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A Robust Solution to the Ghosting Problems of the CMS Level-1 Muon Trigger in the Barrel/Endcap Overlap Region

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Abstract

In certain detector regions the algorithms of the CMS Level-1 Muon Trigger may generate ghost tracks. In the barrel/endcap overlap region most ghost tracks occur when the DT and CSC Track Finders report the same muon or when the Global Muon Trigger cannot match an RPC candidate with a DT/CSC candidate because one of the candidates is found in the barrel and one in the endcap. Solutions to the duplication directly at the level of the track finders are analysed but still found to result in too high duplication at the output of the Global Muon Trigger. Additional measures are explored at the level of the Global Muon Trigger. Requiring confirmation of DT/CSC candidates by the RPC Trigger can solve the ghosting problems but limits efficiency and compromises complementarity. It is therefore proposed to add a DT/CSC-Cancel-Out Unit to the Global Muon Trigger which can settle the ghosting problems without the help of the RPC System. Various ways of combining this Cancel-Out Unit with cancel-out measures at track finder level are studied and compared. A robust solution is presented that achieves very low ghosting and high efficiency both for single-muon and di-muon events, while preserving the complementarity of the trigger systems.

1 Introduction

In a previous agreement [1] it has been decided that the DT and CSC track finders [2, 3, 4, 5, 6, 7] each cover a part of the barrel/endcap overlap region, with a programmable boundary in pseudorapidity between the two systems. More recently, it has been agreed [8] to fix the boundary between the two track finders at approximately $\eta = 1.04$, in order to match the respective boundary between the barrel and the endcap part of the RPC system. Track segments of DT station MB1 and part of the track segments of CSC station ME1/3 are shared between the two track finders in order to avoid a gap in efficiency. Sharing track segments from more than these two stations has been shown not to increase the efficiency much further and it has been concluded that the additional hardware expenses would not be justified. Figure 1 shows a cross-sectional view of the CMS muon system [9] indicating the positions of the involved DT and CSC chambers and of the agreed η-boundary. The overlap region extends from the lowest pseudorapidity at which the CSC Track Finder can find tracks up to the highest pseudorapidity at which the DT Track Finder can find tracks: roughly $0.9 \leq |\eta| \leq 1.2$.

The sector processors of the DT Track Finder in wheel ± 2 include CSC station ME1/3 like a next-wheel neighbour station. Extrapolations are performed from MB1 to ME1/3 and from MB2 to ME1/3. Extrapolations from MB3 to ME1/3 are not included, because they occur only in a very narrow region of pseudorapidity and including them does not produce any significant increase in efficiency [10]. A minimum of two segments is required to form a track: the segments can be either both in the barrel, or one in the barrel (in MB1 or MB2) and one in CSC station ME1/3. In order to form a track with three segments, all three possible extrapolations between the segments are required [11].

The CSC Track Finder performs extrapolations from MB1 to ME2/2 and from ME1/3 to ME2/2 in the overlap region. A segment in ME2/2 is required to form a track. A valid track consists of at least two segments, but tracks with segments only in ME1/3 and ME2/2 are not accepted, since the bending between ME1/3 and ME2/2 is too small to measure the transverse momentum. CSC tracks in the overlap region are therefore of type MB1-ME2/2 or MB1-ME1/3-ME2/2.

The present document deals with the issue of ghosts arising in the overlap region and possible solutions that prevent and/or cancel out these ghosts. The following classes of ghosts have to be considered in the overlap region:

Class 1: Ghosts created due to the overlap of the DT and CSC Track Finders: the same physical muon is found by the DT Track Finder and by the CSC Track Finder. This is the most common case of duplication since the DT and CSC track finders share track segments in stations MB1 and ME1/3.

Class 2: Ghosts created in the Global Muon Trigger (GMT): the Global Muon Trigger processes the barrel data and the endcap data in two separate chains. Depending on the programming of the GMT, ghosts can be created if a muon is found on the barrel side of the η-boundary by the DT Track Finder, and the same muon is found by the RPC Trigger on the endcap side of the boundary. The same applies if a muon is reported by the CSC Track Finder in the endcap, and the RPC Trigger reports the same muon on the barrel side of the boundary.

Class 3: Candidates which are duplicated inside one of the Trigger Systems: simulation studies have shown that the probability for this type of ghosts in the overlap region is very low in all the three (DT, CSC, RPC) trigger systems. It will therefore not be further discussed in this document.

Outside the overlap region ghosts are mostly of class 3; there is only a small probability that ghosts arise because the GMT cannot match the two measurements of the same muon. It is important to keep the double-counting from all these contributions low, because these double-counted muons can falsely trigger a di-muon trigger condition. The ghosting probability of the trigger over the full range of pseudorapidity has to be kept below 0.5 % in order not to dominate the di-muon trigger rate by triggers from ghosts: the rate of di-muon events at trigger-cuts typically used in a di-muon trigger (e. g. 4 GeV/c), is of the order of 0.5 % of the trigger rate of single muon events at the same p_T-threshold.

Measures to reduce the ghosting probability or to cancel out ghosts can be implemented at different stages of the L1 Trigger. Section 2 discusses methods to reduce ghosting at the level of the DT and CSC track finders. A reduction by a factor of three can be achieved at this level but further reduction has to be achieved at the level of the Global Muon Trigger. Section 3 discusses two methods that can be applied in the GMT: they both can reduce the ghosting probability to the desired level. The first method is easy to implement but relies heavily on the performance of the RPC system. The second, more robust method requires an additional cancel-out logic in the GMT which compares the muons found in the DT and CSC track finders. It can work independently of the RPC System and results in even better over-all performance.

2 Preventing Ghosting at the Level of the Track Finders

It is desirable to prevent duplication of muon candidates directly at the place where it occurs, i. e. at the level of the DT and CSC track finders, so that later stages in the processing chain do not have to deal with this problem. A cancel-out scheme at the level of the track finders can make use of the track segments to differentiate between duplicated candidates and real di-muons that are close in space. At later stages this differentiation becomes more difficult.

The amount of ghosting created due to the overlap of the DT and CSC track finders depends on the details of how the overlap region is split into its barrel and its endcap part. Track segments in the barrel only contain the azimuthal angle ϕ and the bend angle ϕ_b. Information on the pseudorapidity η is available from additional θ–layers of drift tubes, but it is not associated to the ϕ–information. For this reason MB1 cannot be split into a barrel-part and an endcap-part along a certain boundary in pseudorapidity. Instead, all the ϕ–segments in MB1 are used by both the DT and the CSC track finder. For the endcap station ME1/1 the situation is different: segments (Local Charged Tracks or LCTs) in this station include information on ϕ, ϕ_b and η so that the station can be split into a part belonging to the DT Track Finder and a part belonging to the CSC Track Finder at a given boundary-value of pseudorapidity. The following ways of sharing segments in ME1/3 (and splitting ME1/3) have been analysed:

ME1/3 is used by both track finders: this is the simplest approach to sharing segments in ME1/3. As shown in Figure 2a [1)] it maximises efficiency of the combined DT/CSC System but also causes a maximum of ghosts.

ME1/3 is split into two halves with an overlap of 1 η-bin: LCTs from ME1/3 up to a certain boundary-value in η are sent to the DT Track Finder. The DT Track Finder uses LCTs with a pseudorapidity up to the boundary value while the CSC track finder uses LCTs with a pseudorapidity starting at the boundary value so that there is a one-bin overlap. As can be seen from Figure 2b, the one-bin overlap keeps the efficiency of the combined DT/CSC System almost as high as in the previous scenario. Ghosts are reduced to a narrower region in η.

