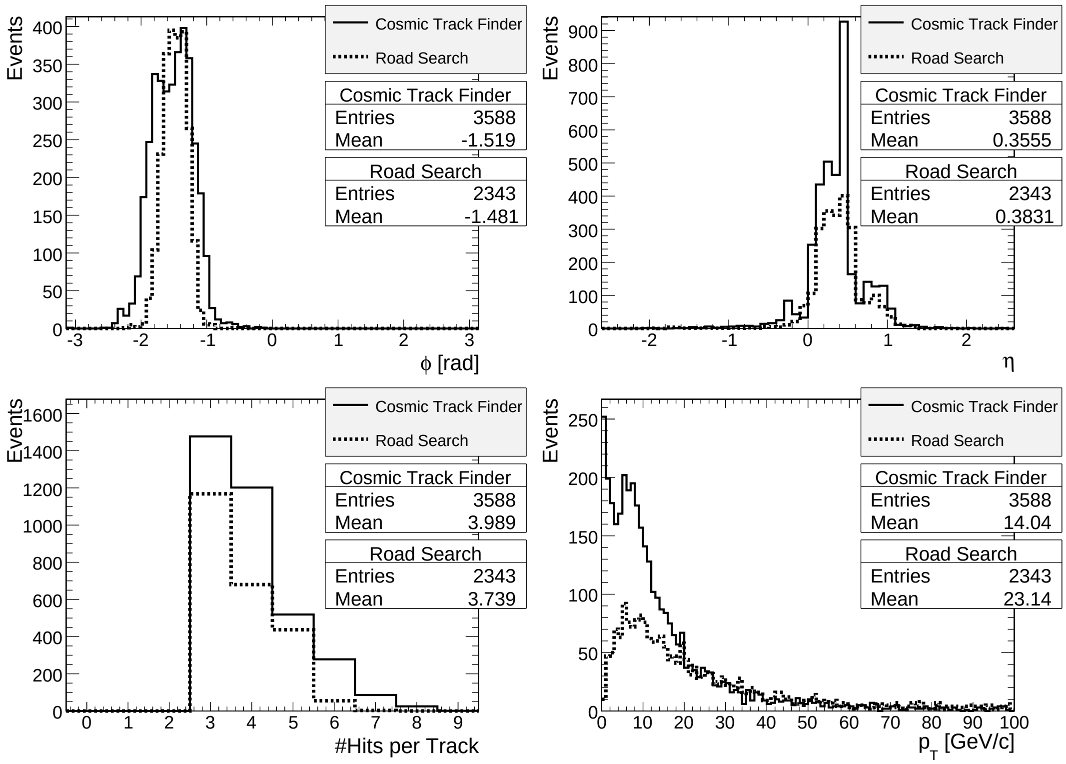


Figure 3: Track distributions for the Cosmic Track Finder (solid line) and the Road Search algorithm (dotted line) in the $\mathrm{B} = 3.8\,\mathrm{T}$ data sample: ϕ (top left), η (top right), number of hits per track (bottom left), p_T (bottom right). The distributions show all reconstructed tracks (including multiple track events for the Road Search algorithm) with at least 3 hits per track.

