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Track Reconstruction in the CMS Tracker

T. Speer[1], W. Adam[2], R. Frühwirth[2], A. Strandlie[3], T. Todorov[4][5] and M. Winkler[5].

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Abstract

An overview of the track reconstruction algorithms used in the tracker of the CMS experiment at the LHC is presented. At the LHC, track reconstruction will be a very challenging task due to the high number of tracks foreseen. In addition to the standard Kalman filter, which serves as the basis for track reconstruction, several non-linear algorithms have been implemented.

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[1] Physik-Institut der Universität Zürich, Zurich, Switzerland

[2] Institute for High-Energy Physics, Austrian Academy of Sciences, Vienna, Austria

[3] Gjøvik University College, Gjøvik, Norway

[4] IReS, Strasbourg, France

[5] CERN, Geneva, Switzerland

1 Introduction

The LHC is a proton-proton collider with a centre-of-mass energy of $\sqrt{s} = 14\,\mathrm{TeV}$. For the first three years, an initial phase with an instantaneous luminosity in the order of $2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ is foreseen, after which the luminosity will be raised to $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. CMS is one of the two general purpose experiments which will be operated at the LHC to explore the full range of physics that can be accessed at LHC energies. To fulfill this task, a robust and versatile tracking system within a strong magnetic field is essential.

Track reconstruction will be a very challenging task due to the high number of tracks foreseen. At high luminosity, an average of 20 minimum bias events are expected per bunch crossing, which will produce more than 1000 reconstructible tracks in the tracker. This will result in track densities which can be as high as 10 tracks per cm^2 per bunch crossing at a radius of 2 cm. Reconstruction efficiencies have to be high and track parameters have to be measured with a good resolution over a large momentum range. The resolution on the transverse momentum is required to be between 1 and 2% at a track-momentum of $100\ \mathrm{GeV}/c$ to be able to reconstruct narrow resonances, and good impact parameter resolutions are needed to reconstruct secondary vertices.

2 The CMS tracker

The tracker [1] is located, together with the electromagnetic and hadronic calorimeters, inside a 4 T solenoidal magnetic field. CMS has chosen an all-silicon configuration with 13 to 14 measurement layers, each able to provide robust and precise coordinate determination. The tracker is thus composed of a pixel detector, providing two to three hits per track, followed by a Silicon Strip Tracker (SST) providing 10 to 14 hits.

The pixel detector is composed of three cylindrical barrel layers and two pairs of disks in the end-caps, such that three points are measured per track for $|\eta| < 2.2$. In the barrel, the three layers are located at radii of 4.3 cm, 7.5 cm and 10.2 cm, and in the end-caps, the two pairs of disks are located at $|z| = 34.5$ cm and 46.5 cm. With a pixel size of $100 \times 150\ \mu\mathrm{m}^2$, the hit resolution is approximately of 10 μm in $r - \phi$, using charge sharing induced by the Lorentz angle of $23°$, and 20 μm in $r - z$.

The SST is divided in four parts. The *Inner Barrel* (TIB) is composed of four cylindrical layers, enclosed by three pairs of disks (*Inner Disks* – TID). It is then followed by the six cylindrical layers of the *Outer Barrel* (TOB). The *End-Caps* (TEC) are made of nine pairs of disks. The maximum radius is 1.1 m. The disks of the TID are composed of 3 rings of modules and the TEC disks of up to 7 rings. The first two layers of both the TIB and the TOB, the first two rings of the TID and rings 1, 2 and 5 of the TEC are instrumented with double sided modules, where the detectors are glued back-to-back with a stereo angle of 100 mrad. With this variety of detectors, there are 14 different sensor geometries. Strip lengths range from 9 cm in the inner part to 21 cm in the outer part, and pitches range from 80 to 205 μm.

3 Track reconstruction

3.1 The Combinatorial Kalman filter

The most often used algorithm for track reconstruction is the Combinatorial Kalman filter (CKF) [2], and it is indeed the main algorithm to reconstruct charged tracks in the CMS tracker. It is mathematically equivalent to a global least-squares minimization (LSM), which is the optimal estimator when the model is linear and all random noise is Gaussian. For non-linear models or non-Gaussian noise, it is still the optimal linear estimator. It is a local method, where one track is reconstructed at a time. As it is a recursive procedure, where the estimates of the track parameters, starting from an initial trajectory, are updated (and improved) with each successive hit, it is able to integrate pattern recognition and track fitting. It is also able to take into account energy loss and multiple scattering in and between layers.