ME1/3 is split into two halves (scheme A): LCTs from ME1/3 up to a certain boundary-value in η are sent to the DT Track Finder and only used in barrel tracks. LCTs with a pseudorapidity above the boundary are not sent to the DT Track Finder and only used by the CSC Track Finder to build endcap tracks. This solution was proposed in Reference [1]. The overlap region is split into two halves. The possible positions of the DT/CSC η-boundary are given by the η-scale of the CSC track segments which has a binning of 0.05 units in pseudorapidity. The boundary is set to a default value of $\eta_{cut} = 1.05$, which is the best possible match to the agreed boundary [8] of $\eta = 1.04$ (A method to fine-tune the position of the boundary will be discussed later, in Section 3.3.). As shown in Figure 2c the efficiency of the combined DT/CSC System is slightly reduced at the boundary. The duplication is also reduced but a probability of 2.10 % inside the pseudorapidity range $0.9 \leq |\eta| \leq 1.2$ remains. Most of it is caused by muons which are actually in the CSC Track Finder's part of the overlap region: the CSC Track Finder finds such a muon as an MB1-ME1/3-ME2/2 track. The DT Track Finder finds the same muon as an MB1-MB2 track. The muon delivers in most cases a segment in ME1/3, but the DT Track Finder cannot extrapolate to it since it does not receive segments in ME1/3 which are on the CSC Track Finder's side of the η-boundary. Since DT segments do not include a pseudorapidity coordinate, the DT Track Finder cannot detect that the track does not belong to its part of the overlap region and the track is duplicated.

The planned η Track Finder [13] will improve the situation. It uses information from the θ-layers of drift tubes to assign a more precise pseudorapidity to the DT tracks. However, assignment of an improved η-coordinate is not guaranteed. The effect of the $\eta-$ Track Finder has not been studied as no simulation of the η Track Finder was available at the time of writing. In most cases this type of duplication can also be prevented without using an improved η assignment by using the following scheme.

1) These and all the other simulation results in this study were obtained with ORCA 4.5.0 [12] using a sample of 100.000 single muons evenly distributed in azimuthal angle ϕ, in pseudorapidity $-2.5 < \eta < 2.5$ and in transverse momentum $2.5\,\text{GeV/c} < p_T < 100\,\text{GeV/c}$. No p_T threshold was applied to the muons when evaluating the efficiency or ghosting probability. As can be seen from Figure 7 the ghosting probability does not show a strong dependence on the transverse momentum, which justifies using a sample of muons with a flat distribution of transverse momentum.

ME1/3 is split into two halves with a scheme to reduce duplication (scheme B): Again, a boundary in η is fixed at a certain value. In this scheme, LCTs in ME1/3 with a pseudorapidity above the boundary are however still sent to the DT track finder, tagged with a tag-bit to indicate that they were above the boundary. This method has the advantage that the DT Track Finder can now reconstruct most of the MB1-MB2 tracks in the CSC Track Finder's part of the overlap region as MB1-MB2-ME1/3 tracks. By including a segment from ME1/3 these tracks now have an associated pseudorapidity information and can be cancelled out if they are in the CSC Track Finder's part of the overlap region. As shown in Figure 2d, this reduces the amount of ghosts by approximately a factor of three compared to the previous scheme at the cost of sending only one additional bit per LCT from the CSC to the DT Track Finder and including a very simple cancel-out logic in the DT Track Finder. The efficiency remains unchanged with respect to the previous approach.

After applying scheme B a ghosting probability due to the overlap of the DT and CSC track finders of 0.75 % remains, normalised to the pseudorapidity range of $0.9 \leq \eta \leq 1.2$. The remaining ghosts at the level of the track finders are of two types: firstly, tracks in the CSC Track Finder's part of the overlap region that have a segment in station ME1/3 but do not have a valid extrapolation to it in the DT Track Finder. This occurs because the precision of the measurement of the bend angle ϕ_b decreases at the edges of stations MB1 and MB2 due to the non-uniform magnetic field in this region. Widening the look-up-tables could reduce this type of ghosts but would at the same time increase susceptibility to noise. Secondly, there are tracks in the CSC Track Finder's part of the overlap region, that do not have a segment in station ME1/3. This is rather common since chambers in station ME1/3 are non-overlapping and there are gaps in ϕ. Tracks of this type are found by the DT Track Finder as MB1-MB2 tracks and by the CSC Track Finder as MB1-ME2/2 tracks. These duplicated tracks could be cancelled by sending also LCTs from station ME2/2 to the DT Track Finder tagged with a 1-bit η information, however it has been agreed [8] not to send segments from ME2/2 to the DT Track Finder. At the level of the DT and CSC Track Finders both types of remaining ghosts can only be prevented using a more complicated cancel-out scheme such as the following one.

Additional cancel-out links from the DT to the CSC track finder (combined with previous schemes): This solution would need additional cancel-out links from the DT to the CSC Track Finder, one for each segment in station MB1. Via these links the DT Track Finder could indicate that a segment is used in a DT track and the CSC Track Finder could then cancel out tracks that are using the same segment. The cancel-out information would be sent several bunch crossings after the segment itself. This solution has been simulated and it has been shown that it can remove ghosts almost completely [14]. However, due to different processing times in the DT and CSC Track Finders, such a solution would complicate synchronisation and might increase overall latency and was therefore not further explored.

Ruling out the very last scheme, the lowest duplication at the level of the track finders can be achieved by splitting ME1/3 into two halves using a scheme to reduce duplication (scheme B). With this scheme the ghosting probability over the pseudorapidity range of $0.9 \leq |\eta| \leq 1.2$) is 0.75 % due to the overlap of the DT and CSC track finders. However, including the ghosts created in the GMT, the ghost rate at the output of the GMT would be too high, unless additional measures are applied to reduce ghosting. The next section deals with the ghosting problem in the context of the GMT and discusses further methods to reduce the remaining ghosts.

3 Reducing Ghosts at the Level of the Global Muon Trigger

The Global Muon Trigger [15, 7] receives muon candidates from the DT, CSC and RPC Systems and combines them to find the best four over-all muon candidates in the detector, which are then forwarded to the Global Trigger [16]. Ultimately, only the ghosting probability at the output of the Global Muon Trigger affects the trigger rates as all L1 trigger algorithms are based on the list of muon candidates found by the Global Muon Trigger. The Global Muon Trigger provides additional means to reduce the ghosts created due to the overlap of DT and CSC track finders. However, depending on its programming, the GMT can also be a source of ghosts in the overlap region.

The GMT processes its input muons in two separate processing chains, one for the barrel and one for the endcap. The barrel-part receives up to four DT muons and up to four RPC muons found in the barrel region. The endcap-part receives up to four CSC muons and up to four RPC muons found in the endcap. Each part matches the muons found by the two complementary systems, separately. If a match was found, the two candidates are merged in order to improve the measurement of the parameters. Muon candidates seen by two systems are always forwarded to the Global Trigger. The GMT can be programmed to suppress candidates found by only one system depending on their pseudorapidity and quality [2]. This functionality can be used to reduce ghosts by requiring DT and CSC candidates to be matched with an RPC candidate. As a last step muon candidates from both processing chains of the GMT are brought together and sorted by rank. The best four candidates are sent to the Global Trigger.

