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Overview of the CMS muon trigger system

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Abstract

This paper is intended to be a brief introduction to other presentations devoted to specific components of the CMS Muon Trigger System. General goals and requirements for the system are summarised. Data flow from the detectors to the global trigger is explained. The emphasis is put on interconnections between various components. Latency issues are discussed. Finally, expected performance of the system is presented.

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1 Requirements

The basic tasks of the CMS Muon Trigger are muon identification, transverse momentum measurement and bunch crossing identification. It has to fullfil the following requirements.

Geometrical coverage: up to $|\eta|$=2.4, in order to cover the entire area of the muon system.

Latency: < 3.2 µs. Total trigger processing, including 2×120 m cables (1.2 µs) to the control room, should stay within the length of the tracker pipelines equal to 128 bunch crossings.

Trigger dead time: not allowed. Every bunch crossing has to be processed in order to maintain high efficiency crucial for physics channels with low cross section.

Maximal output rate: < 15 kHz for luminosities < 10^{34} s^{-1}cm^{-2}. Maximal second level input rate is 100 kHz. Uncertainty in estimates of cross sections and luminosity variations during a single run requires large safety margin. We design the average first level output rate not to exceed 30 kHz which should be shared amongst muon and calorimeter triggers.

Background rejection: trigger rate due to background should not exceed the rate of prompt muons from heavy quark decays. This is necessary to maintain the rate limits stated above. The prompt muon rate is irreducible except for channels where the isolation criterion can be applied (see below).

Low p_t reach: should be limited only by muon energy loss in the calorimeters. It is equal to ~4 GeV in the barrel and it decreases with $|\eta|$ down to ~2 GeV. This is required mainly by b-quark physics at $L = 10^{33}$ s^{-1}cm^{-2}.

The highest possible p_t cut: ~50-100 GeV. Expected threshold needed to keep the single muon trigger rate to be a few kHz at $L = 10^{34}$ s^{-1}cm^{-2} is 15-20 GeV. Uncertainty in estimates of cross sections and background levels requires large safety margin.

Isolation: transverse energy E_t deposited in each calorimeter region of $\Delta\phi \times \Delta\eta = 0.35 \times 0.35$ around a muon is compared with a threshold. This function is needed to suppress the rate of background and prompt muons form heavy quark decays when triggering on muons not accompanied by jets. This is particularly useful in channels like h,A,H$\rightarrow\mu\mu$, h,A,H$\rightarrow\tau\tau$, tt$\rightarrow$WW and gluino decays.

Output to the Global Trigger: up to 4 highest p_t muons in each event. In principle only 3 muons are necessary for the Global Trigger to perform single- and multiobject cuts including the three-muon trigger. Delivering 4 muons we reduce the probability that a low p_t isolated muon will not be selected because of the presence of higher p_t nonisolated muons. This way we also reduce the probability of accepting ghosts instead of real muons.

2 Muon trigger components

The muon trigger system consists of the following items:

- Pattern Comparator Trigger (PACT) based on Resistive Plate Chambers (RPC)
- Drift Tube (DT) Trigger - containing Bunch and Time Identifier (BTI) and Track Correlator (TC)
- Cathode Strip Chamber (CSC) Trigger
- Track Finder (TF) - Regional Trigger
- Muon Sorter
- Global Muon Trigger

Functional relations between the components are shown in Fig. 1. Cumulative latency is given in bunch crossing units (bx). Three shaded backgrounds show the location of the electronics: at the chamber, in the experimental hall and in the control room respectively. The number of links is given. Optical links of 1 Gbit/s are indicated by circles.

DT and CSC electronics first process the information from each chamber locally. As a result one vector (position and angle) per muon station is delivered. Vectors from different stations are collected by the Track Finder which combines them to form a muon track and assign a transverse momentum value. This information is shipped to the Muon Sorter.

