13 High Level Trigger: overview and inputs

13.1 Summary of Level-1 Trigger

The L1 Trigger System is organized into three major subsystems: the L1 calorimeter trigger, the L1 muon trigger, and the L1 global trigger. The muon trigger is further organized into subsystems representing the 3 different muon detector systems, the Drift Tube Trigger in the barrel, the Cathode Strip Chamber (CSC) trigger in the endcap and the Resistive Plate Chamber (RPC) trigger covering both barrel and endcap. The L1 muon trigger also has a global muon trigger that combines the trigger information from the DT, CSC and RPC trigger systems and sends this to the L1 global trigger. A diagram of the L1 trigger system is shown in Fig. 13.1.

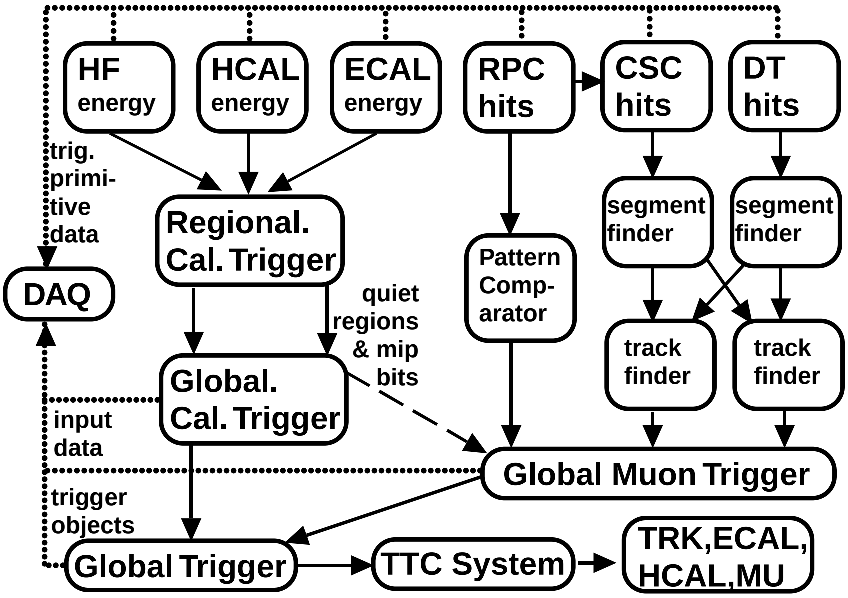

Fig. 13.1: Overview of Level 1 Trigger

The data used as input to the L1 trigger system as well as the input data to the global muon trigger, global calorimeter trigger and the global trigger are transmitted to the DAQ for storage along with the event readout data. In addition, all trigger objects found, whether they were responsible for the L1 trigger or not, are also sent. The decision whether to trigger on a specific crossing or to reject that crossing is transmitted via the Trigger Timing and Control system to all of the detector subsystem front end and readout systems.

13.1.1 Calorimeter Trigger Description

The calorimeter trigger begins with (0.35 η x 0.35 ϕ) trigger tower energy sums formed by the ECAL, HCAL and HF upper level readout Trigger Primitive Generator (TPG) circuits from the individual calorimeter cell energies. For the ECAL, these energies are accompanied by a bit indicating the transverse extent of the electromagnetic energy deposit. For the HCAL, the energies are accompanied by a bit indicating the presence of minimum ionizing energy. The TPG information is transmitted over high speed copper links to the Regional Calorimeter Trigger (RCT), which finds candidate electrons, photons, taus, and jets. The RCT separately finds both isolated and non-isolated electron/photon candidates. The RCT transmits the candidates along with sums of transverse energy to the Global Calorimeter Trigger (GCT). The GCT sorts the candidate electrons, photons, taus, and jets and forwards the top 4 of each type to the global trigger. The GCT also calculates the total transverse energy and total missing energy vector. It transmits this information to the global trigger as well. The RCT also transmits an (η,ϕ) grid of quiet regions to the global muon trigger for muon isolation cuts.

13.1.1.1 Calorimeter Trigger Algorithms

An overview of the electron/photon isolation algorithm is shown in Fig. 13.2. This algorithm involves only the eight nearest neighbours around the central hit trigger tower and is applied over the entire (η,ϕ) plane. The electron/photon candidate E_T is determined by summing the E_T in the hit tower with the maximum E_T tower of its four broad side neighbours. This summed transverse energy provides a sharper efficiency turn-on with the true E_T of the particles.