If no measures to reduce ghosting are applied in the GMT, the ghosting probability at the output of the GMT is high in the overlap region (2.2 %. . . 4.2 %), even if the best scheme (scheme B) to reduce ghost is applied at the level of the track finders. Figures 3a and b illustrate the efficiency and ghosting probability at the output of the GMT with and without fine-tuning of the $\eta-$ boundary in the DT/CSC System as explained in Section 3.3. Methods to reduce the ghosting probability are explored in the next two sections.

3.1 Requiring Confirmation by the RPC System

The RPC System has a well-defined boundary between barrel and endcap at pseudorapidity $\eta = 1.04$. According to ORCA simulation results there is no duplication between the two parts, i. e. a muon at the boundary is reported only once, either in the barrel part or in the endcap part. This can be used to settle the remaining ghosting problem due to the overlap of the DT and CSC Track Finders. The GMT is programmed to forward only DT and CSC muons that have been confirmed by an RPC candidate in a small region around the η-boundary: if a track is found by both track finders (duplicated) then only the candidate that is confirmed by the corresponding RPC candidate, either in the barrel or in the endcap, survives. This method resolves all duplication due to the overlap of the DT and CSC Track Finders. Moreover, with this method no additional ghosts arise in the GMT because unconfirmed DT or CSC candidates are suppressed: if a muon is reported by the DT Track Finder and by the endcap-part of the RPC system then the DT candidate is suppressed and no ghosts arise. The same applies for a muon that is reported by the CSC Track Finder and the barrel part of the RPC System. If the RPC candidate is of low quality it can now happen that also the RPC candidate is suppressed because its low p_T-resolution would result in too high trigger rates [17]. This decreases the efficiency below the one given by the RPC System in the region where the RPC confirmation is applied.

The efficiency loss can be minimised by fine-tuning the position of the η-boundary in the DT/CSC System to better match the one in the RPC System as described in Section 3.3. After fine-tuning more candidates from the DT/CSC System can be matched with the respective candidate in the RPC system. The efficiency loss could also be avoided by allowing duplication at the level of the DT and CSC Track Finders and leaving the ghost cancellation only to the GMT. This could be achieved by sharing segments from (a part of) station ME1/3 between the Track Finders instead of using the schemes to reduce duplication. However, this solution is not desirable as the ghost-busting would depend entirely on the RPC System and the efficiency would be limited in a larger range of pseudorapidity.

Figures 4a and b show the achievable efficiency and ghosting probability using RPC confirmation, with and without fine-tuning of the CSC η-scale as described in Section 3.3. Ghosting at the output of the GMT can almost be completely suppressed in the overlap region. However, the efficiency in the overlap region is below the one of the RPC System. The method relies on the efficiency of the RPC System and on the fact that the RPC System does not have a ghosting problem in the overlap region. A different solution is required in order to achieve real complementarity between the DT/CSC System and the RPC System.

3.2 Using a Dedicated DT/CSC Cancel-Out Unit

This section presents an alternative method, that can cancel the ghosts created due to the overlap of the DT and CSC track finder without the help of the RPC System, thereby increasing the robustness of the over-all system. An additional hardware unit, the DT/CSC Cancel-Out Unit, is required inside the GMT to perform this task. The cancel-out unit compares the η and ϕ coordinates of all the DT and CSC candidates and tries to match the candidates based on their proximity in space. If a match between a DT and a CSC muon is found, then a programmable Cancel Decision Unit decides if one of the muons has to be cancelled and which one.

Figure 5 illustrates the implementation of the DT/CSC Cancel-Out unit. It requires connections between the two processing chains in the GMT that process the barrel and the endcap muons. Only after compacting the design of the GMT to fit on a single VME board it became possible to implement these connections. An identical logic to the one in the Barrel and Endcap Matching Units [15] is used for the matching of DT and CSC muons. It ensures that a given candidate in the DT or CSC System is used only once in a match, i. e. a duplicated candidate can never cancel two candidates in the other System. The Cancel-Decision Unit is implemented as a simple look-up

[2] Suppressed muon candidates are still forwarded to the Global Trigger with a low rank but they are tagged to indicate that they are not to be used in single- and di-muon trigger conditions.

table. Besides the result of the DT/CSC matching it also receives signals indicating which of the DT and CSC muons were matched with an RPC muon in the Barrel and Endcap Matching units. In order to use the same FPGA layout, two identical copies of the DT/CSC Cancel-Out Unit exist, one in the GMT Barrel Logic FPGA and one in the GMT Endcap Logic FPGA. The only difference is the programming of the Cancel-Decision Units which are responsible for cancelling DT and CSC muons, respectively. Tables 1 and 2 indicate the default programming of the Cancel-Decision Unit for the barrel and for the endcap. In order not to cancel out real di-muons, the default programming does not cancel out duplicated candidates if they both are matched with an RPC candidate . This relies on the fact that the RPC trigger does not have a ghosting problem in the overlap region. In case of an unforeseen ghosting problem in the RPC System, the programming of the Cancel-Decision-Unit could be changed to always cancel a duplicated DT/CSC candidate. The DT/CSC System could then even cancel out ghosts in the RPC System by requiring that RPC candidates are matched with a DT/CSC candidate.

Table 1: Default programming of the Cancel Decision Logic for the barrel part of the Global Muon Trigger.

inputs			output	
DT is matched w. CSC	CSC is matched w. RPC	DT is matched w. RPC	cancel DT	Comment
0	x	x	0	no DT/CSC match
1	0	0	0	cancel CSC
1	0	1	0	cancel CSC
1	1	0	1	cancel DT
1	1	1	0	no cancellation

Table 2: Default programming of the Cancel Decision Logic for the endcap part of the Global Muon Trigger.

inputs			output	
CSC is matched w. DT	DT is matched w. RPC	CSC is matched w. RPC	cancel CSC	Comment
0	x	x	0	no DT/CSC match
1	0	0	1	cancel CSC
1	0	1	0	cancel DT
1	1	0	1	cancel CSC
1	1	1	0	no cancellation

The DT/CSC Cancel-Out Unit can remove most of the ghosts that arise due to the overlap of the DT and CSC track finders, but some additional ghosts (class 2) are introduced, depending on how the overlap-region is split into two parts at the level of the track finders.

Figure 6 shows an overview of the efficiency and ghosting probability at the output of the GMT for the different ways of splitting the overlap region at track finder level (compare with Section 2):

ME1/3 is used by both track finders: As shown in Figure 6 a the approach results in the highest efficiency and lowest ghosting rate (0.40 %) at the output of the GMT. The duplication due to the overlap of the track finders is high over a considerable range of pseudorapidity.

ME1/3 is split into two halves with an overlap of 1 η-bin: In this approach the efficiency is almost as high as in the previous one and the ghosting probability of 0.42 % is almost as low (see Figure 6 b). The duplication due to the overlap of the track finders is reduced with respect to the previous approach by a factor of 2.5.

ME1/3 is split into two halves (scheme A): This approach requires fine-tuning of the DT/CSC η-boundary as described in Section 3.3. After fine-tuning the ghosting probability of 0.61 % is still low at the output of the GMT as illustrated in Figure 6c. The GMT efficiency is only slightly lower than in the previous approach. The duplication due to the overlap of the track finders is reduced by another factor of 1.5.

ME1/3 is split into two halves with a scheme to reduce duplication (scheme B): Also this approach requires fine-tuning of the DT/CSC η-boundary as described in Section 3.3. As shown in Figure 6d the duplication at the output of the GMT is still low (0.69 %) with this scheme and the GMT efficiency is as high as in the previous scheme. The duplication due to the overlap of the DT and CSC track finders is reduced by yet a factor of 2.5 [3)].

