Chapter 1

Muon reconstruction in the CMS detector

The reconstruction of muons in CMS combining tracking and calorimeter information is described. The high-level muon physics objects are reconstructed in a multi-faceted way, with the final collection being comprised of three different muon types, Stand-alone, Global and Tracker muons. The reconstruction in the muon spectrometer starts with the reconstruction of hit positions in the DT, CSC and RPC subsystems. Hits within each DT and CSC chamber are then matched to form segments (track stubs). The segments are collected and matched to generate seeds that are used as a starting point for the actual track fit of DT, CSC and RPC hits. The result is a reconstructed track in the muon spectrometer, and is called stand-alone muon. Stand-alone muon tracks are then matched with tracker tracks to generate global muon tracks, featuring the full CMS resolution. Tracker muons are muon objects reconstructed with an algorithm that starts from a silicon tracker track and looks for compatible segments in the muon chambers. A unique collection of muon objects is assembled from the stand-alone, global, and tracker muon collections. Muon isolation quantities using calorimeter information and tracker tracks for muons defined at the three different levels are combined into the muon objects.

1.1 Global reconstruction

To reconstruct a physical particle traveling through the detector, the recHits are associated together to determine points on the particle trajectory. The hits from the position sensitive detectors are analyzed using a pattern recognition algorithm to associate the measurements with trajectories. Independent of the sub detector information used the procedure from hits to tracks follows the same sequence and reconstructing and parameterizing a track occurs in four stages:
1. seeding,
2. trajectory building,
3. trajectory cleaning,
4. trajectory smoothing.

The characteristics of the trajectory as it travels through the detector are then used to define its momentum, charge, and particle identification.

1.1.1 Trajectory seeding

The initial point for the track reconstruction is determined using an estimated trajectory state or set of hits that are compatible with the assumed physics process. The most common types of trajectory seeds in CMS are hit-based seeds and state-based seeds and it is assumed that the trajectories, and therefore the trajectory seeds, are compatible with the beam spot. Hit-based seeds require a hit-pair or hit-triplet compatible with the beam spot to provide the initial vector. Additional options are that the seed direction meet certain criteria, or that the hits be located in a certain geometric region of the detector. State-based seeds do not require any hits and are specified by an initial momentum and direction.

1.1.2 Trajectory building

The Trajectory building starts at the position specified by the trajectory seed, and the building then proceeds in the direction specified by the seed to locate compatible hits on the subsequent detector layers. The track finding and fitting is accomplished using a combinatorial Kalman filter where the full knowledge of the track parameters at each detector layer is used to find compatible measurements in the next detector layer, forming combinatorial trees of track candidates. The Kalman filter method uses an iterative approach to update the trajectory estimate to the next surface with known equation of motion. In this process, the trajectory state which is propagated to the next detector layer is then updated with the information of a compatible hit. The final trajectory estimate is properly weighted with information from the last measurement and the information with predicted state based in all preceding detectors. Several propagators are used during the muon track reconstruction to perform a function of predicting the state of a muon given its initial state vector. The propagators provide a solution of a muon transport in the detector accounting for perfect knowledge of magnetic field $B$, and energy loss in detector material to predict the mean expected path as well as provide a propagation of initial state errors (covariance matrix) to the propagation final point including material effects like multiple scattering and energy loss fluctuations.
Three propagators are used at different stages of muon reconstruction: the *analytic with material* propagator, the *Runge-Kutta* propagator, and the *stepping-helix* propagator. The first two propagators are used extensively inside the silicon tracker volume, while the latter is predominantly used to propagate muons outside the tracker volume. While the first two propagators are used in the standard tracking software, the stepping helix propagator is predominantly used for muon reconstruction only.

### 1.1.3 Trajectory cleaning

The Trajectory building produces a large number of trajectories, many of which share a large fraction of their hits. In the cleaning stage, ambiguities among the possible trajectories are resolved and a maximum number of track candidates are kept.

### 1.1.4 Trajectory smoothing

A backward fitting (smoothing) allows the use of all covariance matrices to be applied to all the intermediate points based on all measurements used so far. Thus, the Kalman filter provides a good method in track finding/fitting since it is linear in the measurements, and its backward complement makes use of the full information, thereby providing room for robustness.

