The Compact Muon Solenoid Experiment**CMS Note**

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Drift Tube Based Pseudorapidity Assignment of the Level-1 Muon Trigger for the CMS Experiment at CERN

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Abstract

CMS, the Compact Muon Solenoid experiment under construction at the CERN Large Hadron Collider, will explore new physics at high energies. Proton-proton collisions at a centre of mass energy of 14 TeV and heavy-ion collisions will be studied. Muons with large transverse momenta are expected to be among the decay products of many new particles. Their identification and selection is the task of the trigger system. Specifically, the Level-1 Muon Trigger has to search for muon candidates and to determine their parameters at a rate of 40 MHz, corresponding to a beam crossing interval of 25 ns. The precise knowledge of the spatial parameters of a track allows to fully make use of the possibility to select topological trigger conditions already at Level-1 in CMS.

Track segments measured in orthogonal layers of drift tube chambers are combined to form a muon candidate. Its transverse momentum is calculated from the track curvature in the (r/ϕ) -projection caused by a magnetic field along the beam direction z . The azimuthal angle ϕ in the plane transverse to the beam is also determined. The pseudorapidity η is a function of the track angle θ relative to the beam axis. Using the information from the bending plane projection only allows a coarse assignment of η in the central region of CMS by determining which chambers were crossed by the track. A method to assign η -values of much greater precision is presented. It relies on track finding performed in the non-bending plane (r/z) and on matching the found tracks with those of the (r/ϕ) -projection. The requirements, the chosen algorithm, its simulated performance and the feasibility for a hardware implementation are described.

1 Introduction

Compact Muon Solenoid (CMS) [1] is a general-purpose experiment designed to study proton-proton and heavy-ion collisions at the Large Hadron Collider (LHC) of CERN. Its main feature is a strong solenoidal magnetic field ensuring high momentum resolution for charged particles. Apart from the superconducting coil [2] the apparatus consists of a silicon inner tracker with an embedded pixel detector [3][4], a lead tungstate crystal electromagnetic calorimeter [5], a copper-scintillator sandwich hadron calorimeter [6] and a sophisticated four station muon system [7] featuring dedicated trigger chambers, the Resistive Plate Chambers (RPC), and tracking chambers, which are also used in the trigger. The latter are made up of Drift Tubes with bunch crossing identification capability (DT) in the central region and Cathode Strip Chambers (CSC) in the forward parts of the experiment. The RPC trigger chambers are mounted on the tracking chambers. To improve detector coverage a forward calorimeter consisting of a copper matrix with embedded quartz fibres is added in the forward regions [6]. A perspective view of the CMS experiment is shown in Fig. 1.

Figure 1: Perspective view of the CMS detector

The purpose of the trigger system of the experiment is the selection of all interesting events in the presence of an overwhelming background. Potentially interesting events at LHC are those including a Standard Model Higgs particle, supersymmetric or any other previously unknown particles as well as top events, WW , ZZ , $W\gamma$ and many others. Background events originate from collisions that carry no new information for the study of matter and its origin. The trigger also has to select events used for calibration, synchronization or testing purposes.

If the trigger discards a bunch crossing, the data is lost forever. For lepton colliders, such as the e^+e^- collider LEP at CERN, where the probability of collisions in a bunch crossing is far below 1 (about 3 events per second) dead times of the trigger system usually do not cause severe inefficiencies. This is because the probability of a second interaction within the trigger processing time is low. On the contrary, since the LHC beam crossing rate will be 40 MHz for protons,

with about 18 superposed events per beam crossing, the trigger system is of crucial importance to the physics to be discovered.

Muons (μ) are important signatures for new particle production due to their power to penetrate large amounts of material. They usually have a clean signal in the muon detectors and can be identified even in the presence of hadronic jets.

The CMS muon system triggers on and reconstructs muon candidates. The drift tube chambers in the central region (barrel) measure the tracks independently in two projections. In this region the magnetic field lines are parallel to the beam axis, which defines the z coordinate. In the bending plane (r/ϕ) tracks form helices, and in the plane along the beam (r/z) they are almost straight lines originating at the interaction point (Fig. 2). As a consequence, two different systems are used to detect muon tracks in each projection. In the first projection the transverse momentum (p_T) and the azimuthal angle (ϕ) transverse to the beam axis are measured. In the second projection the so-called pseudorapidity (η) is determined, which is a function of the angle (θ) between the track and the beam axis.