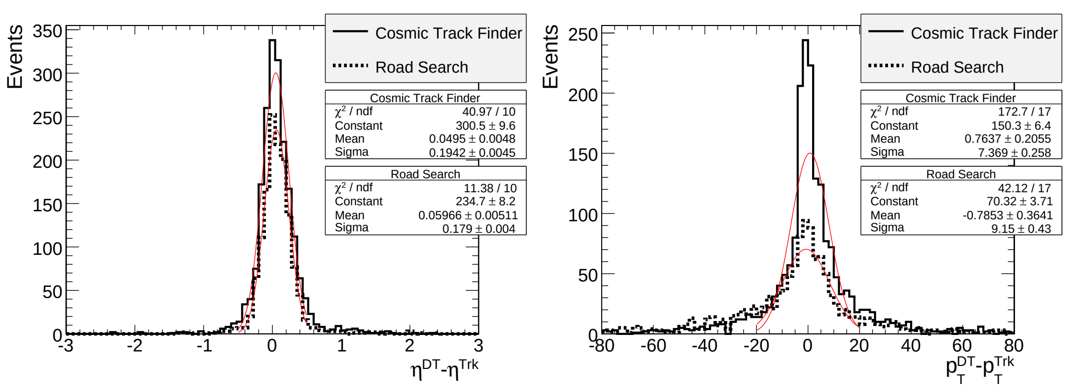


Figure 4: $\Delta\eta$ and Δp_T in the $\mathrm{B} = 3.8\,\mathrm{T}$ data sample for tracks reconstructed in the muon system (DT) and tracks reconstructed in the tracking system (Trk). The dotted line shows the results from the Road Search algorithm, the solid line shows the Cosmic Track Finder results. A gaussian distribution has been fitted to the central region of the histograms.

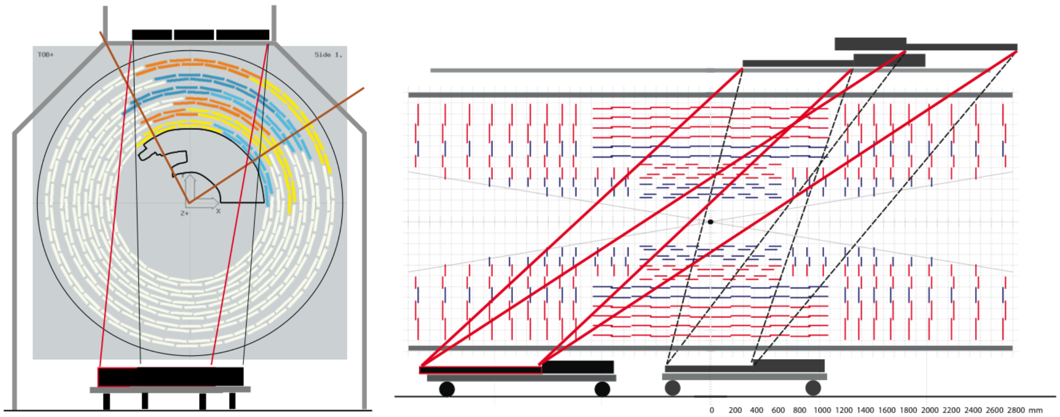


Figure 5: Layout of the trigger scintillator positions used during the cosmic data taking at the TIF. The x-y view is shown on the left side, the r-z view is shown on the right. The straight lines connecting the active areas of the top and bottom scintillation counters indicate the acceptance region. In the x-y view, the active TOB modules are shown in contrasting colors while the active TIB area is framed in black.

5.1 Tracking Performance

The TIF cosmic run data has been split into several data samples according to operating temperature. The number of reconstructed single track events for all three track reconstruction algorithms, without applying any track quality cuts, is presented in Table 2. In contrast to the Cosmic Track Finder, both the CTF and the Road Search algorithms are able to reconstruct more than one track per event. Hence it is expected that the number of single track events is higher for the Cosmic Track Finder in comparison to the other two algorithms. Events with multiple tracks are characterized by a larger amount of mis-reconstructed tracks and require special dedicated studies.

Table 2: Total number of recorded events and number of reconstructed single track events for all three tracking algorithms in the different data samples defined by the operating temperature.

Temperature [°C]	Total Events	Reconstructed Single Track Events		
		Cosmic Track Finder	CTF	Road Search
15	1.2 M	780 k	740 k	710 k
10	1.0 M	290 k	270 k	250 k
-1	900 k	520 k	490 k	450 k
-10	900 k	530 k	490 k	460 k
-15	660 k	85 k	16 k	80 k

To visualize the track reconstruction results the data sample taken at $\mathrm{T} = -10°\mathrm{C}$ has been chosen. The number of reconstructed tracks for all three tracking algorithms is shown in Figure 6, together with several track distributions from single track events. Apart from the different number of reconstructed tracks all three tracking algorithms lead to similar results. The cluster charge distribution shows that neither algorithm is prone to pick up noise hits, which would otherwise appear at small values in the histogram. The η distribution is compatible with the trigger layout. The ϕ distribution shows a peak around $-\pi/2$, compatible with tracks that originate from the top of the detector and travel outside-in.