### 1.2 Stand-alone muon reconstruction

The muon reconstruction starts at the level of the individual chamber. The results are track segments in the Drift Tubes and in the Cathode Strip Chambers, and three-dimensional points in the Resistive Plate Chambers. Despite being different, all of them represent a measurement and therefore they are generally referred as reconstructed hits (*RecHits*) and implemented with the same interface. This feature is crucial for the next step of the muon reconstruction (section 1.1). Based on the Kalman filter technique, track reconstruction starts with the estimation of the seed state from track segments in the off-line reconstruction and from the trajectory parameters estimated by the L1 trigger in the on-line. The track is then extended using an iterative algorithm which updates the trajectory parameters at each step and, in order to reduce the possible bias from the seed, a pre-filter can be applied before the final filter. Once the hits are fitted and the fake trajectories removed, the remaining tracks are extrapolated to the point of closest approach to the beam line. In order to improve the $p_T$ resolution a beam-spot constraint is applied.
1.2.1 Local reconstruction in DT

The position of hits in single drift cells is estimated from TDC measurements. This is done in two steps: initially, an average value for the drift velocity is used to fit a two-dimensional segment in the superlayer. The unknown bunch crossing that originated the hits is a parameter of the fit, which uses the mean-timer technique (??). The parameters obtained are then used to determine the correct effective drift velocity, refine the hit position and the fit. In each chamber, the segments reconstructed in the two \( r - \phi \) superlayers are then refitted together, and the result is combined with the segment in the \( r - z \) superlayer to produce a three-dimensional segment. The direction resolution in the \( r - \phi \) plane is about 0.9 mrad. In the \( r - z \) (non-bending) plane, it is about 9 to 13 mrad for tracks in \(|\eta| < 0.9\).

1.2.2 Local reconstruction in CSC

Each CSC plane measures a point in two dimensions. One coordinate is measured by the wires, which are read out in bunches resulting in a limited precision. The other coordinate is measured by the strips, where the charge distribution of a cluster of three neighbouring strips is fitted to the so-called Gatti function to obtain a precise position measurement. The hits in a chamber are used to fit a three-dimensional straight line segment. The direction resolution of the segment varies from 7 to 11 mrad in \( \phi \) and from 50 to 120 mrad in \( \theta \) for 50 GeV muons.

1.2.3 Local reconstruction in RPC

The hits produced by the RPCs are three-dimensional points. They are obtained by clustering the strips and calculating the centre of gravity of the area covered by the strips in the cluster (i.e. the width of the strips times their full length). Uncertainties are computed assuming that the hit can have happened anywhere in this area with flat probability, e.g. in the simplest case of a rectangular area they are equal to the length of each side divided by \( \sqrt{12} \).

1.2.4 Seed generator

The algorithm is based on the DT and CSC segments (sections 1.2.1 and 1.2.2). A pattern of segments in the stations is searched for, using a rough geometrical criteria. Once a pattern of segments has been found (it may also consist of just one segment), the \( p_T \) of the seed candidate is estimated using parametrisations of the form:

\[
p_T = A - \frac{B}{\Delta \phi} \quad (1.1)
\]

For DT seed candidates with segments in MB1 or MB2, \( \Delta \phi \) is the bending angle of the segment with respect to the vertex direction. This part of the algorithm
assumes the muon has been produced at the interaction point. If segments from both MB1 and MB2 exist, the weighted mean of the estimated \( p_T \) s is taken. If the seed candidate only has segments in MB3 and MB4, the difference in bending angle between the segments in the two stations is used to calculate \( p_T \). In the CSC and overlap region, the seed candidates are built with a pair of segments in either the first and second stations or the first and third stations. \( \Delta \phi \) is the difference in \( \phi \) position between the two segments. Otherwise, the direction of the highest quality segment is used. Although this algorithm is currently used only for the off-line seeding, it can also be used for very fast muon reconstruction, and could be used in the HLT chain.