The latter two schemes are slightly inferior to the first two schemes in terms of GMT efficiency and ghosting probability because of the following effect: in these schemes the duplication is reduced at the level of the track finders, leading to low ghosting at the level of the track finders (especially in the last scheme) and to a well-defined boundary in pseudorapidity. However, even after careful fine-tuning of the position of this η-boundary, additional ghosts (class 2) are created in the GMT because the boundary does not perfectly match the one in the RPC System.

The first two schemes, which reduce ghosting only the the GMT, show the highest efficiency and lowest ghosting at the output of the GMT. They neither require prevention of ghosts at the track finder level nor any fine-tuning of the DT/CSC $\eta-$ boundary. The second scheme, which limits duplication due to the overlap of the track finders to a small region in pseudorapidity, is proposed as a default solution.

Figure 7 shows the ghosting probability at the output of the GMT as a function of the generated muon-p_T for this proposed solution.

3.3 Fine-tuning the DT/CSC η-boundary to match the one in the RPC System

Fine tuning the position of the η-boundary in the DT/CSC System to better match the one in the RPC System reduces the additional ghosts introduced by the GMT, if the DT/CSC cancel-out unit is used. If RPC confirmation is used, fine-tuning increases GMT efficiency rather than reducing ghosts. If schemes A or B as described in Section 2 are used to divide the overlap region into two parts, then the position of the η-boundary between the DT and CSC Track Finders is determined by the η-scale of the CSC track segments. For trigger purposes, this η-scale has a binning of 0.05 units in η, however the resolution of the CSC chambers is much finer. At the CSC Sector Receiver fine resolution η-measurement of the CSC chambers is converted to the coarse trigger scale using a look-up-table. By changing the contents of this LUT, the whole coarse scale or only one bin in the coarse scale can be shifted by a fraction of the bin width in order to fine-tune the η-boundary between the DT and CSC systems. Figure 8 illustrates how the boundary between two bins of the CSC η-scale can be shifted.

Figure 9 shows the effect in terms of efficiency and ghosting probability if the DT/CSC Cancel-Out Unit is used in the GMT and scheme B at track finder level. A minimum of ghosts at the output of the GMT can be found for an η-boundary of $\eta_{cut} = 1.035$. Tuning of the boundary also influences the ghosting at track finder level and the DT/CSC stand-alone efficiency (compare also Figures 2 and 6). Further examples of the impact of fine-tuning the η-boundary are illustrated in Figures 3 and 4.

4 Effects of the Cancel-Out Schemes on Real Di-Muon Events

The initial efficiency to find di-muon events with the two muons close in space depends on the resolution and the single muon efficiency of each of the trigger systems. Cancel-Out schemes to reduce ghosts at the level of the DT and CSC track finders do not reduce this di-muon efficiency as they have access to the track segments. Requiring confirmation of DT/CSC candidates by the RPC System in the overlap region does reduce the efficiency to find both muons at the output of the GMT. Depending on where the muons are reported in the DT/CSC System and in the RPC System, one of the muons can be suppressed.

Using the DT/CSC Cancel-Out Unit, efficiency might be lost only in a special case: if one of the muons is found by the DT track finder but not by the CSC Track Finder and if the other one is only found by the CSC Track Finder and not by the DT Track Finder. Depending on whether the RPC System finds both muons and depending on what side of the η-boundary it reports the muons, one of the two muons might be cancelled. This combination of effects is very rare so that no significant decrease of di-muon efficiency is expected. If duplication at the level of the track finders is allowed, then this case becomes even more rare. The effect of the DT/CSC Cancel-Out Unit on the efficiency to find di-muon events can therefore be neglected, even if the two muons are very close in space.

5 Conclusion

The duplication due to the overlap of the DT and CSC track finders can be reduced to quite a low level directly at the track finders by splitting ME1/3 into two parts and applying a cancel-out scheme. However, even with the best cancel-out scheme possible in hardware, the duplication at the output of the GMT would be as high as 2.2 %

[3] The duplication due to the overlap of the DT and CSC track finders in this section has been evaluated using the fine-tuned η-boundary of $\eta_{cut} = 1.035$ while the respective duplication in Section 2 corresponds to the default η-boundary of $\eta_{cut} = 1.05$

in the pseudorapidity range of $0.9 \leq |\eta| \leq 1.2$. Therefore, additional measures have to be taken at the level of the GMT. Requiring confirmation by the RPC System can solve the ghosting problem, but it limits the efficiency to the one of the RPC System and compromises complementarity. An additional DT/CSC Cancel-Out-Unit is therefore introduced in the GMT which can cancel the duplication due to the overlap of the track finders without the help of the RPC System while maintaining high efficiency. The remaining duplication at the output of the GMT is about 0.4 % in the pseudorapidity range of $0.9 \leq |\eta| \leq 1.2$. This solution results in high efficiency for single as well as di-muon events, low probability for ghosting and a robust system in which the complementarity of the DT/CSC System and the RPC System is preserved.

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[16] **Nucl. Instr. Meth. A 437/3 (2000) 231**, C.-E. Wulz, *"Concept of the First Level Global Trigger for the CMS Experiment at LHC"*.

[17] **CMS Note 2001/003**, H. Sakulin, M. Fierro, *"Studies of the Global Muon Trigger Performance"*.