Figure 2: The two different projections of the CMS detector

Since the LHC particle accelerator delivers proton-proton collisions at a rate of 40 million events per second, the trigger electronics needs to provide a decision to retain or to reject an event for each bunch crossing interval (bx) of 25 ns. The CMS trigger has two distinct stages, the Level-1 Trigger and the High Level Triggers. The latency of the CMS Level-1 Trigger is restricted to 128 bx corresponding to

3.2 μs . Because of radiation levels, access and maintenance, most of the trigger electronics is not located on the detector itself but after a 90 m cable run in the counting room. The consequence of this arrangement is that a large part of the trigger latency is actually due to propagation delays in the optical links between the detector and the counting room, and only a fraction of the total latency time can be used for the processing of the actual trigger algorithms.

Since the computing time available is too short to use ready-made programmable devices such as microprocessors or digital signal processors, the Level-1 Trigger has to use custom built processors. If hints of unforeseen new physics appear it must be flexible enough to adapt the trigger algorithms as needed. It must also be able to accommodate higher backgrounds. It must cope with noisy and dead trigger cells by providing the possibility to selectively mask off individual channels.

A block diagram of the CMS Level-1 Trigger is shown in Fig. 3. Details about the Muon Trigger are given in section 2.4. The Global Muon Trigger combines the two independent components of the Muon Trigger, the DT/CSC based Track Finder and the RPC based Pattern Comparator Trigger (PACT) as described in [12] and section 2. The Level-1 Trigger decision is performed at the level of the Global Trigger. The earlier stages only provide information for this decision. The Global Trigger (refs. [8] and [9]) uses only the information of the Global Calorimeter Trigger and the Global Muon Trigger. Particle rates in the inner tracker are very high, therefore track finding in the inner tracker is too slow to be used in the Level-1 Trigger.

Figure 3: Logical structure of the Level-1 Trigger components

CMS requires all components of the Level-1 Trigger to be dead-time free. Therefore, a trigger decision based on trigger objects delivered by the detector subsystems is provided for each beam crossing, at a rate of 40 MHz. The Global Trigger comprises a novel concept where event selection is not only based on objects exceeding energy or

momentum thresholds but also on complex event topology which is made possible by the availability of space, charge and quality information in the algorithm calculations. The trigger logic is largely programmable in order to satisfy evolving physics requirements.

In the following an algorithm for calculating precise η values for all muon tracks found in the central part of the CMS detector is presented. It will be implemented in the DT based Track Finder electronics.

2 Barrel Muon Trigger

The CMS muon detectors consist of two different components: the barrel chambers in the center and the endcap chambers in the two forward regions. In order to detect a passing muon different types of detectors form a redundant system consisting of Drift Tubes (DT) located outside the magnet coil in the barrel region and Cathode Strips Chambers (CSC) located on the sides. The CMS muon system is also equipped with Resistive Plate Chambers (RPC) dedicated to triggering. The positions of the three detector types are schematically shown in Fig. 4.

The barrel as well as the endcap systems consist of four muon stations interleaved with the iron of the magnetic flux return yoke. The iron decouples adjacent stations in case of muon-induced electromagnetic background: A muon can emit a bremsstrahlung photon which gives rise to an electromagnetic cascade. The iron between adjacent stations has to be at least 30 cm thick to absorb all these cascade particles and to prevent them from penetrating into the next station.

Figure 4: The CMS muon detectors in longitudinal view

Since the central magnetic field has no bending power in the (r/z) plane, the muon tracks form straight lines in this projection. They originate at the vertex. The detector measures the pseudorapidity η using the angle θ between the track projection in the longitudinal plane and the beam direction. η is defined as:

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

Directions parallel to the beam axis, i.e. $\theta = 0^\circ$ or $\theta = 180^\circ$, have pseudorapidities η of $+\infty$ or $-\infty$ respectively.

2.1 Drift Tube Chambers

The barrel muon system [7] is composed of four muon stations. It is divided into five wheels along the z -axis, each approximately 2.5 m long. Each wheel consists of twelve azimuthal sectors, therefore one sector covers approximately 30° . All sectors within the same ϕ range across all five detector wheels are grouped together and called a “wedge” (Fig. 5).

Figure 5: Classification of the different detector parts

Due to the strong magnetic field outside the coil - the magnetic flux density in the return yoke corresponds to the saturation value of 1.8 T - a standalone muon momentum measurement up to high energies is possible. Calculating the curvature of the muon tracks allows the assignment of p_T values. This is essential for the trigger and useful for the off-line matching of a reconstructed track to its image inside the inner tracker.