At CMS, the reconstruction is decomposed into four modular, independent, components. In the most often used procedure, tracks are grown layer by layer, from the first pixel layers to the outer layer of the SST (*inside-out tracking*). In the first phase, the initial trajectory candidates, called *seeds*, are constructed for each pair of hits in two given layers, compatible with a given beam spot and a minimum transverse momentum requirement, using every combination of two pixel layers. The seeds are then cleaned to avoid redundancy. With the fine granularity and the low occupancy of the pixel detector and the high hit purity, the number of seeds obtained is still reasonable, and these are of good quality. In addition, by starting in the pixel detector, hadrons have a higher chance of being reconstructed, since, due to the material in the tracker, these have high interaction probability, with approximately

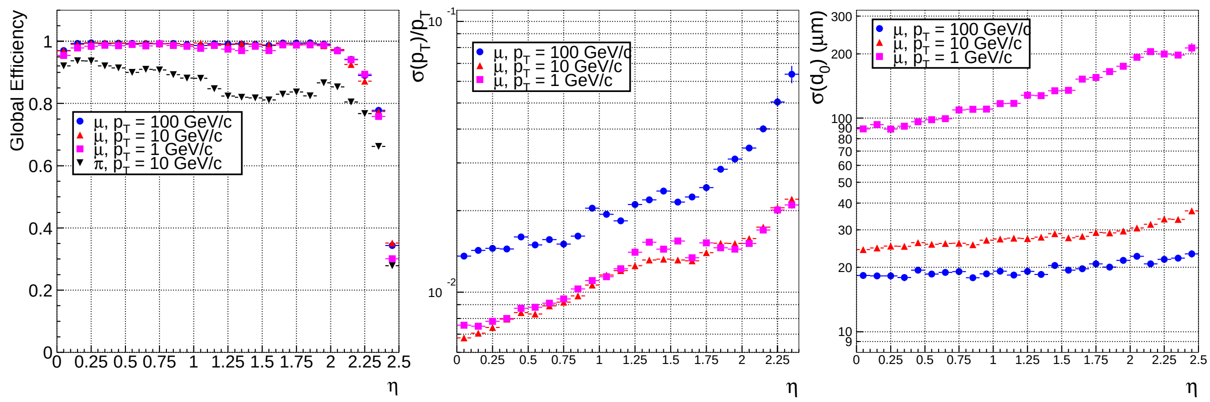

Figure 1: *Track reconstruction efficiency for single tracks with the CKF (left) and resolution of the transverse momentum (middle) and transverse impact parameter (right) for single muon tracks with the CKF.*

20% of 1 GeV pions not reaching the outer layer. This procedure implicitly favours tracks with pixel hits, since these are essential to attain the precision on the track parameters needed at the vertex.

Procedures where tracks are grown from the outermost to the innermost layer (*outside-in tracking*) are used to reconstruct muons and electrons from photon conversions. The seeds are then formed from hits in the outer layer of the tracker, based on muon-chamber seeds for muons and ECAL clusters for electrons. These methods will not be discussed here.

Next, the trajectories are constructed from a given seed. The trajectories are propagated from layer to layer, accounting for multiple scattering and energy loss. On each new layer, new trajectories are constructed, with updated parameters (and errors) for each compatible hit in the layer. In addition, one further trajectory is created, in which no measured hit is used, to account for the possibility that the track did not leave any hit on that particular layer. All resulting trajectories are then propagated to the next layer, and the procedure is repeated until the outermost layer of the tracker is reached. In order not to bias the result, all trajectories are propagated in parallel. To limit the number of combinations, only a maximum number of candidates are retained at each step, based on their χ^2 and number of missing hits.

Each seed usually results in a large number of mutually exclusive trajectory candidates, as these candidates are composed to a large extent of the same hits. In the next phase, the hit assignment ambiguities are resolved by selecting a subset of compatible candidates, based on the number of hits shared by the trajectories and the track quality. Finally, the final fit of the track is performed, where optimal estimates at every measurement point along the track are obtained, with all measurements taken into account.

With this strategy, single track reconstruction efficiencies better than 98% for muons up to $|\eta| = 2.2$ (Figure 1 (left)) are obtained. For pions, efficiencies are obviously lower because of nuclear interactions in the tracker. It has been shown that due to the fine granularity and low occupancy, pattern recognition problems and reconstruction ambiguities are solved after the first few layers, and contamination from spurious hits is low, even with pile up.