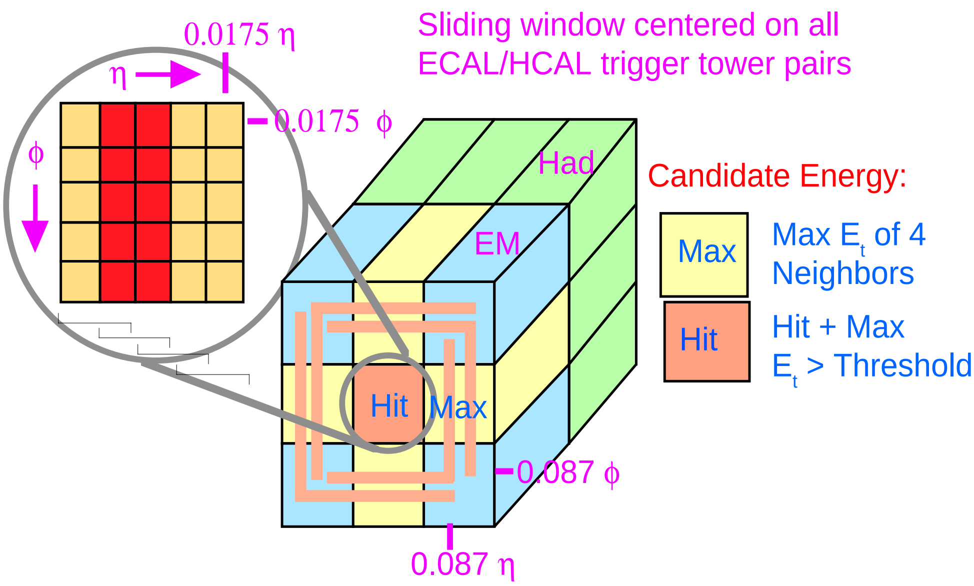

Fig. 13.2: Electron/photon trigger algorithm

The non-isolated candidate requires passing of two shower profile vetoes, the first of which is based on the fine-grain ECAL crystal energy profile. The second is based on HCAL to ECAL energy comparison, e.g. H/E less than 5% (HAC veto).

The isolated candidate requires passing of two additional vetoes, the first of which is based on the passing of FG and HAC Vetoes on all eight nearest neighbours, and the second is based on there being at least one quiet corner, i.e., one of the five-tower corners has all towers below a programmable threshold, e.g., 1.5 GeV. Each candidate is characterized by the (η,ϕ) indexes of the calorimeter region where the hit tower is located.

Single Electron/Photon Triggers

In each calorimeter region (4x4 trigger towers) the highest E_T non-isolated and isolated electron/photon candidates are separately found. The 16 candidates of both streams found in a regional trigger crate (corresponding to 16 calorimeter regions covering $\Delta\eta.\Delta\phi$=3.0x0.7) are further sorted by transverse energy. The four highest E_T candidates of both categories from each crate are transferred to the GCT where the top four candidates are retained for processing by the CMS global trigger.

The nominal electron/photon algorithm allows both non-isolated and isolated streams. The non-isolated stream uses only the hit tower information except for adding in any leakage energy from the maximum neighbour tower. This stream will be used at low luminosity to provide the B-electron trigger. The isolation and shower shape trigger cuts are programmable and can be adjusted to the running conditions. For example, at high luminosity isolation cuts could be relaxed to take into account higher pile-up energies. The electron/photon triggers specification includes also the definition of the η–ϕ region where it is applicable. In particular, it is possible to define different trigger conditions (energy thresholds, isolation cuts) in different rapidity regions.

Double, triple and quad electron/photon triggers can be defined. The requirements on the objects of a multi electron/photon trigger, namely the energy threshold, the cluster shape and isolation cuts and the (η,ϕ) region, are set individually. Requirements on the (η,ϕ) separation between objects can also be defined.

Jet and τ Triggers

The jet trigger uses the transverse energy sums (e.m.+had) computed in calorimeter regions (4x4 trigger towers), except in the HF region where it is the trigger tower itself. The input tower E_T is coded in an 8 bit linear scale with programmable resolution. Values exceeding the dynamic range are set to the maximum. The subsequent summation tree extends to a 10 bit linear scale with overflow detection. Simulation studies showed that a scale of 10 bits with LSB=1 GeV gives adequate jet trigger performance.

The jet trigger uses a 3x3 calorimeter region sliding window technique which spans the complete (η,ϕ) coverage of the CMS calorimeters (Fig. 13.3) seamlessly. The central region E_T is required to be higher than the eight neighbour region E_T values. In addition, the central region E_T can is required to be greater than a fixed value, e.g., 5 GeV, to suppress spurious soft jets.