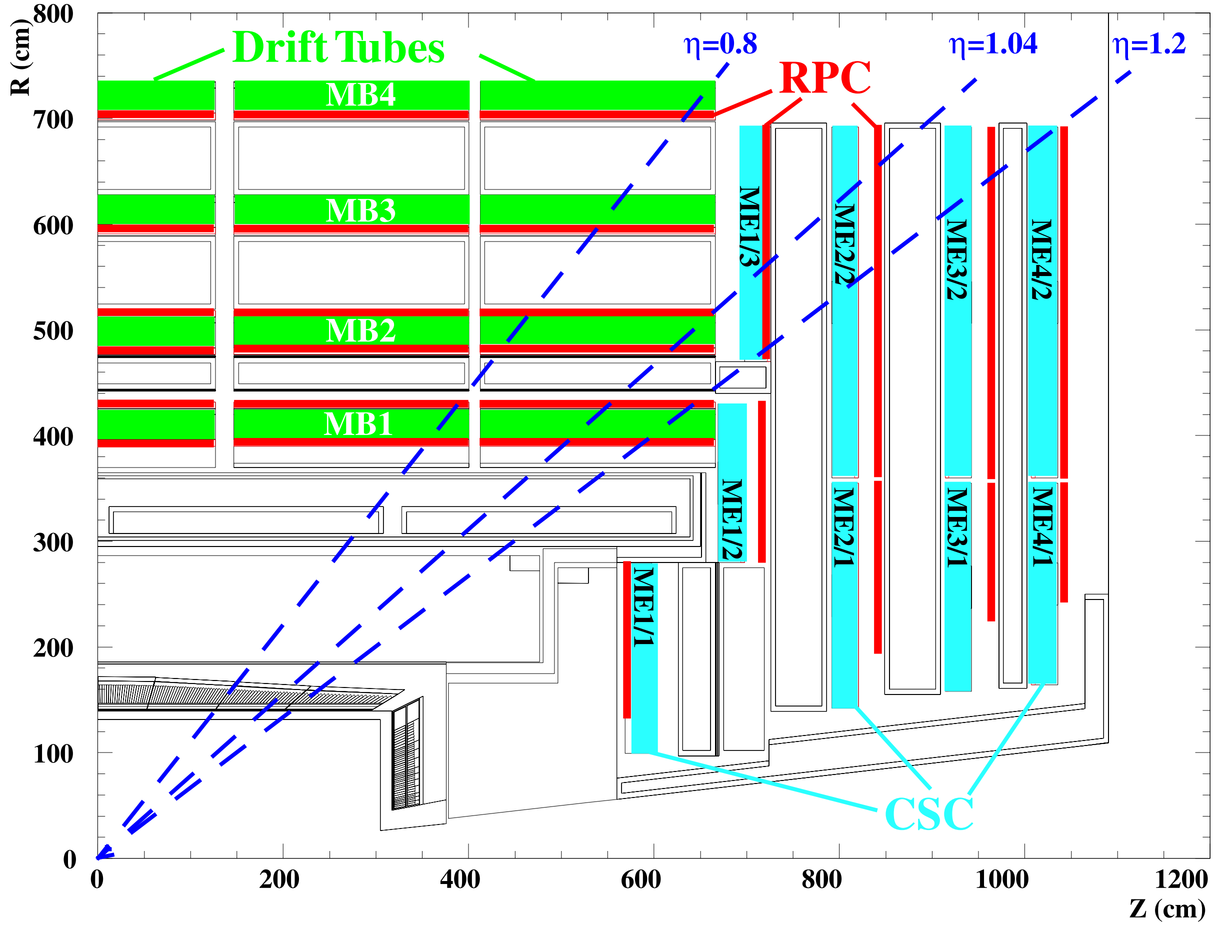

Figure 1: CMS Muon System. In the overlap region the DT Track Finder receives segments from CSC station ME1/3. The CSC Track Finder receives segments from station MB1.

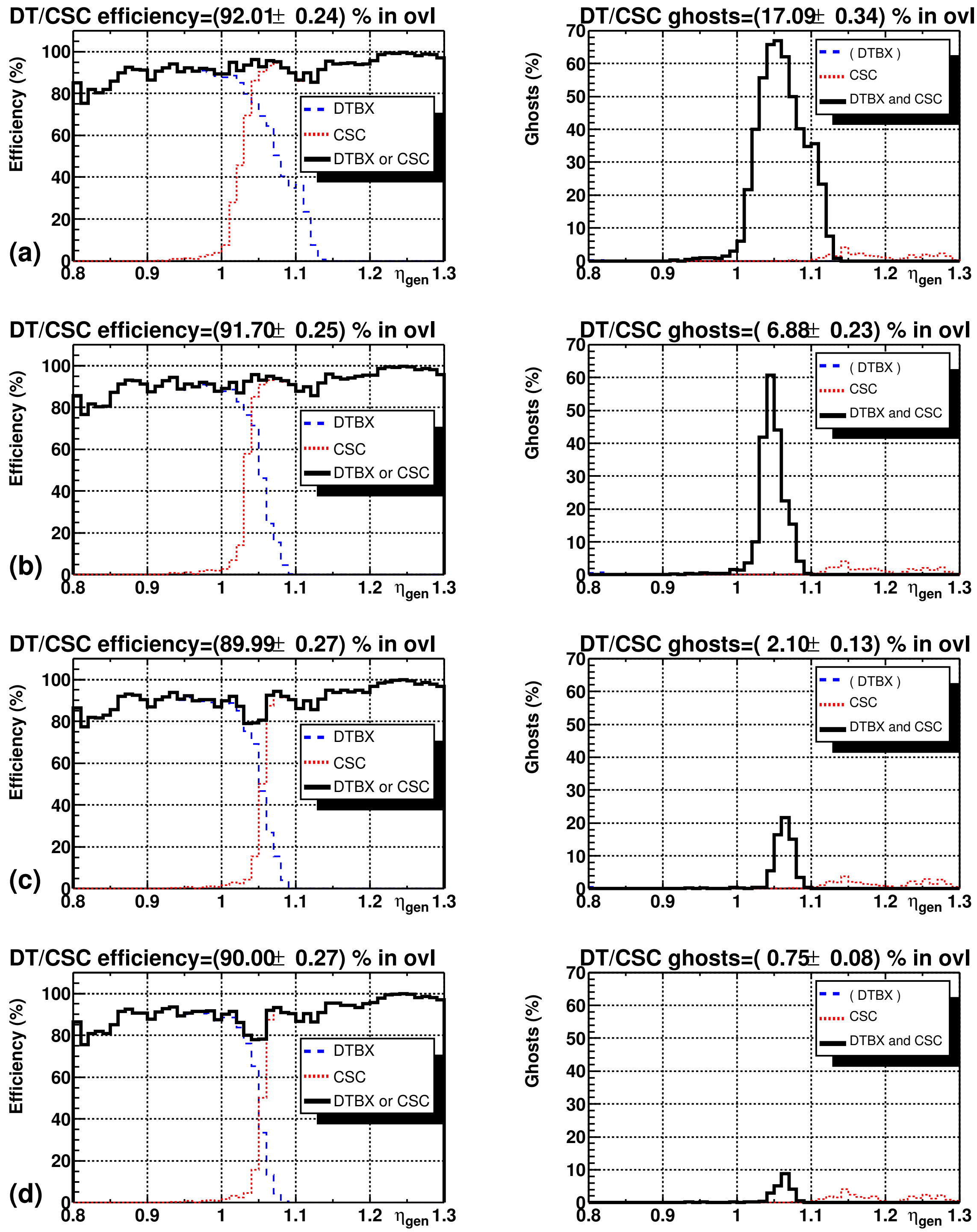

Figure 2: Efficiency and ghosts in the overlap region at the level of the DT and CSC track finders applying **various schemes to divide the overlap region into a barrel part and an endcap part**: (a) ME1/3 is used by both track finders, (b) one bin in η of ME1/3 is shared between both track finders, (c) ME1/3 is split into a barrel-part and an endcap-part at η=1.05 ("scheme A", see text), (d) ME1/3 is split into a barrel-part and an endcap-part at η=1.05 using a scheme that allows the DT track finder to cancel duplicated MB1-MB2 tracks by attaching an η-tag to the CSC segments ("scheme B", see text). Efficiency and percentage of ghosts are given inside the pseudorapidity range of $0.9 \leq |\eta_{gen}| \leq 1.2$. DT/CSC ghosts are candidates reported by both the DT and the CSC track finder. Simulated with ORCA 4.5.0, CMS121 geometry.