5.2 Hit Reconstruction Efficiency

The hit reconstruction efficiency for modules was estimated using the capability of the Kalman fitter to provide optimal predictions of the track parameters on all surfaces crossed by a track. For the pattern recognition part the CTF was used and the analysis was performed for all modules of a layer at a time. In order to avoid any bias due to correlations between hit and track finding efficiencies none of the hits in the layer under consideration were used in seeding or pattern recognition.

To obtain a sample of well reconstructed events, certain quality criteria were applied. Cosmic showers were rejected by retaining only single track events, and the acceptance was restricted by requiring one track hit in the first TIB layer and one track hit in one of the last two TOB layers. A correct measurement of the track in the r-ϕ

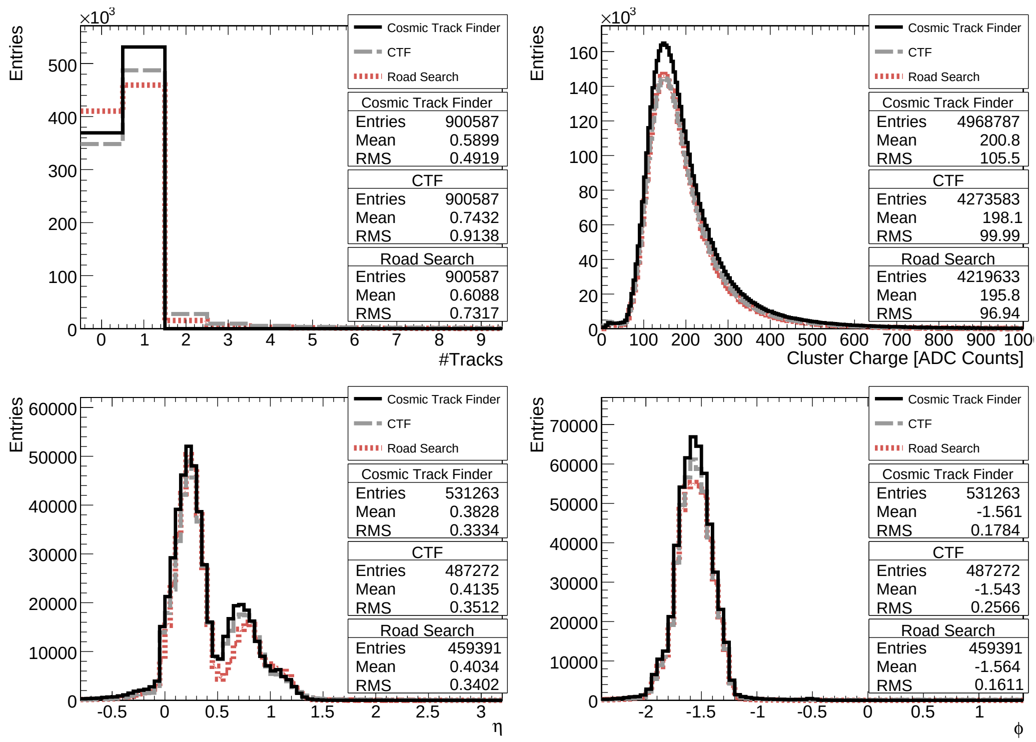


Figure 6: Number of reconstructed tracks (top left) and several track distributions in single track events using data taken at $\mathrm{T} = -10°\mathrm{C}$: cluster charge of hits belonging to the track (top right), η (bottom left), ϕ (bottom right). The results of the Cosmic Track Finder are shown as a solid line, while results from the CTF are shown as a dashed line and results from the Road Search algorithm are shown as a dotted line.

and r-z planes was established by mandating at least four reconstructed hits, with at least three hits from layers with $r\phi$ and stereo modules. To compensate for the removal of the hits in the layer under test, at most five "lost" hits and no more than three consecutive ones were required.

