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Track Reconstruction Performance in CMS

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Abstract

The expected performance of track reconstruction with LHC events using the CMS silicon tracker is presented. Track finding and fitting is accomplished with Kalman Filter techniques that achieve efficiencies above 99% on single muons with p_T >1 GeV/c. Difficulties arise in the context of standard LHC events with a high density of charged particles, where the rate of fake combinatorial tracks is very large for low p_T tracks, and nuclear interactions in the tracker material reduce the tracking efficiency for charged hadrons. Recent improvements with the CMS track reconstruction now allow to efficiently reconstruct charged tracks with p_T down to few hundred MeV/c and as few as three crossed layers, with a very small fake fraction, by making use of an optimal rejection of fake tracks in conjunction with an iterative tracking procedure.

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Track Reconstruction Performance in CMS

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The expected performance of track reconstruction with LHC events using the CMS silicon tracker is presented. Track finding and fitting is accomplished with Kalman Filter techniques that achieve efficiencies above 99% on single muons with p_{T} >1 GeV/c. Difficulties arise in the context of standard LHC events with a high density of charged particles, where the rate of fake combinatorial tracks is very large for low p_{T} tracks, and nuclear interactions in the tracker material reduce the tracking efficiency for charged hadrons. Recent improvements with the CMS track reconstruction now allow to efficiently reconstruct charged tracks with p_{T} down to few hundred MeV/c and as few as three crossed layers, with a very small fake fraction, by making use of an optimal rejection of fake tracks in conjunction with an iterative tracking procedure.

1. Introduction

Tracking at the LHC is an experimental challenge. At the design luminosity of 10^{34} cm^{-2}s^{-1} the proton-proton collisions at $\sqrt{s}$=14 TeV will produce on average 20 superimposed events at a bunch crossing rate of 40 MHz. Each bunch crossing will produce on average about 2000 charged tracks in the $|\eta| < 2.5$ range, resulting in a density of 2.5 charged tracks per cm^2 at $\eta = 0$, at a distance of 4 cm from the interaction region.

The CMS experiment [1] is one of the two general purpose experiments at the LHC. In CMS track reconstruction relies on a silicon pixel and micro-strip tracker immersed in a 3.8 T solenoidal magnetic field along the beam line. The CMS reference system has origin at the detector and interaction region center, with the z-axis along the beam line, the y-axis upwards and the x-axis in the direction of the LHC center. The transverse plane is denoted as the xy or $r\phi$ plane.

2. The CMS tracker

The CMS inner tracker [2] is the largest silicon tracker ever built. It consist of over 15 thousand pixel and silicon strip modules covering an area of more than 200 m^2, arranged around the interaction point as depicted in Figure 1.

The pixel detector consist of about 66 million $100{\times}150$ μm^2 pixels arranged in three barrel layers at 4.4, 7.3 and 10.2 cm from the beam line, and two endcap layers at 34.5 and 46.5 cm on each side of the interaction point.

The tracker inner barrel (TIB) and outer barrel (TOB) form ten cylindrical layers of silicon strip detectors around the beam line at radii ranging from 25 to 108 cm. The tracker inner disks (TID) and end-caps (TEC) consist respectively of three and nine concentric ring structures extending the tracker volume to $z = \pm 270$ cm along the beam line, covering down to $|\eta| = 2.5$.

The silicon strip pitches vary from 80 μm in the inner layers to 184 μm in the outer layers. Strips are mostly arranged in the z direction in the barrel layers, yielding $r\phi$ measurements, and in the radial direction in the endcap disks, yielding $z\phi$ measurements.

As shown in Figure 1, the innermost layers and rings of each subsystem are equipped with back-to-back sensors mounted with a stereo angle of 100 mrad between the strips. These stereo layers allow z measurements in the barrel layers and r measurements in the endcaps, i.e. full three-dimensional determinations of the track position.