Every muon station contains modules of drift tubes measuring the track coordinates in the (r/ϕ) plane. Only the inner three stations are equipped to measure in addition the track position in (r/z) . As shown in Fig. 6 a single chamber in sta-

Figure 6: Cross section of a muon chamber in the (r/z) view (station 1 or 2)

DT ... Drift Tube
L ... Layer
SL ... Super Layer
RPC ... Resistive Plate Chamber

tions one, two or three consists of twelve layers (L) of drift

tubes arranged in three superlayers (SL) of four layers each. The tubes of one superlayer are arranged in four layers with an offset of half a tube width each. The outer two (r/ϕ) superlayers measure the ϕ coordinate in the bending plane, whereas the central (r/z) superlayer measures the z coordinate along the beam axis. The chambers are 2.56 m long in z , and the width in (r/ϕ) increases from 2 m in the innermost station to 4 m in the outermost station. The position of the chambers can be seen in Fig. 4.

In the endcap region the muon detector also consists of four muon stations but mounted vertically and using a different method for particle detection. The working principle of the CSC detector at CMS is described in [7].

To calculate the η value in the barrel data coming from the central superlayer of the DTs are used. This superlayer consists of drift cells with wires oriented along the beam direction and is read out by a special logic, housed in the DT Trigger Electronics.

2.2 Drift Tube Local Trigger Electronics

The maximum drift time of the particles in the drift tubes of 400 ns is much longer than the delay between two consecutive bunch crossings (25 ns). This means that the muon causing the electron avalanche in the tube will be detected by the wire only after several bunch crossings have occurred. Therefore it is necessary to identify the bunch crossing to which the detected muon belongs. The method is based on a generalized meantimer technique described in [10].

The so-called ‘Bunch and Track Identifier (BTI)’ was explicitly developed to apply the technique working on groups of four layers of staggered drift tubes, aiming to identify tracks giving signals in at least three of the four layers. This method is based on the fact that - considering the small width (6 cm) of one superlayer - the particle’s path is a straight line. The distances of the wires along the path, which give rise to the measured “points” are equal.

Figure 7: BTI layout consisting of nine DT cells. A passing muon hits different wires which are then recognized by the BTI.

Each BTI is connected to nine wires grouped as shown in Fig. 7. To enable an effective measurement the BTI’s overlap by five wires, i.e. the next BTI will start from the cell labelled 5 in Fig. 7. This overlap assures the redundancy needed to limit the inefficiency in case of a BTI failure.

The BTI's deliver the input for both the (r/ϕ) Track Finder and the η Track Finder. In the former case, the outputs of the BTI's from two superlayers are correlated by a device called Track Correlator to so-called "track segments", thus reducing the noise and improving the angular resolution. Track segments contain not only the hit location, but in addition angular information of the particle's path. In the latter case there is only one superlayer per chamber, therefore only the hit coordinates are retrieved, which are then sent to the θ Trigger Server.

2.3 Trigger Server

The Trigger Server (TS) is a device that forwards the track segments to the Regional Muon Trigger, which has to construct complete tracks with the local trigger information and to determine their parameters.

2.3.1 Transverse View (r/ϕ)

The Trigger Server of the ϕ -layer selects the best two track segments per chamber out of all segments delivered by the Track Correlator and delivers their location and direction angles to the Regional Trigger.

2.3.2 Longitudinal View (r/z)

The DT θ Trigger Server in the longitudinal view (TSL) has to group the information coming from approximately 64 BTI's of each θ -superlayer. It sends a corresponding bit pattern to the η Assignment Unit according to the output of the BTI's of one chamber. Studies on the Regional Muon Trigger [11] have shown that the minimum pattern resolution, without significant loss of track finding efficiency, corresponds to the space covered by eight BTI's. As a consequence only 8 different values are calculated per chamber. The TSL receives two bits from each BTI, one for the trigger strobe pulse and one for the corresponding quality. For both of them the TSL performs a logical OR in groups of eight BTI's. The output is formed by two bits for each group: in total there are eight bits for the trigger pattern plus eight bits for the corresponding quality information. The "quality" bit gives information whether three or four out of four wires registered a passing muon. In the former case a low trigger signal (LTRG) is issued, whereas a high trigger signal (HTRG) is assigned in the case of the latter. If fewer than three wires detected a hit, no signal is produced.

2.4 Regional Muon Trigger (Track Finder)

The Regional Muon Trigger in (r/ϕ) -projection is subdivided in units covering 30° -sectors in ϕ , the so-called "Sector Processors". Their task is to find muon tracks originating at the interaction point and to measure their transverse momenta p_T and their location in ϕ . If a track passes a chamber, the chamber trigger logic forwards a track segment to the Track Finder. The track finding is done by extrapolating from one track segment to the next. For p_T measurement this is sufficient, because in the barrel region the magnetic field is uniform, thus the p_T value can be

calculated from the bending angle of the track. Chambers have inefficiencies - in only $\sim 85\%$ of the cases a crossing muon gives rise to at least three track segments belonging to one track. However, only two compatible track segments are already sufficient¹ to form a track candidate, leading to a track acceptance of about 96% [12].