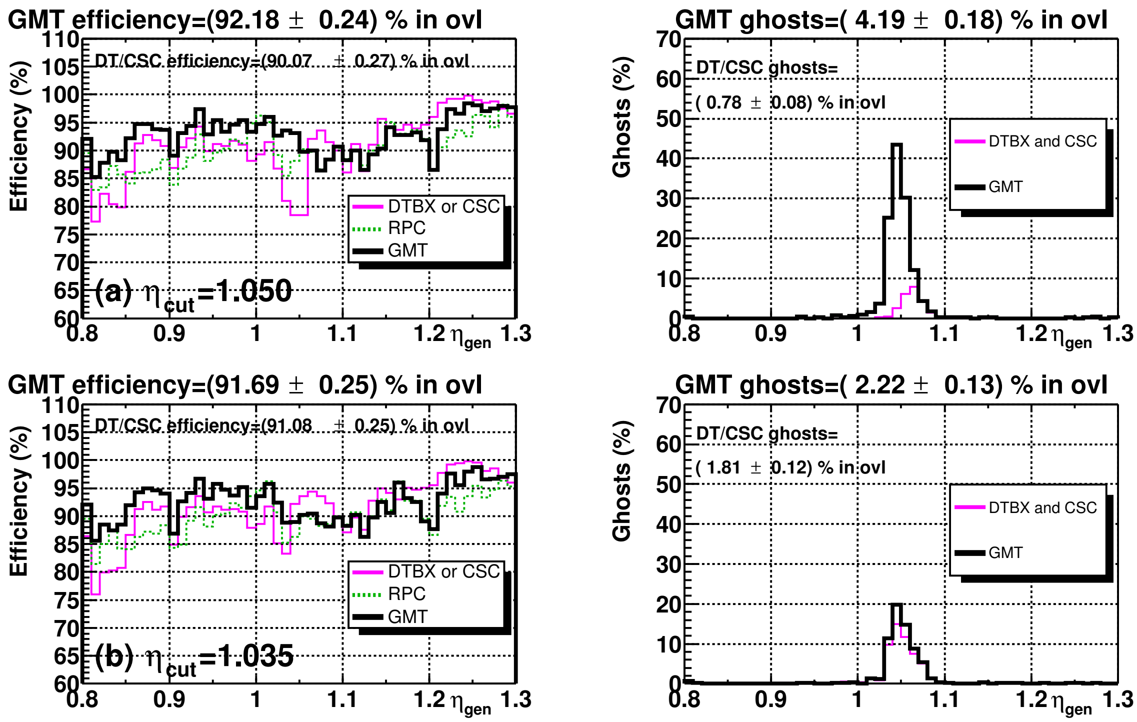

Figure 3: Efficiency and ghosts in the overlap region at the output of the Global Muon Trigger. **Duplication is prevented only at track finder level using scheme B (see text)**. Also shown are efficiencies and ghosts of the DT and CSC track finders and the RPC Trigger. (a) default η-boundary in DT/CSC System, (b) fine-tuned η-boundary in the DT/CSC System as described in Section 3.3. Efficiency and percentage of ghosts are given inside the pseudorapidity range of $0.9 \leq |\eta_{gen}| \leq 1.2$. DT/CSC ghosts are candidates reported by both the DT and the CSC track finder. Simulated with ORCA 4.5.0, CMS121 geometry, RPC efficiency 95 %.

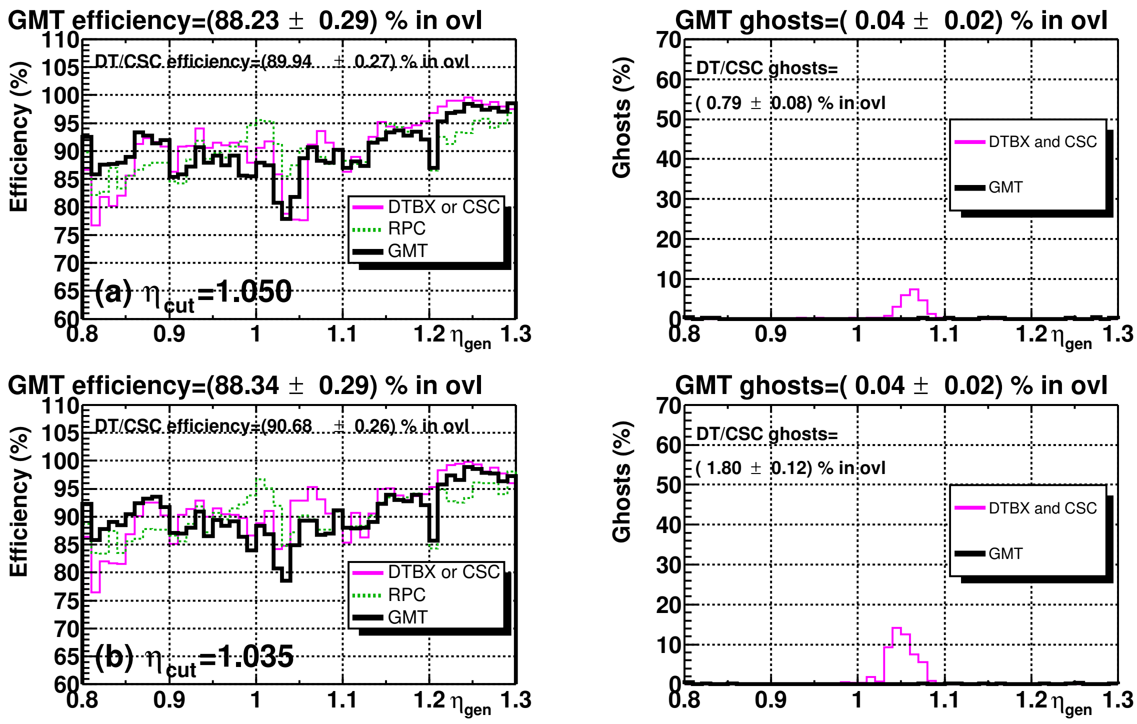

Figure 4: Efficiency and ghosts in the overlap region at the output of the Global Muon Trigger, **using the RPC System for confirmation at the GMT**. Also shown are efficiencies and ghosts of the DT and CSC track finders and the RPC Trigger. (a) default η-boundary in DT/CSC System, (b) fine-tuned η-boundary in the DT/CSC System as described in Section 3.3. Efficiency and percentage of ghosts are given inside the pseudorapidity range of $0.9 \leq |\eta_{gen}| \leq 1.2$. DT/CSC ghosts are candidates reported by both the DT and the CSC track finder. Simulated with ORCA 4.5.0, CMS121 geometry, RPC efficiency 95 %.

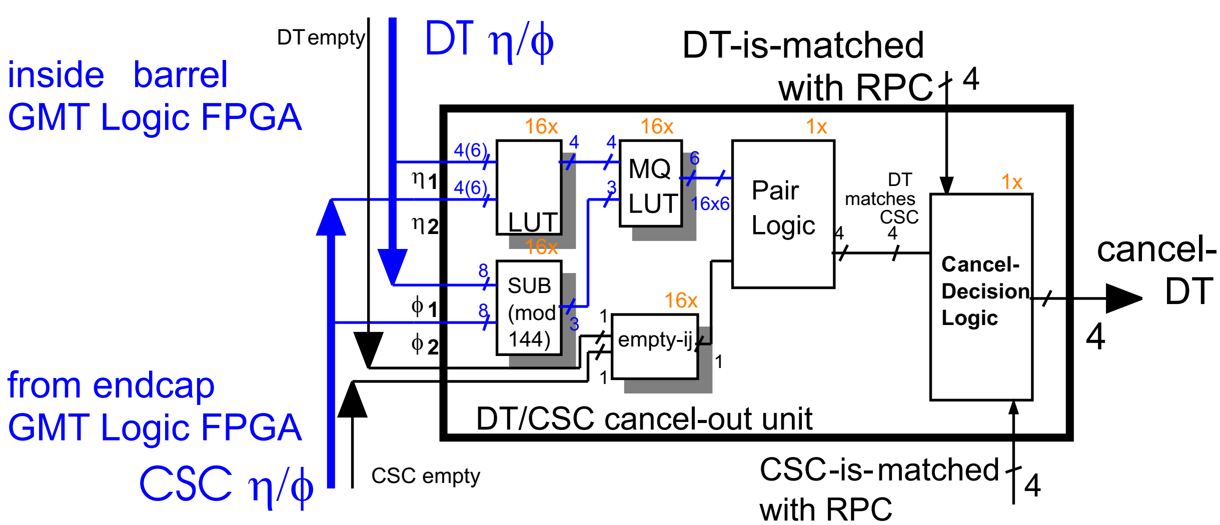

Figure 5: **DT/CSC Cancel-Out Unit** inside the GMT Barrel Logic FPGA. The same logic exists inside the GMT Endcap Logic FPGA. The space coordinates of all DT and CSC candidates are compared to find duplicated candidates (subtractors, Match Quality LUT and pair logic). This information together with information whether the DT and CSC candidates were matched with an RPC candidate is then sent to the Cancel-Decision Unit, which decides whether to cancel a duplicated candidate.