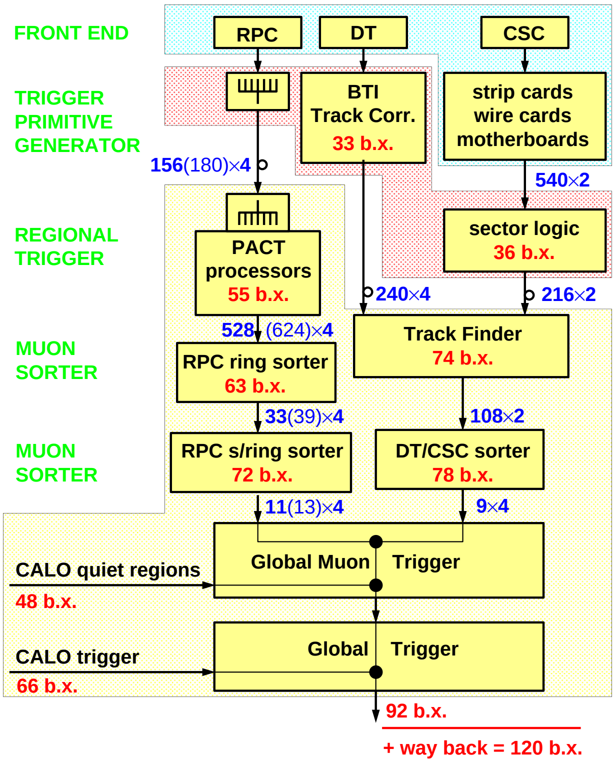

Fig. 1. Block diagram of CMS 1st Level Muon Trigger

In the case of RPC there is no local processing apart from synchronisation and cluster reduction. Hits from all stations are collected by PACT logic. If they are aligned along a possible muon track, a p_t value is assigned and the information is sent to the Muon Sorter.

The Muon Sorter selects 4 highest p_t muons from each subsystem in several detector regions and sends them to the Global Muon Trigger. The Global Muon Trigger compares the information from TF (DT/CSC) and PACT (RPC). So called quiet bits delivered by the Calorimeter Trigger are used to form an isolated muon trigger. The 4 highest p_t muons in the whole event are then transmitted to the Global Trigger. Finally transverse momentum thresholds are applied by the Global Trigger for all trigger conditions.

2.1 RPC Pattern Comparator Trigger

The trigger is based on 4 RPC planes. There is one RPC plane in each muon station except MB1 and MB2. These stations contains additional planes referred to as MB1' and MB2'. They are used to trigger on low momentum muons (p_t < 6 GeV) which cannot reach MB3 and MB4. In the baseline design RPC cover the η-range up to |η|=2.1, but the space for a possible installation of chambers is left up to |η|=2.4 in case of upgrade. RPC are read out by strips covering $\Delta\eta \approx 0.1$ and $\Delta\phi = 5/16°$ each. If the signal is shared by more than 2 strips the cluster size is reduced by removing strips on the cluster edge. For low p_t muons, when the resolution is limited by multiple scattering, the strips are grouped by 2, 4 or 8, depending on the momentum.

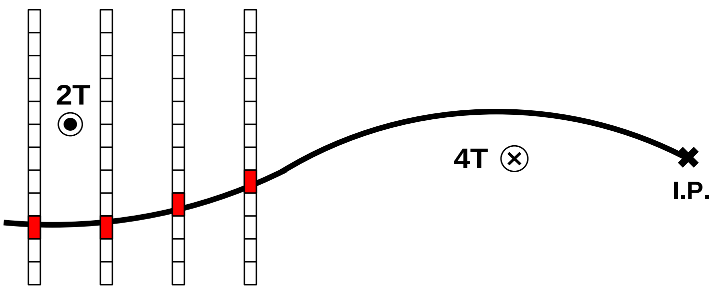

Fig. 2. PACT principle of operation.