### 1.2.5 Pattern recognition and track reconstruction

In the standard configuration the seed trajectory state parameters are propagated to the innermost compatible muon detector layer and a pre-filter is applied in the inside-out direction. Its main purpose is to refine the seed state before the true filter. The final filter in the outside-in direction is then applied and the trajectory built. The algorithm is flexible enough to perform the reconstruction starting from the outermost layer instead of the innermost. The pre-filter step can optionally be skipped, hence increasing the speed of the reconstruction which could be important for the High Level Trigger. However, the standard reconstruction can already meet the strict HLT speed requirement. The pre-filter and filter are based on the same iterative algorithm used in two different configurations. In both cases it can be subdivided into different sub-steps: search of the next compatible layer and propagation of the track parameters to it, best measurement finding and possibly update of the trajectory parameters with the information from the measurement. The process stops when the outermost (for the pre-filter) or the innermost (for the filter) compatible layer of muon detectors is reached. At each step the track parameters are propagated from one layer of muon detectors to the next. A suitable propagator must precisely take into account material effects like multiple scattering and energy losses due to ionisation and bremsstrahlung in the muon chambers and in the return yoke. In order to reduce the processing time, the propagator must be fast. The trajectory is extrapolated in sequential steps using helix parametrisations. The required precision is obtained by using smaller steps in regions with larger magnetic field inhomogeneities. Multiple scattering and energy losses in each step are estimated from fast parametrisations, avoiding time-consuming accesses to the detailed material and geometry descriptions. The resulting propagated state contains these effects in its parameters and errors. The best measurement is searched for on a \( \chi^2 \) basis. The \( \chi^2 \) compatibility is examined at the segment level, estimating the incremental \( \chi^2 \) given by the inclusion in the fit of the track segment. In case no matching hits (or segments) are found, the search continues in the next station. For the update of the trajectory parameters the pre-filter and the filter follow
two different approaches. As the pre-filter should give only a first estimate of
the track parameters, it uses the segment for the fit. The parameters are almost
always updated as the $\chi^2$ cut imposed at this stage is loose (of the order of one
hundred). The final filter instead uses the hits composing the segment with a
tighter $\chi^2$ cut (of the order of 25) which can reject individual hits. This results
in a more refined trajectory state. The RPC measurements are not aggregated
in segments, so that for them the only distinction between the pre-filter and the
filter is the $\chi^2$ cut. The mechanism for updating the trajectory parameters can be
seen as a combination of the predicted trajectory state and the hit in a weighted
mean, as the weights attributed to the measurement and to the predicted tra-
jectory state depend on the respective uncertainties. In order to finally accept
a trajectory as a muon track, at least two measure- ments, one of which must
be of the DT or CSC type, must be present in the fit. This allows rejection
of fake DT/CSC segments due to combinatorics. Moreover the inclusion of the
RPC measurements can improve the reconstruction of low momentum muons and
those muons which escaped through the inter-space between the wheels (and the
DT sectors), leaving hits in only one DT/CSC station. In figures 1.1, 1.2, and 1.3
the effect of the inclusion of the RPC measurements in the track fitting is shown.
After the fake track suppression the parameters are extrapolated to the point of

Figure 1.1: Efficiency of the reconstruction in the muon spectrometer as a function
of $\eta$ with (black square) and without (red triangle) the inclusion of RPC in the
track reconstruction
Figure 1.2: *Efficiency of the reconstruction in the muon spectrometer as a function of $p_T$ with (black square) and without (red triangle) the inclusion of RPC in the track reconstruction.*

closest approach to the beam line. In order to improve the momentum resolution a constraint to the nominal interaction point (IP) is imposed. The matrix error of the IP is diagonal and its values are: (15 $\mu$m 15 $\mu$m 5.3 cm).

### 1.3 Track reconstruction in the Tracker

As in the muon system, the reconstruction process starts with the seed finding, but while in the muon system the trajectory is built during the pattern recognition, in the tracker the pattern recognition and the final fit are performed separately. Two different algorithms have been implemented. The first uses two or three consecutive hits, in the pixel and/or in the strip detector, to find the seeds. Based on the Kalman filter technique, the algorithm uses an iterative process to pass from one layer to the next and to perform the pattern recognition. The principle is very similar to that used in the muon spectrometer alone (Section 1.2.5). The second algorithm, called road search, uses only the silicon strip detector to find the seeds: it takes one hit in the inner layer and one in the outer and considers the possible paths which can connect the two initial hits. The pattern recognition is performed collecting the measurements around the paths.
Both the algorithms end with a final fit of the collected hits, followed by the suppression of fake tracks.