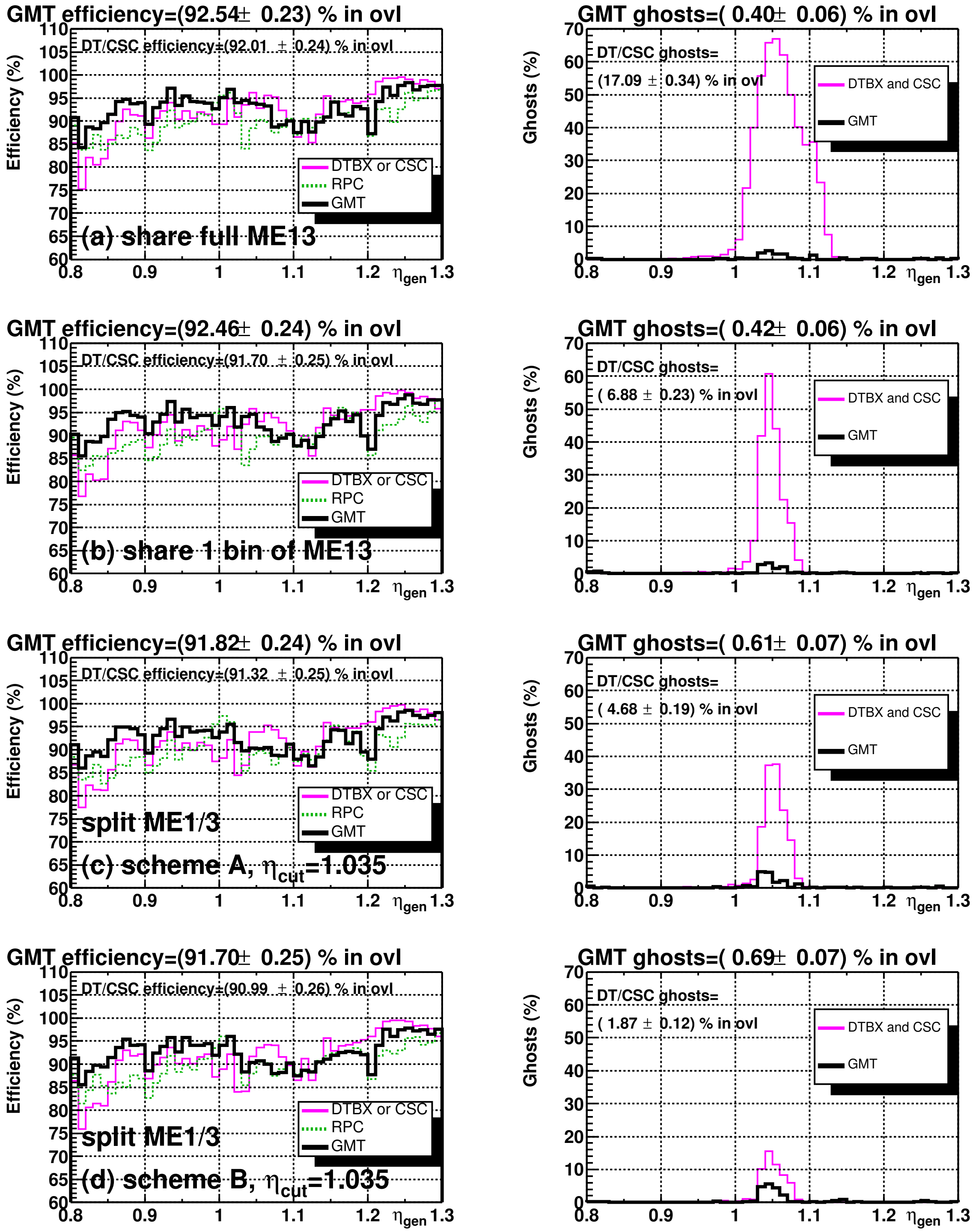

Figure 6: Efficiency and ghosts in the overlap region at the output of the Global Muon Trigger, using the **DT/CSC Cancel-Out Unit** inside the GMT. Also shown are efficiencies and ghosts at the DT and CSC track finders and the RPC Trigger. **Various schemes to divide the overlap region into a barrel part and an endcap part are used at track finder level:** a) Maximum duplication – whole ME1/3 is used by both track finders, (b) ME1/3 is split between DT and CSC track finders with a 1-bin overlap, (c) ME1/3 is split between DT and CSC track finder with no overlap ("scheme A", see text), (d) Ghosts are suppressed at the level of the track finders using a scheme that allows the DT track finder to cancel duplicated MB1-MB2 tracks by attaching an η-tag to the CSC segments ("scheme B", see text). **Option (b) is the proposed default solution.** In cases (c) and (d) the DT/CSC η-boundary is optimally tuned to $\eta_{cut} = 1.035$ (see Figure 9). Efficiency and percentage of ghosts are given inside the pseudorapidity range of $0.9 \leq |\eta_{gen}| \leq 1.2$. DT/CSC ghosts are candidates reported by both the DT and the CSC track finder. Simulated with ORCA 4.5.0, CMS121 geometry, RPC efficiency 95 %.

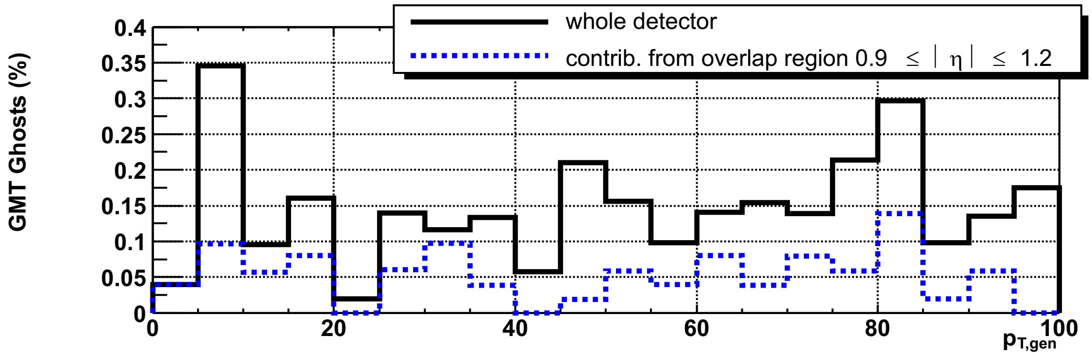

Figure 7: **Ghosting probability at the output of the GMT as a function of generated muon p_T.** The ghosting probability over the whole detector as well as the contribution to it from the overlap region of $0.9 \leq |\eta_{gen}| \leq 1.2$ are shown. The **DT/CSC Cancel-Out Unit** is used in the GMT. At track finder level ME1/3 is split between DT and CSC track finders with a 1-bin overlap (see text). For the ghosting contribution from the overlap region there is no strong dependence on the muon-p_T which justifies using a sample that is evenly distributed in transverse momentum $2.5\,\mathrm{GeV/c} < p_T < 100\,\mathrm{GeV/c}$. Simulated with ORCA 4.5.0, CMS121 geometry, RPC efficiency $95\,\%$.