The basic logical unit of PACT is called *segment*. It covers $\Delta\eta \approx 0.1$ rapidity unit times $\Delta\phi = 2.5°$. It is defined by 8 strips in a reference muon station. As the reference station we have chosen MF2 and the first RPC plane in MB2. Each *segment processor* is equipped with a Pattern Comparator (PAC) chip which compares patterns of hits from 4 RPC planes with predefined *valid patterns*. The valid patterns are first obtained from simulation and will be corrected later using real reconstructed muon tracks. Because a given pattern can be created by muons from a certain p_t range we assign a maximal p_t value to it. The pattern must consist of at least 3 hits from different planes. If it consists of 4 different plane hits a *3/4 quality bit* is set to 1. Otherwise it is set to 0. This bit is used further to select the best muon candidates (see Sec. 2.5.) because a missing hit can cause overestimation of the muon momentum. Full information delivered by each segment processor is described in Tab. 1. This information is further processed by the Muon Sorter. Detailed description of PACT can be found in Ref. [1].

2.2 Drift Tube Trigger

Each of 4 muon stations in the barrel is equipped with 12 layers of Drift Tubes. They are arranged in 3 quartets called *superlayers* (SL). Two of the superlayers measure the $r\phi$ coordinate, one measures η. Tracks in each SL are recognised by Bunch and Track Identifier (BTI) using generalised meantimer technique. Signals from 4 DT layers are connected to clock driven shift registers. Shifting time in the registers compensates the drift time, thus 4 signals are aligned in a fixed time after the particle passage, approximately equal to the maximal drift time. This enables bunch crossing identification. Cases when only 3 aligned hits are found are also accepted but they are called *Low Quality Triggers* (LTRG) in contrast to *High Quality Triggers* (HTRG), based on 4 aligned hits.

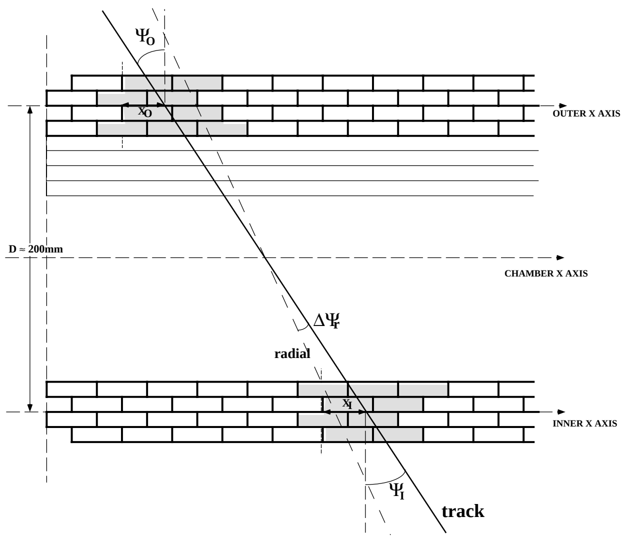

Fig. 3. Drift Tube trigger principle.

A single tube is 40 mm wide (drift direction) and the distance between planes of tubes is 13 mm. The maximal drift time with a drift velocity of 50 µm/ns is about 400 ns. The clock cycle of 25 ns and the drift velocity determine the position measurement unit to be equal to 1.25 mm. A lever arm of at least 22 mm gives an angular precision better than 60 mrad. A single BTI unit is connected to 2+2+2+3 tubes in 4 layers respectively.

