CMS Muon High Level Trigger: Level 3 reconstruction algorithm development and optimization

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The Compact Muon Solenoid (CMS) is a general purpose detector operating at CERN UX5. CMS has an excellent muon system ensuring efficient muon reconstruction and identification. The CMS trigger system is split into a Level 1 trigger (L1) and a High Level Trigger (HLT). The L1 receives data at the LHC bunch crossing rate of 40 MHz with a latency time of 3.2 \( \mu s \). During this time the data are stored in front end pipe-line memories. To minimize the CPU processing time the HLT is subdivided into two software levels. The Level 2 trigger (L2) which uses the information provided by the muon detectors and the calorimeters.

At Level 3 trigger (L3) the full detector information, including the silicon tracker, is available. At each level selection criteria are applied to reject fake events.

The CMS High Level Trigger is designed to reduce, when the LHC will reach designed luminosity, the L1 accepted rate from 100 kHz to 100 Hz.

1 Introduction

In the following we present the development of the Level 3 Inside-Out hit based muon reconstruction algorithm. The study is based on CMSSW 2_0_10 software release. All the results presented are revalidated using CMSSW 2_1_0_pre6 release. The muon HLT L2 relies on the muon reconstruction in the muon detectors: DTs, CSCs and RPCs[1]. The information from L1, the local reconstructed hits satisfying the L1 request, are used to create muon seeds. The seeds are used to built the L2 muon track candidates. After fitting and smoothing[6] steps the track informations in the innermost muon layer are used by the L3 algorithm to propagate the track back to the interaction point (vertex constrain). We have four L3 seeding algorithms: two state based and two hit based. The Inside-Out hit based algorithm uses regional reconstruction where a region of interest is defined around the muon direction. All possible muon tracks are built inside the region of interest starting from pixel seeds and mixed seeds. During the matching stage the most probable tracker muon candidate is matched to the L2 muon according to four criteria. (for a review refer to [1]) The last step is a fit and a smooth of the final L3 Muon (global Muon) track.

2 The Level 3 seeding and reconstruction

The selection of a muon at L3 begins with the reconstruction in the muon system. In the on-line HLT reconstruction environment, the tracks in the silicon tracker are not yet fully reconstructed so it is necessary for the muon HLT to reconstruct the tracker tracks. Because reconstructing tracks in the central tracker require a large CPU time, special care must be taken to insure that the muon HLT algorithm reconstructs only tracks in a small region of the central tracker corresponding to likely muon candidates.

Regional track reconstruction is accomplished by reconstructing only the tracks from a small collection of Level 3 muon seeds. Thus, HLT Level 3 reconstruction begins with the creation of Level 3 muon trajectory seeds initiated for every Level 2 muon[3]. There are two strategies for the reconstruction of the tracker

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1 The seed is a state vector with a first estimation of track position, direction and \( p_T \), for more information see 2 and 3

2 A mixed seed is a hit based seed built starting from one hit in the pixel endcap tracker and one hit in the silicon strip tracker.

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trajectories and tracks. The first strategy, Inside-Out, starts with a trajectory seed at the inner surface of the central tracker and performs pattern recognition along the direction of the seed towards the outer surface of the tracker. The second strategy, Outside-In, starts with a trajectory seed on the outer surface of the tracker and performs pattern recognition along the direction of the seed towards the interaction point. In addition to these two strategies for trajectory building, there are two types of trajectory seeds. The first type of seed, hit-based seed, uses combinations of hits found in the tracker layers to form a initial position and direction of the seed. The second type of seed, state-based seed, uses a trajectory state on a detector to define the seeds initial position and direction. With these two trajectory building strategies and two types of seeds, muon HLT reconstruction has four choices for the L3 muon trajectory seed algorithm. These four seeding algorithms will be described in more detail in [3] and their reconstruction performances are compared in Sec: 5. The Level 3 Seeding step of the muon HLT reconstruction sequence produces a collection of Level 3 muon trajectory seeds. The Level 3 muon trajectory seeds are not used for HLT filtering or selection, but they are used as input to the Kalman[4] filter based pattern recognition[2].