Since tracks may cross detector wheel and sector boundaries, adjacent Sector Processors have to perform intercommunication. Due to the design of the trigger system every Sector Processor determines the best two muon tracks. All processors of one wedge forward their selected tracks to the Wedge Sorter (WS), which selects up to two muon tracks per wedge and forwards them to the DT Sorter. The DT Sorter in turn selects the best four muon candidates of all wedges and sends them to the Global Muon Trigger (GMT) [12].

Although the Regional Trigger in (r/ϕ) -projection, which does not use the θ superlayer, is by definition unable to measure the z coordinate along the beam direction, it can nevertheless assign a coarse η value due to the information, on which chambers were crossed by a track. With this method a coarse, location dependent, resolution in η can be achieved. Moreover, the resolution depends on the number of track segments a track consists of. If a change of wheel has not taken place, the η value will be particularly coarse, especially in the central wheel. The final hardware implementation of the DT Regional Trigger therefore foresees a separate track finding processor in the (r/z) -plane for each wedge. The tracks thus found are then matched with those seen in the bending plane projection, resulting in a more accurate determination of η than the one by the Track Finder in (r/ϕ) alone. The η assignment scheme is also more flexible, as will be explained later.

3 η Assignment Unit

3.1 Design Principle

There are two possibilities to assign an η value to a track: (a) using the coarse information of the (r/ϕ) Track Finder, taking advantage of the known position where a track crosses detector wheel boundaries; (b) using the θ superlayer data from the first three muon stations to calculate a precise η value. Both of them are foreseen in the design of the device that calculates η . Originally the coarse η assignment was planned to be implemented on the (r/ϕ) Sector Processor boards, and the precise η assignment on a separate board. However, it turned out to be more practical to calculate both the coarse and the precise η values on a single electronic board, the so-called η Assignment Unit (EAU), which performs two steps. The first one is the stand-alone track finding in the (r/z) plane, and the second one is the

¹ In principle one track segment would already be sufficient. Requiring two compatible segments helps to suppress noise, however.

matching with the (r/ϕ) track information. Since the track finding is done independently in the two projections of the detector, the EAU tries to match the η track to the muon tracks found in (r/ϕ) . If the match is successful, the improved η value is definitely assigned to the track, otherwise the coarse assignment is used. The sub-unit of the EAU that finds the tracks in (r/z) is called η Track Finder (ETF), and the sub-unit that tries to combine the muon track information of both projections, namely (r/ϕ) and (r/z) , is called the η Matching Unit (EMU).

Although the η Assignment Unit could theoretically find additional tracks not seen by the (r/ϕ) Track Finder in the barrel, this possibility has not been implemented due to background considerations. Therefore only the tracks selected by the (r/ϕ) Sector Processors have an η value assigned.

3.2 Input and Output

Two different inputs are relevant for the η assignment. One comes from the θ superlayers for the η track finding and the other comes from the (r/ϕ) Track Finder for the matching. A special Sector Collector sends the θ data to the Regional Muon Trigger using an optical link with the data format described in Tab. 1.

Table 1: Summary of the input data for the η Assignment Unit from each muon chamber

Content	# of Bits
Position	8
Quality	8

In principle, each chamber can resolve around 64 different positions in the z direction. However, as already mentioned before, a study [11] has demonstrated that there is little impact on the system resolution using even fewer positions. Therefore, only 8 instead of 64 different θ positions per chamber are forwarded to the η Assignment Unit (EAU). In order to obtain these 8 values per chamber eight adjacent BTI's are grouped together in a logical OR. Since the θ data contains only the grouped information coming from the BTI's in one superlayer, no track correlation like in the (r/ϕ) plane is possible, or necessary. Therefore the data arrives 5 bx earlier at the input of the EAU than the corresponding track segments arrive at the (r/ϕ) Sector Processors.

For the matching and also for the calculation of the coarse η values there has to be an intercommunication between the Sector Processors and the EAU. In each wedge there is a single EAU, which receives track segments coming from the first three muon stations in all five wheels belonging to one wedge. The chamber hits are sent in the form of two eight-bit patterns, one for the quality and one for the position (cf. Tab. 1). In addition, signals for calibration and control purposes are transmitted to the Sector Collector.

In total, this results in $5 \times 3 \times 16 = 240$ bits for each bx and wedge, forwarded from the Sector Collector using eight optical links per wedge. This results in 96 optical links for the

whole detector. In addition, for each found track the (r/ϕ) Sector Processor sends a five-bit information of chamber addresses to the EAU. Since the (r/ϕ) Track Finder consists of two modules in the central wheel, in total six Sector Processors are sending the track address data of up to two muons each, resulting in 12×3 bits per wedge.