Track pairs from inner (SL_I) and outer (SL_O) ϕ-superlayers are combined by the *Track Correlator* (TC). It compares their angles, ψ_I and ψ_O, with the angle ψ_{COR} defined by the positions x_I and x_O with precision of 10 mrad. If the correlation is successful then ψ_{COR} and x_{COR} are transmitted. Otherwise HTRG is chosen. If both tracks have the same quality the one from SL_I is taken. Each TC serves 5 SL_I and 15 SL_O in order to match the BTI angular acceptance. It selects up to 2 candidate BTI pairs preferring HTRG over LTRG and smaller deviation from radial direction $\Delta\psi_r$ which should corresponds to higher p_t tracks. HTRG has preference over $\Delta\psi_r$ for the first candidate, and vice versa for the second one. TC also receives information from the θ-superlayer. It is used together with H/L bits from ϕ-superlayers to determine two trigger quality bits TRG0 and TRG1. The described algorithm flow is the standard one, but other choices are available using programmable control bits. TC outputs from one chamber are collected by *Trigger Server* (TS). TS selects up to 2 candidates using the same criteria as TC. In addition, positions of all tracks detected by BTI in θ-superlayers are coded in 32 bits with 8 cm resolution. More details on DT trigger electronics can be found in Ref. [2].

2.3 Cathode Strip Chamber Trigger

Endcap muon stations are equipped with Cathode Strip Chambers. Each chamber consists of six detecting layers. They are read out by radial strips and wires perpendicular to them, except MF1/1 where the wires are tilted by 22°. The strip width $\Delta\phi$ varies from 2.0 to 4.3 mrad and the length $\Delta\eta$ from 0.35 to 0.60 η units. The wires are ganged in groups of $\Delta\eta \approx 0.02$-0.04 (i.e. 25-50 mm). Signals from strips and wires are first processed independently by electronics attached to the chambers.

Typical signal is shared by a few strips. The first task of the strip electronics is to find the center of the cluster with a half strip precision. Currently two possibilities are being envisaged:

- use discriminated signals and calculate the cluster center from strips on the cluster edge,
- use a net of analog comparators looking at the highest signal and its neighbours.

One CSC strip card handles 16 strips $\times$ 6 layers. The strip signals are brought into coincidence within *roads* within a time bucket of 100 ns for the local strip trigger. For p_t in the range 10 - 100 GeV the road is 4 $\times$ half strip wide. For low p_t, between 2.5 and 10 GeV, the half strip signals are grouped by 4 (to the width of two strips) and the road is 4 $\times$ double strip wide. One or two missing hits in a road are allowed, i.e. 4/6 (4 out of 6) and 5/6 patterns are accepted in addition to 6/6 ones. The best pattern in a road and then the best one on a entire strip card is found by *priority encoding*. First 6/6 patterns take priority over 5/6 and 4/6, then low bend-angle (high p_t) take priority over high bend-angle (low p_t).

The main task of the wire card is to recognise the bunch crossing. It is not straightforward because signals from six layers are spread within t_d=50 ns interval due to the drift time. The signals are shaped to be longer than t_d and coincidence of at least 4 out of 6 signals is required. Second arriving signal is used to determine the bunch crossing. We do not use the first one, because a single hit can be caused by background.

A subsequent logic performs the following basic functions:

- Converts strip card information into number of hits N_h, position ϕ and bend angle ψ.
- Converts wire card information into number of hits N_h and position η.
- Requires coincidence between track segments seen by strips and by wires.
- Applies alignment corrections to muon track segments.
- Combines information from chambers in 30° sectors resolving overlaps with neighbours in ϕ.
- Transmits up to two tracks per 30° sector to the Track Finder

The CSC trigger electronics is described in more detail in Ref. [3].

2.4 Track Finder

The main task of the Track Finder is to combine track segments delivered by DT and CSC from different stations into full muon tracks and assign p_t values to them. Its basic unit called *sector processor* covers $\Delta\phi=30^o$ and $\Delta\eta$=0.35. It matches track segments from different stations by an extrapolation method. Having 4 muon stations several station$\rightarrow$station extrapolations can be done in parallel. In the barrel they are: 1$\rightarrow$2, 2$\rightarrow$3, 4$\rightarrow$3, 1$\rightarrow$3, 2$\rightarrow$4, and 1$\rightarrow$4. The extrapolation is based on position ϕ and bend angle ψ of a track segment. The bend angle ψ is used as a starting direction and as a measure of p_t to find the track curvature. In the barrel the $p_t(\psi)$ relation is unique but in the forward region it depends also on η. A pair of track segments is considered as matched if the extrapolation of the first one coincides with the position (and possibly the angle) of the second one within a given accuracy.