The resolutions on the transverse momentum and the transverse impact parameter d_0 are shown for muons in Figure 1 (middle and right). At a p_T of 100 GeV$/c$, the p_T resolution is around 1-2% up to $|\eta| = 1.75$, after which the lever arm of the measurement is reduced, and the material in the tracker accounts for between 20 and 30% of the resolution.The d_0 resolution is dominated at high momentum by the resolution of the first hit in the pixel detector. The resolution of track parameters is obviously progressively degraded by multiple scattering at lower momenta.

The resolutions reach an asymptotic value after using only the first five to six hits. This allows the CKF to be used in the High-Level Trigger (HLT) already, by stopping track reconstruction once enough information is available. The precision is then sufficient for most HLT applications such as vertex reconstruction or b-tagging.

3.2 Adaptive filters

As mentioned above, LSM estimators are optimal when the model is linear and all random noise is Gaussian. However, the probability density functions involved are usually non-Gaussian, as the measurement errors usually have a Gaussian core with tails and the material effects (energy loss and multiple scattering) have long tails.

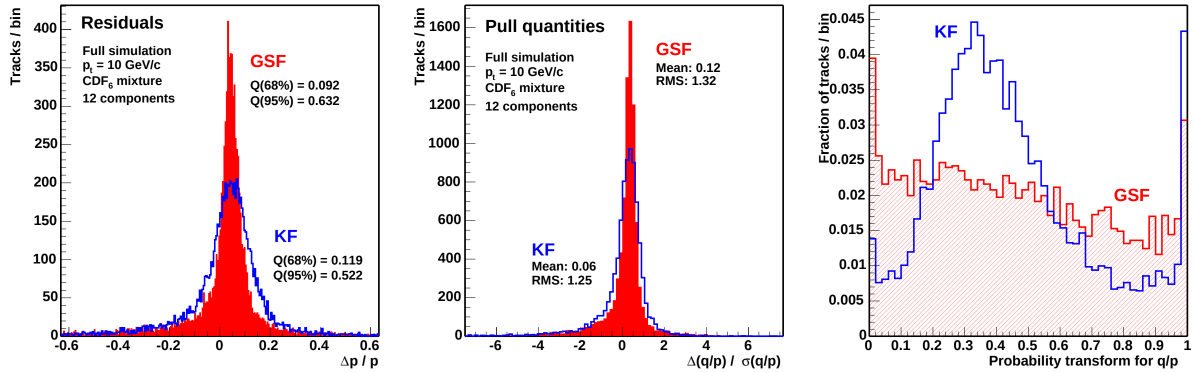

Figure 2: *Normalized momentum residuals (left) and Pull quantities for q/p (right) for electrons of $p_T = 10\ \mathrm{GeV}/c$. GSF (KF) results are shown as solid (open) histograms. Right: Distributions of the probability transform for q/p.*

Furthermore, the large background noise, occurring for example from neighbouring tracks, electronic noise or δ electrons, can cause hit degradation and hit assignment errors.

3.2.1 The Gaussian-sum filter

One method that takes non-Gaussian distributions better into account is the Gaussian-sum filter (GSF) [3]. In this method, all involved distributions are modeled by mixtures of multi-variate Gaussian probability density functions. The main component of the mixtures would describe the core of the distributions and the tails would be described by one or several additional Gaussians. This is particularly useful for electron reconstruction, as the Bethe-Heitler distribution of bremsstrahlung energy loss is highly non-Gaussian and can be modeled by a Gaussian mixture.

As a non-linear generalization of the Kalman filter (KF), the GSF can be seen as the weighted sum of several Kalman filters. It is indeed implemented as a number of such filters run in parallel where only the weights of the components are calculated separately. As, at each step, the mixture modeling the state vector is convoluted with the energy loss mixture, the number of components of the state vector rises exponentially. This number has thus to be limited to a predefined maximum at each step, which is achieved by clustering (collapsing) components which are close, according to a defined distance metric, pair-wise until the desired number of components is reached. The output of the filter is the full Gaussian mixture of the state vector, which can be used in subsequent applications, such as a GSF vertex fit.

The GSF has been found to be most efficient for low energy electrons (of the order of a few tens of GeV), while little gain should be expected at higher energies. In Figure 2 are shown the distributions of the normalized momentum residuals, pull quantities and probability transform for q/p for electrons of $p_T = 10\ \mathrm{GeV}/c$. As can be seen, the core of the distributions improve with respect to the KF, but the tails are only slightly improved. This is due in part to the fact that radiation in the first layer can not be detected, which can be compensated by a vertex constraint, and also to non-Gaussian tails in the measurements in the pixel detector. Such non-Gaussian measurement errors can be modelled by a mixture of Gaussians. The GSF is then able to take these into account in the fit, which would not only be beneficial for electrons but for all track fits.