The CMS tracker, with *i)* an excellent silicon detector spatial resolution, *ii)* a large level arm *iii)* a large number of layers and *iv)* a large bending magnetic field, is designed to achieve an

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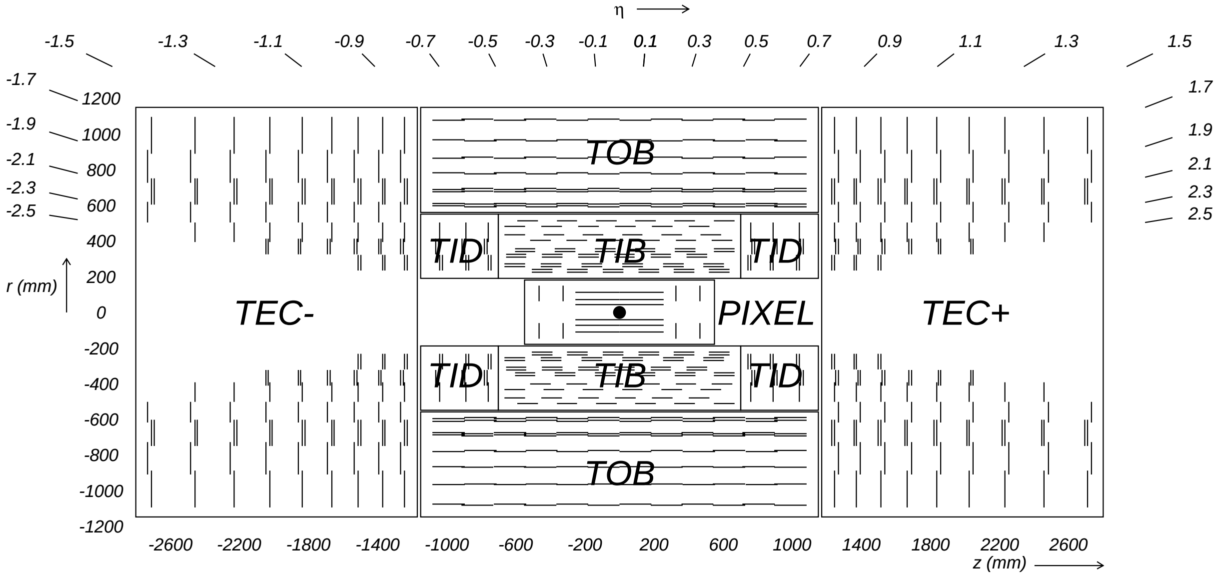

Figure 1. View in the $r - z$ plane of the CMS inner tracker showing the dimensions and the pseudorapidity coverage. Segments represent detector modules.

outstanding momentum resolution for high p_{T} tracks.

3. Track reconstruction

Different algorithms are used in CMS for track reconstruction. All methods use the reconstructed positions (hits) of the passage of charged particles in the silicon detectors to determine the helix trajectories of the charged tracks and therefore measure their directions and momenta. The main standard algorithm designed for the reconstruction of proton-proton collisions is the Combinatorial Track Finder (CTF). The CTF proceeds in three stages: (1) seeding, (2) finding and (3) fitting.

In the seeding stage pairs of hits, that are compatible with the interaction region above a lower p_{T} limit, are considered as possible candidates of charged tracks. Pixel hits provide the best track seeding, given their three-dimensional position information and lower occupancy. The seeding efficiency with pixel hits drops in the $2 < |\eta| < 2.5$ forward region where a mixed seeding of hits from pixels and inner strips is needed to achieve a fully efficient track finding in the whole tracker acceptance.

The track finding stage is based on a standard Kalman Filter pattern recognition approach [3]. Starting with the seeded parameters, the track trajectory is extrapolated to the neighboring tracker layers and compatible hits are assigned to the track. The Kalman Filter is a succession of alternating prediction and filtering steps. At each stage the Kalman Filter updates the track parameters with new hits, allowing for a missing (lost) hit in a layer, in case of detector inefficiencies. The updated tracks are assigned a quality and only the best ones are kept for further propagation. Possible ambiguities with tracks sharing several hits are resolved in favour of the best quality trajectories. During the extrapolation, the uncertainties of each track trajectory in the $r\phi$ transverse plane converge to a low level for tracks traversing many (≥ 5) layers, so that the hit assignment becomes fast and efficient.