The next step is to combine all matched pairs into a full track. At least two matched track segments are required. Resulting track candidates are checked whether they are not caused by the same real muon. The last step is to assign unique ϕ, η and p_t to the track. The p_t is calculated as a function of the bend angle between two stations ϕ_i-ϕ_j. In the forward region also the η information must be used. The resulting values are then transmitted to the Muon Sorter. A single sector processor can deliver up to 2 tracks. They are selected using p_t and quality bits. For more information about the Track Finder see Ref. [4].

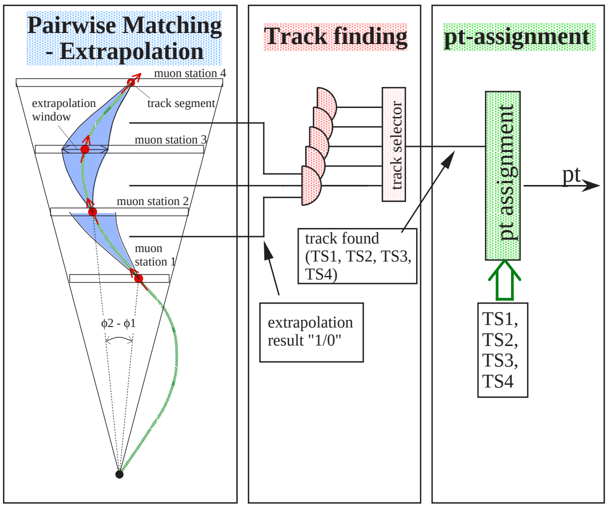

Fig. 4. Track Finder algorithm.

2.5 Muon Sorter

The Muon Sorter receives the information from PACT and TF. One single sorter chip accepts up to 8 muons on the input and delivers up to 4 muons on the output, sorted according to their p_t and quality bits. The sorting chips are arranged in a form of a tree sorting out the 4 highest p_t muons among all candidates in several detector regions (see Fig. 5). In the case of PACT the first step of sorting is done already at 526 (or 624 in the case of upgrade from $|\eta|$=2.1 to 2.4) *Trigger and Readout Boards* (TRB) grouping 8 segment processors each. Their outputs (4 per TRB) are further processed by 33 (39) *ring sorters*, each covering a *ring* of $\Delta\eta\approx0.1$ and $\Delta\phi=360°$. Then the rings are grouped by 3 into 11 (or 13) *superrings* of $\Delta\eta\approx0.35$ and $\Delta\phi=360°$. Thus 11×4 (or 13×4) muons are delivered to the Global Muon Trigger. The TF sectors are grouped into 9 regions of $\Delta\eta\approx0.5$ and $\Delta\phi=360°$ thus providing 9×4 muons on the Muon Sorter output. This segmentation is, however, still a subject to optimisation. More details on the Muon Sorter can be found in Ref. [5] .

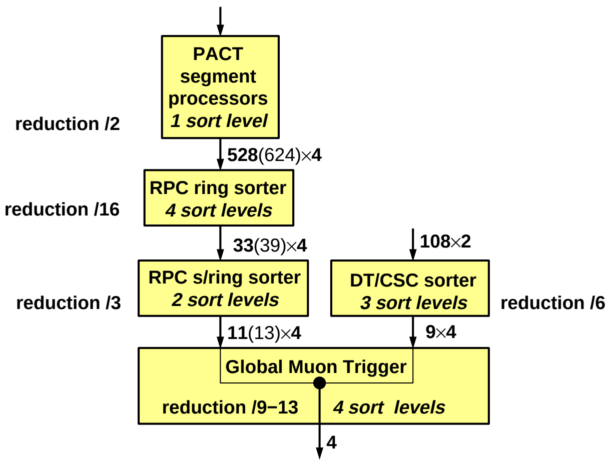

Fig. 5. Muon Sorting tree.