The efficiency for a module was measured by requiring an intersection with the interpolated track and by checking for the presence of a hit. Due to the alignment uncertainty, the distance between the hit and the predicted track position was not used. An upper cut of 30° on the angle of incidence of the track w.r.t. to the normal to the module plane, applied in TIB layer 2, selected topologies similar to the ones expected from proton-proton collisions. In order to avoid artificial inefficiencies at the edge of the sensitive region a fiducial area was defined.

The method has been validated on simulated events before being applied to data. In simulation it yields to efficiencies compatible with 100 %, as expected. An artificial inefficiency of 5 % was generated by randomly removing hits from TIB layer 3 and TOB layer 4. The algorithm perfectly reproduces this inefficiency as shown in Figure 7. The results of the TIF data set taken at $\mathrm{T} = -10°\mathrm{C}$ are also shown in Figure 7. The efficiency exceeds 99.8 % for all measured layers. Corresponding efficiencies have been obtained in the other data sets.

6 Conclusions

First results with the CMS tracking algorithms have been obtained by studying cosmic muon data obtained from the MTCC and from the tracker commissioning at the TIF. Both the CTF and the Road Search algorithms, designed to reconstruct tracks in proton-proton collisions, were modified to reconstruct cosmic muon tracks. Their results have been compared to each other and to results from a dedicated cosmic muon tracking algorithm, the Cosmic Track Finder. All three algorithms deliver comparable results and show a good agreement. The tracking results are used to perform more elaborate studies about the performance of the CMS tracker, including the hit reconstruction efficiency.

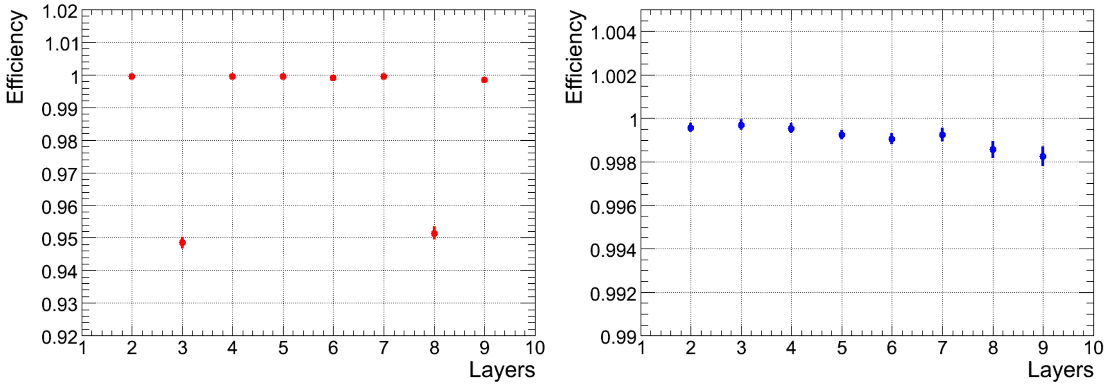


Figure 7: Layer efficiency in simulated events (left) and in data taken at $\mathrm{T} = -10°\mathrm{C}$ (right). Layers 1 to 4 correspond to TIB layers 1 to 4, layers 5 to 10 correspond to TOB layers 1 to 6. In simulation, 5 % of the hits are artificially removed from TIB layer 3 and TOB layer 4.

References

[1] The CMS collaboration, *Detector Performance and Software Physics Technical Design Report, Volume I*, CERN/LHCC 2006-001, CMS TDR 8.1.

[2] CMS Collaboration, *Tracker Technical Design Report*, CERN/LHCC 98-6, April 1998;
CMS Collaboration, *Addendum to the CMS Tracker TDR*, CERN/LHCC 2000-016, February 2000.

[3] R. Fruhwirth, *Application Of Kalman Filtering To Track And Vertex Fitting*, Nucl. Instrum. Meth. A 262 (1987) 444.

[4] D. Abbaneo *et. al.*, *Tracker Operation and Performance at the Magnetic Test and Cosmic Challenge*, CMS Note 2007/029.

[5] C. Delaere *et. al.*, *CMS Tracker Commissioning and First Operation Experience*, in proceedings of ”16th International Workshop on Vertex Detectors”, PoS(Vertex 2007)002