The final estimate of the five parameters of each track helix is completed in the third stage applying again the Kalman Filter for the trajectory fitting [4]. Each trajectory is refitted using a least-squares fit in two stages. A first forward fit, inside-out from the interaction region, removes the approximations and biases of the seeding and finding stages. A second outside-in smoother fit yields the final best estimates of the track parameters at the origin vertex.

In the central region $|\eta| < 1$, the obtained p_{T} resolution is better than 1% for tracks with $p_{\mathrm{T}} \leq 10\,\mathrm{GeV/c}$. At higher p_{T} the momentum resolution worsens approximately as $\Delta(1/p_{\mathrm{T}}) \sim 0.2\ \mathrm{TeV}^{-1}$. The resolution on the transverse and longitudinal impact parameters in the central region is $\Delta d_0 \sim 10\ \mu\mathrm{m}$ and $\Delta z_0 \sim 20\ \mu\mathrm{m}$, for single muons of very high $p_{\mathrm{T}} > 100$ GeV/c. At lower p_{T} the track impact parameter resolution worsens approximately with an additional $\Delta d_0 \sim \Delta z_0 \sim 100\mu\mathrm{m}/p_{\mathrm{T}}(\mathrm{GeV/c})$.

The first results obtained with cosmic data [5] prove that the CMS tracker is ready for collision data.

4. Reconstruction efficiency and fake rate

The reconstruction of single muons with the CTF algorithm is almost fully efficient over the whole acceptance range [1].

For charged hadrons (mostly pions) the reconstruction is more problematic due to their nuclear interactions in the tracker material, that corresponds to $\sim 0.4X_0$ at $\eta \sim 0$ and grows abruptly to $\sim 1.8X_0$ for $|\eta| \simeq 1.5$. In this situation a considerable fraction of pions sustain nuclear interactions while crossing the tracker and only a shorter initial part of their trajectory can be reconstructed.

The problem with the reconstruction of tracks with few hits is related to their combinatorial fake rate, i.e. to the amount of reconstructed tracks that are not originating from a true charged particle.

In a typical LHC collision event with QCD jets and a high density of charged tracks, the CTF track finder yields a significant fraction of fake tracks. The number and fraction of fake tracks as a function of the number of crossed layers is shown in Figure 2 where tracks are reconstructed with $p_{\mathrm{T}} > 300$ MeV/c, using simulated LHC collisions events with a medium effective centre-of-mass energy $\hat{p_{\mathrm{T}}}$=170-230 GeV/c.

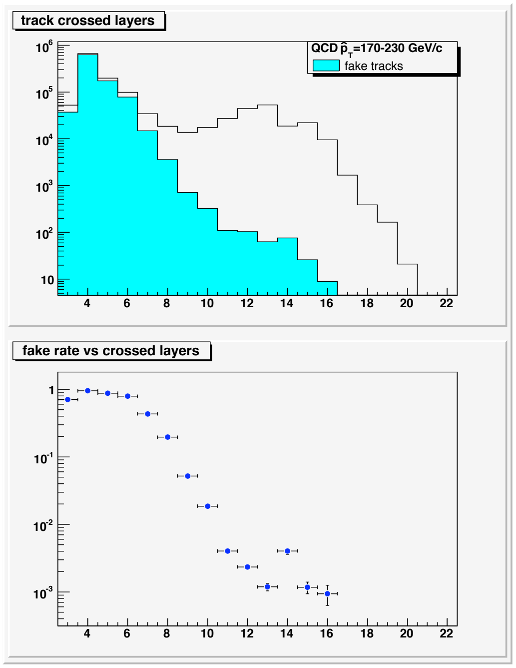

Figure 2. Distribution of true and fake tracks (top) and fake rate fraction (bottom) as a function of the number of crossed layers, using simulated QCD $\hat{p_{\mathrm{T}}}$=170-230 GeV/c, and reconstructing tracks with p_{T} >300 MeV/c.