### Table 1: The four algorithms for Muon HLT Level 3 Trajectory Seeding.

<table>
<thead>
<tr>
<th>Name</th>
<th>Starting Position</th>
<th>Direction</th>
<th>Seed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside-Out Hit Based</td>
<td>Innermost Tracker Layer</td>
<td>Towards outer layer</td>
<td>Hit pairs/Triplets</td>
</tr>
<tr>
<td>Inside-Out State Based</td>
<td>Innermost Tracker Layer</td>
<td>Towards outer layer</td>
<td>Extr. Muon state</td>
</tr>
<tr>
<td>Outside-In Hit Based</td>
<td>Outermost Tracker Layer</td>
<td>Towards interaction point</td>
<td>Hit pairs/Triplets</td>
</tr>
<tr>
<td>Outside-In State Based</td>
<td>Outermost Tracker Layer</td>
<td>Towards interaction point</td>
<td>Extr. Muon state</td>
</tr>
</tbody>
</table>

3 Hit-Based seeding algorithm

Hit-based seeds use combinations of hits found on the tracker layers to form a seed initial position and direction. In the offline reconstruction environment, all combination of hits on adjacent inner tracker layers are combined to form seeds. However, using all possible combinations leads to a very high number of initial seeds for the entire central tracker and the subsequent trajectory building consumes more CPU time than is available for on-line reconstruction for the HLT[6]. Since we only want to reconstruct tracks that correspond in position, direction, and energy with the Level 2 muons, we restrict the initial trajectory seeds to be in a region of interest in the tracker which is defined by the Level 2 muon.

4 Inside-Out Hit Based algorithm

The Inside-Out Hit-Based (IOHB) seed option uses standard hit-pair and hit-triplet generators to form the pair and triplet combinations of hits on adjacent tracker layers. The hit-pair and hit-triplet generators can be restricted to consider only hits that are within a defined tracking region of interest. In the HLT they select pairs or triplets of hits in the pixel detector, and the inner hit is required to be in the $\eta - \phi$ tracking region-of-interest. In the case we have Level 2 muons with $\eta > 2.0$, the hit-pairs can be a combination of pixel and strip layers. The mixed pairs are created to avoid a drop in seeding efficiency in the endcap due to the fact that the endcap pixel disks are made of only two pixel layers and so if one layer is inefficient we have no enough hits to create a seed. The selected hits are parameterized to give an initial direction and trajectory-state which are used to define a trajectory seed.

4.1 Region of Interest definition

In the case of Level 3 muon reconstruction, we use a rectangular $\eta - \phi$ tracking region to choose the initial region of the tracker to search for tracker hits that correspond to the Level 2 muon track. A good
definition of the region of interest is a key task to optimize the reconstruction efficiency, fake rate, and CPU reconstruction time. The L3 muon $\eta - \phi$ tracking region is defined by a set of seven parameters (see [6] and [3]):

1. **Region origin**: the position of the origin of the tracking region.
2. $\Delta Z$: the allowed $z$ spread of the region origin $z$ coordinate along the mean value.
3. $\Delta R$: the allowed $r$ spread of the region origin $x$-$y$ coordinate along the mean value. Usually defined by detector geometry considerations.
4. **Direction**: vector giving the direction from the origin around which the tracking region will be opened.
5. $\Delta \phi$: the $\phi$ size of the tracking region.
6. $\Delta \eta$: the $\eta$ size of the tracking region.
7. The minimum $p_T$ of tracks in the region - used to determine the curvature of the tracking region.

The origin is chosen to be the beam spot or, if it is not known, the primary vertex as defined by the pixel vertexing algorithm. $\Delta Z$ is defined by the pixel vertex, or is chosen to be a fixed value if the beam spot is used as the origin.

The direction and minimum $p_T$ are taken to be the direction of the Level 2 muon track and as 60% of the Level 2 muon $p_T$, respectively. The values for $\Delta \eta$ and $\Delta \phi$ are extracted from the perigee error estimates of the Level 2 muon direction.

### 4.2 Cleaning package

Even with the constraint that the initial tracker hits for the trajectory seed are within the region-of-interest, there are many redundant and fake seeds found. The muon HLT reconstruction uses an additional seed cleaning step to remove the redundant and fake trajectory seeds. The seed cleaning is a three level filter that we can summarize as follows:

1. **Redundant Seed Cleaner**. At this step the algorithm checks, finds and removes the redundant seeds. Redundant seeds can occur if the trajectory seed collection is produced using hit-pairs and hit-triplets. In this case for each three hits in the hit-triplet seed there will be three superfluous hit-pair seeds corresponding to each combination of pairs that can be formed out of three hits.

2. **$p_T$ Cleaner**. The second cleaning step removes seeds that do not have an estimated $p_T$ that corresponds to the initial Level 2 muon $p_T$.