The jets and τs are characterized by the transverse energy E_T in 3x3 calorimeter regions. The summation spans 12x12 trigger towers in barrel and endcap or 3x3 larger HF towers in the HF. The ϕ size of the jet window is the same everywhere. The η binning gets somewhat larger at high η due to the size of calorimeter and trigger tower segmentation. The jets are labelled by (η,ϕ) indexes of the central calorimeter region.

Single and three prong decays of τ leptons form narrow clusters of energy deposits in the calorimeter. Since the decays involve charged pions which deposit energies in the hadron calorimeter, the electron/photon trigger does not capture them. Therefore, the transverse profiles of active tower patterns are analysed to tag narrow jets as potential τ lepton decays. An active tower is defined as a trigger tower with ECAL or HCAL E_T above a separately programmable

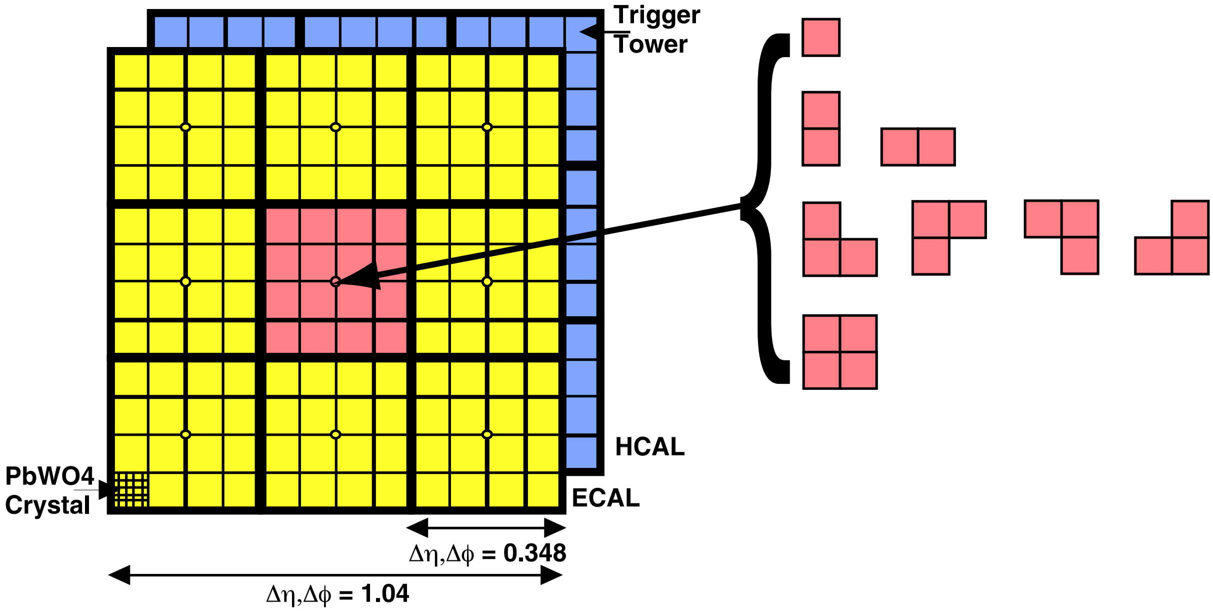

Fig. 13.3: Jet and τ trigger algorithms.

threshold. The calorimeter region has τ-veto set ON if the active towers do not form any of the 8 patterns shown in the Figure 13.3, i. e., the pattern is not confined within 2x2 contiguous trigger towers of the calorimeter region. A jet is defined as 'τ-like' if none of the 9 calorimeter region τ-veto bits are ON. The τ-veto bits are therefore used for both τ-like energy deposit identification and quite stringent isolation. This strict isolation requirement is tolerable because such cuts are necessary to find τs even in later offline analysis.

In addition counters of the number of jets above programmable thresholds in various η regions are provided to give the possibility of triggering on events with a large number of low energy jets. Jets in the forward and backward HF calorimeters are sorted and counted separately. This separation is a safety measure to prevent more background susceptible high η region from masking central jets. Although the central and forward jets are sorted and tracked separately through the trigger system, the global trigger can use them seamlessly as the same algorithm and resolutions are used for the entire η–φ plane.

Single, double, triple and quad jet (τ) triggers are possible. The single jet (τ) trigger is defined by the transverse energy threshold, the (η,φ) region of validity and eventually by a prescaling factor. Prescaling will be used for low energy jet (τ) triggers, necessary for efficiency measurements. The multi jet (τ) triggers are defined by the number of jets (τs) and their transverse energy thresholds, by a minimum separation in (η,φ), as well as by a prescaling factor. The global trigger accepts the definition, in parallel, of different multi jet (τ) triggers conditions.