It can be seen that the number of fake tracks decreases exponentially as a function of the number of crossed layers. The fraction of fake tracks approaches unity for tracks crossing few layers, while tracks with many crossed layers (> 10) have a natural fake rate at the per mill level. The rate of reconstructed fake tracks also increases sensibly in the low p_{T} <1 GeV/c region.

Analysis and results published in the CMS Physics TDR [1] used only tracks with a minimum of 8 crossed layers and p_{T} >0.8 GeV/c, that allowed to keep the fake rate at the 0.5% level. This reduces the overall tracking efficiency at the 80% level for tracks with p_{T} >0.9 GeV/c [1], with no possibility to reconstruct the high multiplicity of tracks $p_T < 0.8$ GeV/c that don't even reach the CMS calorimeters.

5. Fake tracks filtering

The ability to reconstruct low p_T and short charged tracks, with a low fake rate, has been recently recovered by applying a track quality filter adapted to the track kind. The rejection of fake tracks is obtained by applying optimal cuts to five independent variables: 1) the track fit χ^2 probability, 2) the track d_0 distance to the beam line and 3) measured error δd_0, 4) the track longitudinal compatibility with the interaction vertices Δz_i and 5) measured error $\delta \Delta z_i$.

The applied cuts are optimised as a function of the track p_T, $|\eta|$ and number of crossed layers in order to achieve the best efficiency for a given fake rate level. In practice no quality cuts are applied to tracks with many hits ($>$ 10 crossed layers), while progressively harder cuts are needed for tracks with fewer hits and lower p_T. Results are shown in Figure 3 where an average efficiency around 90% for all tracks with $p_T > 300$ MeV/c is obtained with the "tight" selection, keeping the fake rate at the per mill level.

6. Iterative tracking

A further improvement to the tracking is obtained using an iterative procedure in the track reconstruction, i.e. running different times the CTF algorithm. After a first CTF iteration a high purity filter is applied to the reconstructed tracks and these are put in a first track collection. Hits associated with the tracks in the first collection are removed, and the remaining hits are used for a second CTF iteration. This procedure is repeated three or four times with a different seeding and filtering at each iteration.

The iterative procedure allows a faster and better reconstruction of charged tracks with respect to a single CTF iteration, raising by about 5% the reconstruction efficiency with similar fake rate levels. This is therefore the current default track reconstruction procedure in CMS.

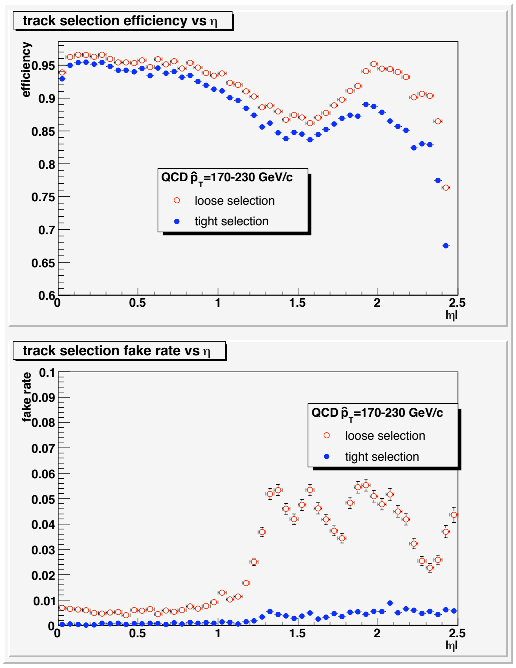

Figure 3. Track reconstruction efficiency and fake rate for all charged particles with $p_T \geq 300$ MeV/c as a function of the track pseudorapidity η. The looser filter selection (empty dots) ensures a higher efficiency at the cost of a larger fake rate in particular in the $|\eta| > 1$ forward region.

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