Since each (r/ϕ) Sector Processor selects the best two muon candidates (if present), this results in at most 12 muon tracks, for which the η Assignment Unit has to calculate an η value. Each track is assigned a six bit η value defining an η range from -1.3 to 1.3. An additional bit is foreseen to indicate whether the matching was successful or not, resulting in $(6 \times 2 \times 6) + (6 \times 2) = 84$ bits. Table 2 shows a summary of all input and output signals for one EAU.

Table 2: Input and output of the η Assignment Unit

	Input from		
	Information	Format	# Bits
DT-TSL	θ superlayer hit data	8 bit Position 8 bit Quality	240
(r/ϕ) Track-Finder	found track address	5 bit address	60
	Output to		
	assigned η values	12 x 6 bit η Track Data 12 x 1 bit Assignment Identifier	84

The η Track Finder optical link receivers will be mounted on daughter boards (mezzanine cards) that will be plugged on to the Sector Processor board.

4 Algorithm

4.1 Track Finding

In [11] it is shown that for the track finding in the (r/z) plane a pattern matching method is the most suitable one. When a track passes different chambers detecting hits the information is sent through corresponding electronic systems (refs. [12] Chap. 9.1) to the η Assignment Unit. Each combination of hits is interpreted as a pattern pointing back to the vertex (cf. Fig. 8), which is compared to a precalculated list.

Figure 8: For the track finding in the (r/z) plane a pattern matching method is used

If a matching pattern is found a corresponding η value is assigned to the track in the (r/z) plane. The calculation of this pattern list, based on simulation data as long as no real data are available, is the task of the simulation software described in [13]. Each η track has an assigned quality, depending on the number and the quality of the hits used to form the track (cf. Tab. 3).

4.1.1 Requirements for a valid η Track

The tracks viewed in the z projection are approximately straight lines (cf. Fig. 9). Therefore, knowing the position of the vertex, a single hit indicating the z coordinate where a particle passed the chamber is sufficient to assign an η value to this track. The question, how many hits should be required to form a valid track, arises.

Figure 9: Muon tracks with different values for p_T

Since the design of the muon detector foresees only the inner three muon stations to be equipped with a θ superlayer and considering the efficiency of the chamber trigger logic shown in [11], it is clear that requiring only two hits results in a very low track acceptance. In other words, too few η tracks would be found and as a result too few tracks seen in the r/ϕ projection would receive an improved η value. In ref. [11] it was shown that a single low quality track segment has to be accepted as a valid track in order to achieve an acceptable matching rate. This can also be derived from the η Track Finder efficiency shown later in Fig. 16.

This is not as bad as it appears at first sight. What could happen is that a wrong η value is assigned to a (r/ϕ) track which still must be in an acceptable range. This range is defined in such a way that the unphysical track matches the track found in (r/ϕ) . In this way no additional tracks are forwarded to the Global Muon Trigger by the η Assignment Unit. If an η track cannot be matched the track is simply discarded. From this point of view even the η tracks with the lowest quality can be used for the matching. The η Assignment

Unit merely sorts the track information the chamber trigger logic delivers rather than filtering out ghosts by throwing away data. It is in the Matching Unit where the unmatched η tracks will be filtered out.

Another question is whether a single hit can belong to more than one track. In contrast to the input in (r/ϕ) , the granularity of the trigger primitives is rather coarse. Therefore, the probability for two muons to overlap is higher than in the bending plane. As a consequence, two tracks must be allowed to share the same hit. The last requirement is the vertex constraint: every found muon track must point back to the interaction region. In the case of the η Track Finder only patterns that belong to tracks coming from the interaction point are stored, thus the vertex constraint is embedded in the pattern list by construction.

4.1.2 The η Track Finder (ETF)

The reconstruction of tracks using (r/z) plane hits, which lie on a straight line pointing back to the interaction vertex, is the task of the η Track Finder. A pattern matching method has been chosen. A list of possible patterns has been generated using simulated data samples, each pattern belonging to a certain η value. Therefore, if a set of hits matches a particular pattern, a track is found and the pattern η value is assigned to the track.

Since a track can consist of different subpatterns, it may occur that using only part of the hits multiple tracks will be found for a single real track. Therefore, a cancellation has to be implemented ensuring that the track with the highest quality is taken. Thus, each track belonging to a pattern also has a quality information attached.

The following scheme is used to define a unique quality for each η hit combination. The different combinations of the η hit quality (LTRG or HTRG) in the three different stations result in 26 quality numbers shown in Tab. 3.