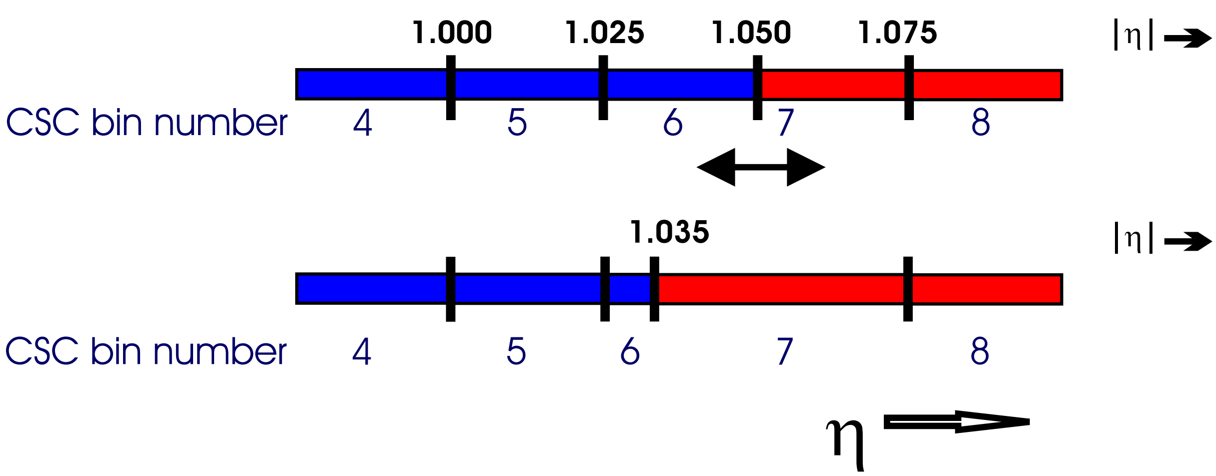

Figure 8: Tuning of the pseudorapidity scale of the CSC segments. The pseudorapidity is internally measured at high precision and converted to a coarse scale with units of 0.05 in η for trigger purposes. Adjusting the boundary between two bins in the coarse scale can be used to fine-tune the position of the η-boundary in the DT/CSC System.

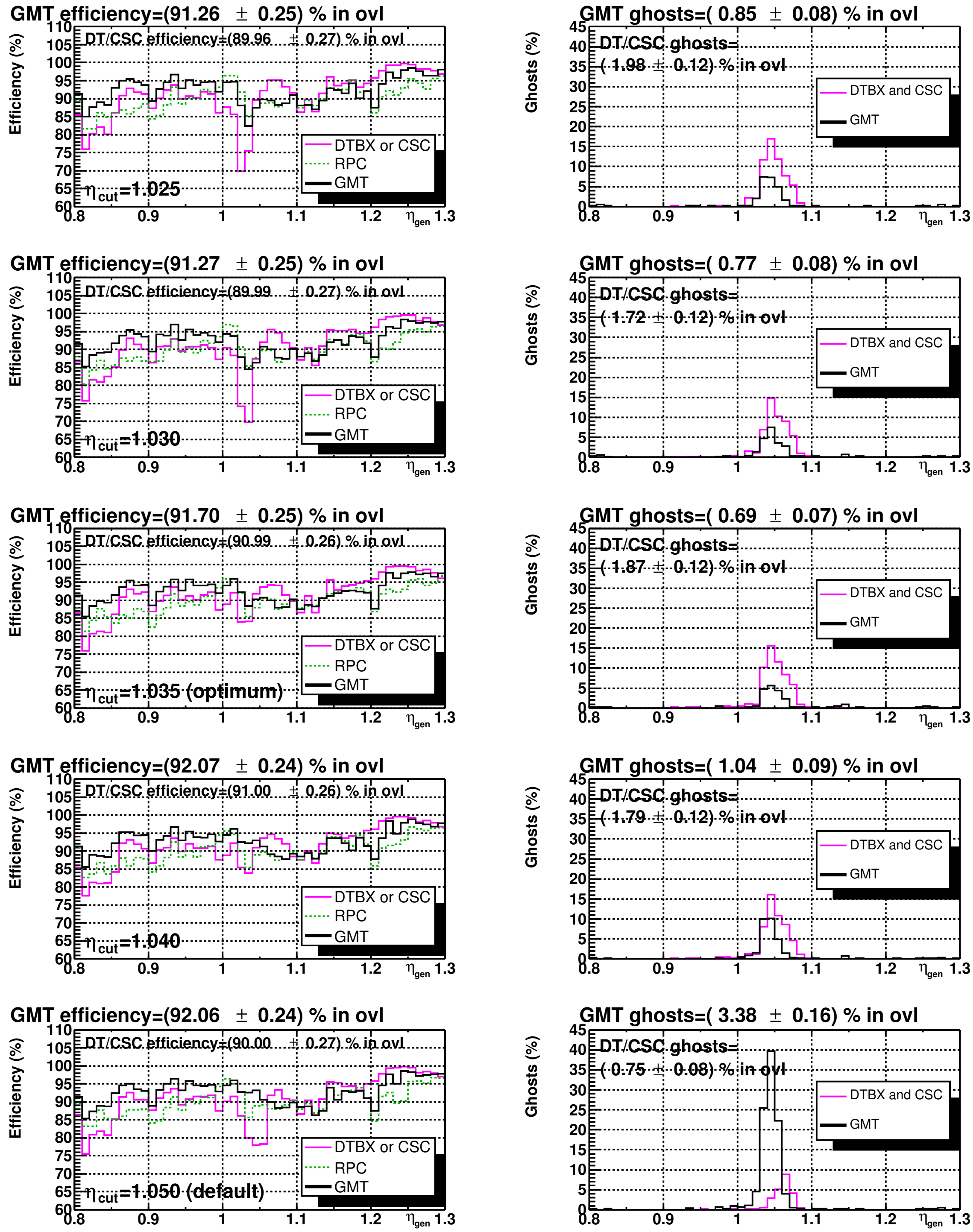

Figure 9: Efficiency and ghosts in the overlap region at the output of the Global Muon Trigger, using the DT/CSC cancel-out unit inside the GMT. Also shown are efficiencies and ghosts of the DT and CSC track finders and the RPC Trigger. Ghosts are suppressed at the level of the track finders using a scheme that allows the DT track finder to cancel duplicated MB1-MB2 tracks by attaching an η-tag to the CSC segments ("scheme B", see text). From top to bottom the results for different **fine-tuning** of the DT/CSC η-boundary are shown as indicated in the figure. The ghosts at the output of the GMT show a minimum for a boundary of $\eta_{cut} = 1.035$ which is the best match to the according boundary in the RPC System. An eta-boundary of $\eta_{cut} = 1.05$ (last row) is the default without any fine-tuning. Efficiency and percentage of ghosts are given inside the pseudorapidity range of $0.9 \leq |\eta_{gen}| \leq 1.2$. DT/CSC ghosts are candidates reported by both the DT and the CSC track finder. Simulated with ORCA 4.5.0, CMS121 geometry, RPC efficiency 95 %.