3.2.2 The Deterministic Annealing Filter and the Multi-Track Filter

As already mentioned, in very dense environments such as high E_T b-jets or τ-jets, degradation due to large background noise may occur at two levels. Due to the high track density, hits may be degraded due to contamination by nearby tracks, and since a large number of hits would be found in the small search window, the wrong hit may be chosen by the CKF. Instead of the hard hit assignment done in the KF, a soft hit assignment may be more suitable, and the final hit assignment may be deferred to the final track fit, where the full track information can be used.

The *Deterministic Annealing Filter* (DAF) [4] is an iterative KF with annealing. It is a single-track fit which allows for competition between hits, such that several hits may compete for a track on the same surface. The assignment probabilities of the hits (their weights) depend then on the distance to the track and on competing measurements. This approach has been extended to a concurrent multi-track fit, the *Multi-Track Filter* (MTF) [4]. This filter allows for competition between tracks and hits, such that each hit on a layer can belong to each of several tracks.

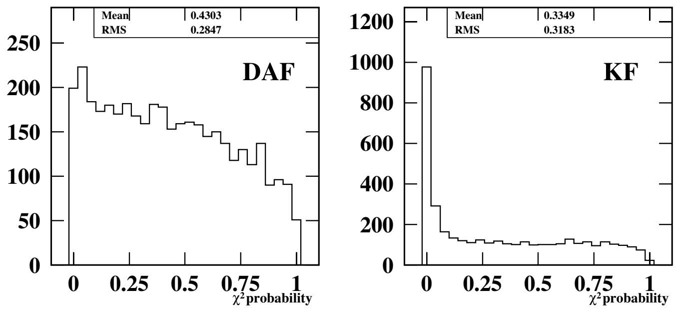

Figure 3: χ^2*-probability of track with* $p_T > 15$ GeV/c *reconstructed with the DAF (left) and the KF (right) in b-jets of* $E_T = 200$ GeV.

Both filters need an initial hit collection and initial estimates of the track parameters for each track to fit (*track seeds*). At present, the initial pattern recognition is done by the CKF, and the tracks to refit are selected in its output. For the DAF, the hits are simply collected in a cone around the selected track. For the MTF, a collection of tracks close in momentum space is chosen, and hits are collected around these tracks. It is obvious that with this seeding strategy, the track finding efficiencies can not be improved with respect to the CKF.

For "isolated tracks", even at high luminosity, where ambiguities are few, neither of the two filters provide a measurable improvement in track quality. In denser environments, an improvement can be seen for the tracks fitted with the DAF with respect to the same tracks fitted with the KF. Both the estimates of the track parameters and their error estimates are improved, and the overall track quality is markedly improved (Figure 3). The MTF yields similar results, with little improvement over the DAF. There is only a slight improvement of the overall track quality, and while there is some improvement of the error estimate of the track parameters, the improvement of the estimates themselves is negligible.

Better seeding methods would nevertheless be needed, since this step is especially delicate. As they are slower then the standalone KF, these methods can only be used where appropriate. If they do not show their full potential at the track densities foreseen at the LHC in *pp* collisions, even at high luminosity, they will become essential in the much higher densities already foreseen in the heavy ion collisions which will be undertaken at the LHC or later in a possible upgrade of the LHC.

4 Conclusion

CMS has a very robust and versatile tracker and track reconstruction algorithms, with sufficient redundancy to operate in a very challenging environment. The Combinatorial Kalman filter, which is the default algorithm for most applications, has shown to have a very good performance even in difficult environments, such that it is suitable for high luminosity and even heavy ion collisions. The track reconstruction efficiency is high and the fake rate is low, thanks to an efficient and robust pattern recognition algorithm. This is due to the capabilities of the tracker, as it has a low occupancy and reconstructed hits have a high purity. In addition, the CKF is fast enough to be used in the High Level Trigger, since the track parameter resolutions reach an asymptotic value after using only the first five to six hits.

More sophisticated algorithms are available for specific applications, such as the GSF for electron tracks or the DAF and the MTF for dense jets. These adaptive algorithms have shown improvements with respect to the KF in difficult situations.

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