Table 3: Definition of all possible η track quality numbers. They are grouped together according to their quality significance.
(0...no TS, 1...LTRG, 2...HTRG)

Q.#	Station			Q.#	Station			Q.#	Station		
	1	2	3		1	2	3		1	2	3
1	0	0	1	10	1	1	1	19	2	1	1
2	0	1	0	11	0	1	2	20	0	2	2
3	1	0	0	12	0	2	1	21	2	0	2
4	0	1	1	13	1	0	2	22	2	2	0
5	1	0	1	14	1	2	0	23	1	2	2
6	1	1	0	15	2	0	1	24	2	1	2
7	0	0	2	16	2	1	0	25	2	2	1
8	0	2	0	17	1	1	2	26	2	2	2
9	2	0	0	18	1	2	1				

This list of η track qualities, sorted according to all combinations of hit qualities, is used in the calculation of the pattern lists. The matching logic uses the same scheme and provides a simple correlation between the track information

coming from the (r/ϕ) Sector Processors and the found η tracks.

For the analysis of the EAU performance a simpler scheme is more useful, grouping the tracks according to their number of hits and hit qualities, while discarding the station information. This scheme is shown in Tab. 4 and used in Fig. 16 and Fig. 18.

Table 4: Definition of all possible η track classes according to their number of hits and hit quality used to form the η track.

Track Class #	η Track containing at least
1	... one LTRG
2	... one HTRG
3	... two LTRG
4	... one LTRG and one HTRG
5	... two HTRG
6	... two LTRG and one HTRG
7	... one LTRG and two HTRG
8	... three HTRG

4.2 Matching

Each muon track found in the bending plane needs to have an η value assigned. The muon tracks in the (r/z) plane are found independently, thus the computed η values need to be matched to the (r/ϕ) tracks. To perform the matching with the tracks found in the bending plane, each Sector Processor of a wedge sends track address data for all found tracks to the η Assignment Unit board. Using these address data a coarse η value is calculated in parallel and later on used if the match was not successful. In other words, if no track of the (r/z) plane fits the track found in (r/ϕ) , the coarse η value will be used.

The calculation of the coarse η value is also based on a pattern matching method, in analogy to the η Track Finder. The pattern of the chambers used to reconstruct the track in the (r/ϕ) plane is searched in a precalculated list containing the corresponding η values. These η values are determined with the simulation software package.

In order to perform the matching, the η Assignment Unit receives coded track address data from the (r/ϕ) Track Finder. Either the muon chambers used to reconstruct each muon track, or the corresponding η value can be used in the comparison. Thus, in the first case a track can be matched if the used chambers can be combined, whereas in the second case only the possible η ranges are checked. The (r/ϕ) address data contain the necessary wheel, station and sector information of all (r/ϕ) track segments (TS) used to reconstruct each track found in the (r/ϕ) plane as shown in Tab. 5. Fortunately a lot of combinations turn out to be not possible because of one of the following reasons:

- the track would have to bend back in η
- the track consists only of a single track segment
- the track would not be found by the Sector

Processor

- the track lies inside the same η boundaries.

In the next step this track information is compared to the reconstructed η tracks. If a suitable combination is found, an η value can be selected.

Table 5: Track address data used for matching. Since each track found in (r/ϕ) belongs to one Sector Processor, the sector and wheel numbers of the starting track segment are known. Only the remaining information has to be defined, e.g. if the track stays in the same wheel ("S") or changes to the next one ("N"). The combinations that must not be used because of bending back ("b"), not found by the Sector Processor ("n"), being equal ("e") or single tracks ("s") are shaded.

Id #	St.1	St.2	St.3	St.4	reason	Id #	St.1	St.2	St.3	St.4	reason
0	0	0	0	0			S	0	0	0	s
	0	0	0	S	s	9	S	0	0	S	
	0	0	0	N	s	10	S	0	0	N	
	0	0	S	0	s	11	S	0	S	0	
1	0	0	S	S		12	S	0	S	S	
2	0	0	S	N		13	S	0	S	N	
	0	0	N	0	s	14	S	0	N	0	
	0	0	N	S	b		S	0	N	S	b
	0	0	N	N	n		S	0	N	N	e
	0	S	0	0	s	15	S	S	0	0	
3	0	S	0	S		16	S	S	0	S	
4	0	S	0	N		17	S	S	0	N	
5	0	S	S	0		18	S	S	S	0	
6	0	S	S	S		19	S	S	S	S	
7	0	S	S	N		20	S	S	S	N	
8	0	S	N	0		21	S	S	N	0	
	0	S	N	S	b		S	S	N	S	b
	0	S	N	N	e		S	S	N	N	e
	0	N	0	0	s	22	S	N	0	0	
	0	N	0	S	b		S	N	0	S	b
	0	N	0	N	n		S	N	0	N	e
	0	N	S	0	b		S	N	S	0	b
	0	N	S	S	b		S	N	S	S	b
	0	N	S	N	b		S	N	S	N	b
	0	N	N	0	n		S	N	N	0	e
	0	N	N	S	b		S	N	N	S	b
	0	N	N	N	n		S	N	N	N	e

In the second case only the corresponding η values are used. Hence, what is compared is the η value belonging to the improved pattern and the possible η range corresponding to the raw pattern. This kind of matching is called "virtual matching" in the following.