### 1.4 Matching tracker tracks to stand-alone muon tracks

The first step in reconstructing a global muon track is to identify the silicon tracker track to combine with the stand-alone muon track. This process of choosing tracker tracks to combine with stand-alone muon tracks is referred to as track matching. The large multiplicity of tracks in the central tracker necessitates the selection of a subset of tracker tracks that roughly correspond in momentum and position to the stand-alone muon track. The definition of the region of interest (ROI) has a strong impact on the reconstruction efficiency, fake rate, and CPU reconstruction time. The method of track matching proceeds in two steps. The second step is performed by propagating the muon and the selected tracker tracks onto the same plane and looking for the best $\chi^2$ value from the comparison of track parameters. In the case of very poor $\chi^2$ comparison which results in no matches, the matching is subsequently attempted by comparing the
track separation in $\eta - \phi$ space. If there is a suitable match between tracker track and stand-alone muon track, then the hits from the tracker and the stand-alone muon track are combined in one collection and a final fit is performed over all hits. After the final global fit is made for all stand-alone track matches in the event, fake tracks are suppressed. The reconstruction of the muons ends with the matching of the global muon track and the energy deposits in the calorimeters.

1.5 High energy muon reconstruction

Muons with energies of several hundred GeV and more, have a high probability of producing electromagnetic showers in the iron of the CMS magnet return yoke. These large energy losses can significantly degrade the performance of the muon track fitter. Two main effects can contribute to this degradation:

- the muon can lose a large fraction of its energy, so that the part of the track following the energy loss should be discarded, being the particles momentum changed.

- the shower can contaminate the muon detectors, causing incorrect trajectory measurements in the local reconstruction algorithms. These measurements in the track fit can lead to incorrect reconstructed momentum values.

To minimize these effects, two different and complementary approaches have been developed. The first one is based on the fit of the hits from the tracker and the first muon station with hits, with the aim of minimizing the effect of a large change in muon momentum after showering. The second strategy, named Picky muon reconstruction, consists of a fit of the muon chamber hits selected by an algorithm applying tight cuts for hit compatibility with tracker track trajectory. This approach minimizes the influence of contaminated chambers, while preserving the hits from chambers providing good trajectory measurement, despite containing a shower. These two refits optimized for showering muons are considered along with the standard global muon fit and the fit using only the hits from the inner tracker, and the global goodness-of-fit of each four trajectories is evaluated. Two algorithms have been developed for selecting the best trajectory, basing the decision of the comparison of the goodness-of-fit variables. Known as the cocktails, these were found to perform better than any of the four individual algorithms. The performance comparison between all the approaches is shown in Fig. 1.4

1.6 Tracker muon reconstruction

Standard muon track reconstruction starts from the muon system and combines stand-alone muon tracks with tracks reconstructed in the inner tracker. This approach naturally identifies the muon tracks in the detector. However, a large
Figure 1.4: Reconstructed $p_T$ distributions for $p_T = 1\,\text{TeV/c}$ single muons for the different refits. Starting from the top left plot, the distributions show a fit with the Tracker only, followed by the default Global fit, First Muon Station, Picky muon reconstructor, and the cocktails algorithm.
fraction of muons with transverse momentum below 6-7 GeV/c (see Fig. 1.2) does not leave enough hits in the muon spectrometer to be reconstructed as stand-alone muons. Moreover, some muons can escape in the gap between the wheels. A complementary approach consists in considering all silicon tracker tracks and identifying them as muons by looking for compatible signatures in the calorimeters and in the muon system. Muons identified with this method are called Tracker Muons. The algorithm for the muon identification of the tracker tracks extrapolates each reconstructed silicon track outward to its most probable location within each detector of interest (ECAL, HCAL, HO, muon system).