3. **Direction Cleaner**. The third step of seed cleaning is to remove seeds that have an initial direction that does not correspond to the initial Level 2 muon direction. This step removes seeds created inside region of interest but pointing outside the region.

The cuts in each of the three steps filter are optimized to reduce as much as possible the number of fakes living untouched the seeding efficiency.

### 5 Efficiency comparison between the four algorithms.

In this section we discuss a study of the L3 track reconstruction efficiency for muons in the $t\bar{t}$ sample achievable with the four seeding algorithms. The preselection criteria used are available in [6]. We show that the IOHB algorithm has the best efficiency over the whole $\eta$ and $p_T$ range.

We take assume the start up[6, 7] misalignment scenario. Since we are interested in HLT algorithm development our test is based on the study on the following points:
all the reconstruction efficiencies reported in this section are computed starting from trigger hits, cluster and segments. To save time at this step only degraded resolution variables are taken into account.

2. The fake rates reported in this section should be considered only as the algorithmic L3 reconstruction fake rate.

In Figure 1 the reconstruction efficiency versus $p_T$ and $\eta$ for the four algorithms is investigated. The IOHB efficiency is up to 5% better than the one achieved by the other algorithms depending on the $p_T$ bin. Start

In Figure 2 the performances of the four algorithms are investigated in terms of muon track fake rate in start up conditions. It is clear that in terms of fake rates the four algorithms are compatible all achieving similar performances.

6 Time study for Inside-Out Hit Based algorithm

Considerations about trigger rate and L1 rejection factor permit to evaluate[6] that for the entire HLT we have in average no more than 40 ms ($\sim 10$ ms for the L2 and $\sim 30$ ms for the L3) with tails less than 1s. In this section we evaluate the time requested by the muon HLT using each one of the four L3 algorithms.
The modules take into account to evaluate the L3 time using the single muon non isolated HLT trigger path are in Table 2. In Figure 3 we show the total L3 reconstruction time for the four algorithms. As it is clear from the figure, the execution time peaks between 12 ms to 16 ms depending on the algorithm. The IO Hit based is the most time intensive with a peak time of 16 ms and tails up to 150 ms. However considering the L3 time requirements at start up we can conclude that all four algorithms satisfy the CMS time request.

In Figure 4 on the left we show the time taken by the L3 seeding. From the plot we can conclude that understand that the time difference between the IO hit based algorithm and the others is due to the seeding time. This is a feature of the algorithm. Opening a region of interest around the L2 direction with origin on the beam line causes fake rate problems to the seeding algorithm due to the high hits multiplicity in the first pixel layer (It is under study a improvement on seeding time using the primary pixel vertex as tracking region origin[6]). A reliable HLT time estimation using IOHB algorithm, reported in Table 2, is achieved by running online in the CERN machine (lxbuild067) a CMS standard \(t\bar{t}\) sample.

<table>
<thead>
<tr>
<th>HLT module</th>
<th>Average time</th>
<th>Exclusive time</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3 Muon Seeds</td>
<td>1.7 ms</td>
<td>5.5 ms</td>
</tr>
<tr>
<td>L3 Muon Candidate</td>
<td>5.9 ms</td>
<td>19 ms</td>
</tr>
<tr>
<td>L3 Muon Fit</td>
<td>3.0 ms</td>
<td>9.5 ms</td>
</tr>
<tr>
<td>L3 Reco Total</td>
<td>9.94 ms</td>
<td>30.5 ms</td>
</tr>
<tr>
<td>L3 Isolation</td>
<td>0.1 ms</td>
<td>1.0 ms</td>
</tr>
<tr>
<td>L3 Average time</td>
<td>~ 10 ms</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: HLT time evaluation with IOHB. In this table we report a detailed time study of the HLT trigger algorithm.

7 Conclusions

In this paper we reviewed the CMS muon High Level Trigger presenting the IOHB algorithm. The IOHB performances are analyzed both in terms of reconstruction efficiency and timing. A comparison with the other three level three L3 algorithms is done. The results show that all the four algorithms fulfill the CMS HLT time requirement. The IOHB resulted the best in terms of muon reconstruction efficiency and with

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Fig. 4: Left: Performance of the four algorithms at the seeding level. Right: Performance of the four algorithms at the L3 trajectory building level.

a L3 average reconstruction time of $\sim 10$ ms. It satisfies the CMS requirement also taking into account a factor three due to simulation uncertainties.

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References