Generally, if more than one η track fits the (r/ϕ) track, the η track with the higher quality is used. If no match is possible, the coarsely calculated η value - retrieved from the position of the used muon chambers in (r/ϕ) - is taken.

The next question is the impact of the minimal quality of the reconstructed η track and the minimal number of muon chambers requested to be equal. In the simulation different matching schemes have been studied in order to verify the impact of the quality of the η track and the minimal match-

ing criteria between the tracks found by the (r/ϕ) and η Track Finders. Setting a minimal threshold results in up to 26×4 different matching schemes that can be used. What is called matching scheme is therefore a combination of setting different minimal thresholds for track qualities and matching combinations as shown in Fig. 10.

Figure 10: Different possible combinations of η track quality and the matching of tracks found in (r/ϕ) and (r/z)

In Fig. 17 the matching efficiencies for the various schemes are shown and compared with different resolutions. Choosing one of the different possible schemes defines the matching probability and the relative η resolution.

The settings for the matching can be adjusted in the simulation software which then generates different lists of patterns including the information on which (r/ϕ) track can be matched with which η track. This option allows to change the matching and track identification scheme very quickly. Together with the modularity of the simulation software and the algorithm itself it offers a flexible η assignment method.

After the matching the last step is the assignment of the calculated η value.

4.3 η Assignment

If the two tracks can be matched, the η value calculated by the η Track Finder is assigned to the (r/ϕ) track candidate. Otherwise, if a matching is not possible, the coarse η value is assigned to the (r/ϕ) track candidate. Therefore it is possible to assign an η value to each track found in the bending plane. It is important that an η value is assigned and forwarded to the Wedge Sorter simultaneously with the p_T and ϕ values, whenever a track is found by the DT Track Finder. An additional bit is forwarded to the Global Muon Trigger with the information whether the assigned η value corresponds to the coarse or to the improved assignment method.

5 Simulation Results

In order to calibrate and test the performance of the η Assignment Unit a sample of one million positively and nega-

tively charged single muon events was generated. The muon sample is flatly distributed in the following parameters:

- p_T : (3.5 ... 100.0) GeV
- ϕ : (0.0 ... 2π) rad
- θ : (0.0 ... π) rad

Since the input to the η Track Finder is restricted to a single wedge, some tracks can neither be found nor matched. The probability (Φ) for changing the sector in both views is shown and compared in Fig. 11.

Figure 11: The probability (Φ) for a track to change the sector is shown for both projections. The probability for tracks found in (r/ϕ) and (r/z) is compared and plotted versus the generated η value

Most of these tracks have a track segment or a hit in an inner station. They are not lost for matching because they can be reconstructed using the track data of the remaining chambers. However, depending on the minimal η track quality to be required and the matching scheme applied, they can be rejected. In the actual scheme, using only one LTRG for a valid η track, the impact of lost tracks is very low as is shown in Tab. 6.

Table 6: Probabilities for a track changing the sector between different stations in the case of the (r/ϕ) Track Finder (a). If a track changes the sector in (r/ϕ) it is checked whether the track in (r/z) changes the sector as well (b) and the loss for the matching is calculated (c).

between stations	(a) probability for a (r/ϕ) track / %	(b) probability for a (r/z) track / %	(c) matching loss / %
1 - 2	5.86	19.35	2.17
2 - 3	1.45	0.11	0.04
3 - 4	6.55	0.00	0.04

It has to be kept in mind that the percentage of lost tracks increases if the EAU is forced into a higher quality scheme. This can have a considerable impact if the EAU would be used for other purposes than the η assignment, e.g. the suppression of non-prompt muons. Adding the input from adjacent wedges - at least from station two - would then certainly be an improvement.

5.1 Resolution Studies

The maximal resolution that the EAU could theoretically achieve is the intrinsic resolution of the muon chamber, corresponding to approximately 64 different values as shown in Fig. 12.b. Since these 64 values are OR-connected to only eight different values per chamber, this basic resolution decreases and sets already a limit for the EAU.

The η assignment, which was using only the information of the station where the track changed the wheel, is improved by a new coarse scheme using all combinations of chambers to assign an η value to the track. This scheme, which uses partially overlapping η ranges, offers a better resolution and is important for the matching. To summarize, Fig. 12 shows a comparison between the resolutions for the system granularity, the old coarse assignment and both the new coarse and improved η assignments.