The algorithm collects and stores all the relevant information into a final Muon object. Specific muon identification criteria can be developed based on these variables. However, if a Global Muon is reconstructed using the same silicon tracker track, the Global Muon fit is stored in the same Muon object and the default momentum of the muon in the object is taken from the Global Muon fit. The momentum of the silicon tracker track fit is still retrievable through the reference to the silicon tracker track which is stored in the muon object. The muon identification efficiency improves by combining all three different approaches, identifying a muon as global one or stand-alone one or the tracker one.

1.7 Reconstruction efficiencies

Global, stand-alone and tracker reconstruction efficiencies as a function of $\eta$, $\phi$ and $p_T$, are shown in Figures 1.5, and 1.6. The stand-alone reconstruction efficiency has a dip at $|\eta| \sim 0.3$ which is due to a discontinuity between the central wheel and the contiguous ones. The $0.8 < |\eta| < 1.2$ region is problematic for the seed-finding algorithm because the DT and CSC segments are used together to
estimate the seed state. Moreover the stand-alone reconstruction efficiency has a periodic structure in the azimuthal angle due to the DT system segmentation in sectors. There is also a barrel inactive region at $\phi = 1.2$ because of the presence of instrumentation services (chimneys) in two wheels. The overall integrated efficiency, for momenta above 10 GeV/c, is more than 99%. For low momenta the efficiency decreases because a significant fraction of muons loses energy in the material before the muon stations or because of the bending in the magnetic field. At TeV/c momenta the muon reconstruction efficiency also decreases, even if very slowly, due to the increased bremsstrahlung probability. The inner tracker is less affected by multiple scattering and energy loss than the muon system. Moreover the magnetic field in the tracker volume is homogeneous and almost constant. The integrated efficiency is almost constant for all $p_T$ values and its value is above 99.5%. The efficiency loss at $|\eta| = 0$ is due to the tracker geometry: the tracker is made of two half-barrels joined together, and the junction surface is at $|\eta| = 0$. Also $|\eta| \sim 1.8$ is a problematic region for tracker track reconstruction because of the transition from TID to TOB/TEC subsystems. The global reconstruction efficiency is the product of the tracker, stand-alone and matching efficiency and for $p_T$ between 10 GeV/c and 1 TeV/c it is larger than 98%. These efficiencies include inside themselves, the efficiency of the matching of the stand-alone tracks with the inner tracker tracks: it is of the order of 99.5% and, at the first order, it does not depend on the muon kinematic but it depends mainly from the resolution of the stand-alone track parameters evaluated at the tracker surface.
1.8 Momentum resolution

The dependence of the $p_T$ resolution on the $p_T$ itself is described by the following formula

$$\frac{\delta p_T}{p_T} = 0.0136 \frac{x}{X_0} \sqrt{\frac{4A_N}{N}} \oplus \frac{\sigma \cdot p_T}{0.3BL^2} \sqrt{4A_N}$$

(1.2)

where $\beta = v/c$, $x/X_0$ is the thickness of the scattering medium in radiation lengths, $B$ is the magnetic field value, $L$ the length of the tracking system, $N$ the number of measurements, $\sigma$ their individual errors and

$$A_N = \frac{180N^3}{(N-1)(N+1)(N+2)(N+3)}.$$  (1.3)

The first term represents the contribute of multiple scattering and it is constant with respect to $p_T$. This term is dominant in the stand-alone muon reconstruction particularly in the barrel and it has the effect to maintain the resolution almost constant up to 100 GeV/c. Above this value, the second term starts to become important. In the tracker the multiple scattering is lower than in the muon system and the dominant term is the one directly related to measurement precision. As the $p_T$ increases, the measurement term becomes more and more important, but can be balanced by a longer path length in the magnetic field (i.e. a larger $L$): this is accomplished using the tracker and the muon system together. The combination of the information from the tracker and the muon chamber ensures the best $p_T$ estimation both at low and high momenta.

The Fig. 1.7 shows the transferse momentum resolution trend as function of transferse momentum itselfs for barrel, barrel-endcap overlap, and endcap regions.
Figure 1.7: Resolution in different $\eta$ regions for the different muon reconstruction steps.