2.6 Global Muon Trigger algorithms

The Muon Sorter delivers up to 4 muon candidates in several detector regions for both RPC and DT/CSC subsystems. Combining this information is the main task of the Global Muon Trigger. Final sorting to select 4 highest p_t muons in the whole detector is done at the end because the matching can suppress some ghosts which otherwise could be selected instead of real muons.

Combining RPC and DT/CSC information the spatial coordinates should be compared first to determine whether the two candidates can be attributed to the same physical muon. Let us consider two cases.

Candidate is seen by only one subsystem.
A decision should be taken whether this candidate should be considered as a real or a fake muon. It should be based on (in order of preference):

- quality bits: if they are high a real muon case is more probable
- background level at the given detector region: in a high background region a fake μ is more probable
- p_t of the candidate: it is more harmful for physics to lose high p_t muons; probability of low p_t fake muon is much higher
- current running conditions: one should trade off efficiency against fake muon rate

Candidate is seen by both subsystems.
A decision should be taken which momentum estimate should be chosen. It should be based on (in order of preference):

- quality bits: their high value indicates a more reliable estimate
- background level at the given detector region: the two subsystems have different response to background, e.g RPC are more sensitive to uncorrelated hits whereas DT/CSC can be affected by correlated background (additional tracks).
- p_t of the candidates: DT/CSC are more precise at high p_t, but they can underestimate p_t, RPC are less precise but they can only overestimate p_t.
- current status of each detector in a given region: e.g. noisy chambers can cause p_t overestimation.

In any track recognition system there is a trade-off between the track recognition efficiency and the number of accepted fake tracks. Tightening cuts one can reduce the number of fake tracks for the expense of efficiency loss. Having two different subsystems one can improve the efficiency/fakes balance. Less correlated the subsystems are, better improvement can be achieved. This is because the characteristics of fake tracks in the two subsystems are different. Details of practical application of these ideas are currently under investigation.

The last operation of the Global Muon Trigger is the isolated muon trigger algorithm. It checks whether there was a significant energy deposit in a calorimeter around a given muon. So called *quiet bits* delivered by the calorimeter trigger are used for this purpose. A quiet bit is assigned to each *calorimeter region* of $\Delta\phi \times \Delta\eta = 0.35 \times 0.35$ and it is set if the transverse energy E_t deposited in this region is below a threshold.

Finally the information is delivered to the Global Trigger which performs all foreseen cuts and selections.

3 Latency

Cumulative latency of Muon Trigger components expressed in bunch crossings is indicated in Fig. 1. The total latency is about 120 b.x., i.e. 3 μs. This number is only approximate because implementation details of various components are not yet known. The biggest uncertainty is in the CSC logic, trigger distribution system ("way back") and in the length of optical fibres connecting the detector with the control room.

4 Simulated performance

Various aspects of the CMS Muon Trigger response to different particles was investigated using PYTHIA event generator and CMS simulation package CMSIM, based on GEANT. Results are described in numerous technical notes listed in Ref. [6]. The trigger rate expected at low and high luminosity is the most important outcome of these studies. Single and double muon trigger rates are presented in Tab. 1. It was found that the design rate limit of 15 kHz can be maintained with p_t thresholds low enough to fulfil physics program presented in the CMS Technical Proposal [7].

Tab. 1. Simulated Muon Trigger rates.

trigger	luminosity	p_t cut	rate
1 μ	10^{33} s^{-1}cm^{-2}	7 GeV	9.5 kHz
2 μ	10^{33} s^{-1}cm^{-2}	2-4 GeV	0.6 kHz
1 μ	10^{34} s^{-1}cm^{-2}	20 GeV	7.8 kHz
2 μ	10^{34} s^{-1}cm^{-2}	4 GeV	2.3 kHz

References

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