Figure 12: Resolution plots for four different cases:
a.) The resolution of the η assignment as it is currently implemented in the detector simulation.
b.) The resolution of the θ superlayer using the maximal granularity of 64 different η values per chamber.
c.) The new coarse η assignment using all combinations of the chambers used from a track found in (r/ϕ) .
d.) The improved η assignment using 8 different η values coming from each chamber and calculating 64 different η values.

Not only the number of hits delivered by each chamber influences the resolution of the η assignment, but also the number of different η values which are finally assigned. This occurs because the simulation can produce more pat-

terns than fit into the maximal number of different η values. Since the algorithm is implemented in hardware, only numbers mapping in a bitwise scale are of interest. At the moment the number of output bits is set to 6, resulting in a maximal number of 64 different η values for the whole η region. Figure 13 shows the influence of the different granularities of the assigned η scale on the η resolution. Thus, the choice

Figure 13: Depending on the number of assigned η values the resolution of the η assignment changes. The chosen 6 bit η range - corresponding to 64 different η values - results in an acceptable η resolution

of a 6 bit η range corresponds to an insignificant loss in resolution, while keeping the hardware implementations reasonable.

Figure 14 shows the η resolution achieved by the η Track Finder as a function of the generated η values. The improved resolution - using the middle superlayer of the muon stations (circles) - is compared to the raw resolution achieved with the coarse η assignment (triangles).

Figure 14: Pseudorapidity resolution versus the η coordinate for both the coarse (blue triangles) and the improved (red circles) η assignment

Figure 15: η Track Finder efficiency versus different track qualities

5.2 Track Finding Efficiency

According to the definition of the different η track qualities Fig. 15 shows the probability to find an η track with respect to the minimal η track quality used in the EAU simulation. The efficiency drastically decreases when higher quality tracks are required. By comparing efficiency with different track classes it can be shown that requiring more than a LTRG for a valid track introduces inefficiencies of the order of 10% and higher to the EAU (c.f. Fig. 16).

Therefore, it is strongly recommended to use an η Track Finder method in which a LTRG is allowed to be a valid track, as long there is no improvement in the efficiencies of the chambers or any other change in the muon detector system performance.

Figure 16: η Track Finder efficiency versus different track classes

5.3 Matching Efficiency

Figure 17 presents the calculated standard deviation (σ) of the η resolution for each η assignment scheme. The resolution improves with a higher matching probability because of the large fraction of improved η values assigned. Studies on the mis-matching probability - i.e. a wrong η track is matched to the (r/ϕ) track - due to multiple scattering or delta rays have been performed, but they did not show a significant impact. Anyhow, the assignment scheme can easily be tuned in case of a much higher expected background rate which influences the η resolution.

To illustrate the same dependence in a more compact way, Fig. 18 shows the matching efficiencies as a function of the different track classes. In this plot the resolution values almost remain constant, because the requirement for a certain track class contains different track qualities.

In order to reach a highly efficient η assignment, the best choice is the so called “virtual matching” scheme, by comparing only the η value of the improved pattern to the corresponding η range of the coarse pattern. In case of the minimal quality scheme for the η track finding, a single LTRG is enough for efficient track reconstruction. Therefore the calculated matching efficiency reaches 100 percent if a match is possible in principle. Another option for the matching is to use at least one chamber to reconstruct the track in both projections. This causes inefficiencies, however, as can be seen in Fig. 17 to Fig. 20.

Figure 17: Using the calculated standard deviation the resolution for each assignment scheme and its impact on efficiency and overall resolution can be compared (for the definition of the matching schemes see Tab. 3)

Figure 18: Using the calculated standard deviation, the resolution for each track class and its impact on efficiency and overall resolution can be compared (for the definition of the matching classes see Tab. 4)

Figure 19: p_T dependence on the matching efficiency, requiring at least one LTRG for an η track and at least one chamber to have one TS in (τ/ϕ) and one in (τ/z) for a successful match

Figure 20: η dependence on the matching efficiency, choosing one LTRG to be required for an η track and at least one chamber to have one TS in (r/ϕ) and one in (r/z) for a successful match

Fig. 19 shows the dependence of the matching efficiency versus the transverse momentum p_T . Figure 20 compares the matching efficiency to the generated pseudorapidity η .

To summarize, an optimal algorithm implementation can be set using a single LTRG as minimal η track quality and using the “virtual matching” for the comparison between the two Track Finders. In this case all possible tracks will be matched to the (r/ϕ) track candidate and the best possible resolution will be obtained.

6 Conclusion

An algorithm to assign pseudorapidity values to muon tracks found in the barrel by the Level-1 Trigger of the CMS experiment has been developed. Detailed simulation studies have been performed in order to determine the choice of its parameters. The feasibility of the hardware implementation has also been validated.

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