The four highest energy central and forward jets, and central τs in the calorimeter are selected. Jets and τs occurring in a calorimeter region where an electron is identified are not considered. The selection of the four highest energy central and forward jets and of the four highest energy τs provides enough flexibility for the definition of combined triggers.

Energy Triggers

The E_T triggers use the transverse energy sums (e.m.+had) computed in calorimeter regions (4x4 trigger towers in barrel and endcap). E_x and E_y are computed from E_T using the coordinates of the calorimeter region center. The computation of missing transverse energy from the energy in calorimeter regions does not affect significantly the resolution for trigger purposes.

The missing E_T is computed from the sums of the calorimeter regions E_x and E_y. The sum extends up to the end of forward hadronic calorimeter, i.e., $|\eta|=5$. The missing E_T triggers are defined by a threshold value and by a prescaling factor. The global trigger accepts the definition, in parallel, of different missing E_T triggers conditions.

The total E_T is given by the sum of the calorimeter regions E_T. The sum extends up to the end of forward calorimeter, i.e., $|\eta|=5$. The total E_T triggers are defined by a threshold value and by a prescaling factor. The global trigger accepts the definition, in parallel, of different total E_T triggers conditions. The total energy trigger is implemented with a number of thresholds which are used both for trigger studies and for input to the luminosity monitor. Some of these thresholds are used in combination with other triggers. Other thresholds are used with a prescale and one threshold is used for a stand-alone trigger. The lower threshold E_T trigger also provides a good diagnostic for the calorimeter and its trigger.

The H_T trigger is defined as the scalar sum of the E_T of jets above a programmable threshold with a typical value of jet E_T > 10 GeV/c^2. This trigger is not as susceptible as the total E_T given by the sum of the calorimeter regions E_T deposits to both noise and pileup effects. The Although total E_T is a necessary technical trigger, it has limited use from physics point of view. The H_T trigger can capture high jet multiplicity events such as those from fully hadronic top decay, hadronic decays of squarks and gluinos. Although these events have several hundred GeV/c^2 energy, they may actually fail the jet triggers because individual jet E_Ts may be quite a bit softer than the sustainable thresholds. In addition, the H_T trigger can use individually calibrated jet energies unlike the total E_T trigger which cannot be easily calibrated.

13.1.2 Muon Trigger Description

Each of the L1 muon trigger systems has its own trigger logic. The RPC strips are connected to a Pattern Comparator Trigger (PACT), which is projective in η and ϕ. The PACT forms trigger segments which are connected to segment processors which find the tracks and calculate the p_T. The RPC logic also provides some hit data to the CSC trigger system to improve resolution of ambiguities caused by 2 muons in the same CSC.

The Cathode Strip Chambers form Local Charged Tracks (LCT) from the Cathode Strips, which are combined with the Anode wire information for bunch crossing identification on a Trigger Motherboard The LCT pattern logic assigns a p_T and quality, which is used to sort the LCT on the Motherboard and the Muon Port Card that collects LCTs from up to 9 CSC chambers. The top 3 LCTs from all the MPCs in a sector are transmitted to the CSC Track Finder, which combines the LCTs into full muon tracks and assigns p_T values to them. The CSC and Drift Tube Track-Finders exchange track segment information in the region where the chambers overlap.

The Barrel Muon Drift Tubes are equipped with Bunch and Track Identifier (BTI) electronics that finds track segments from coincidences of aligned hits in 4 layers of one drift tube superlayer. The track segments positions and angles are sent to the Track Correlator (TRACO), which attempts to combine the segments from the two Super Layers (SL) measuring the ϕ coordinate. The best combinations from all TRACOs of a single chamber together with the SL η segments are collected by the Trigger Server. The Trigger Server then sends the best two segments (if found) to the Track Finder, which combines the segments from different stations into full muon tracks and assigns p_T values to them.

The Global Muon Trigger sorts the RPC, DT and CSC muon tracks, converts these tracks into the same η, ϕ and p_T scale, and validates the muon sign. It then attempts to correlate the CSC and DT tracks with RPC tracks. It also correlates the found muon tracks with an η-ϕ grid of quiet calorimeter towers to determine if these muons are isolated. The final ensemble of muons are sorted based on their initial quality, correlation and p_T and then the 4 top muons are sent to the Global Trigger.

13.1.2.1 Muon Trigger Algorithms

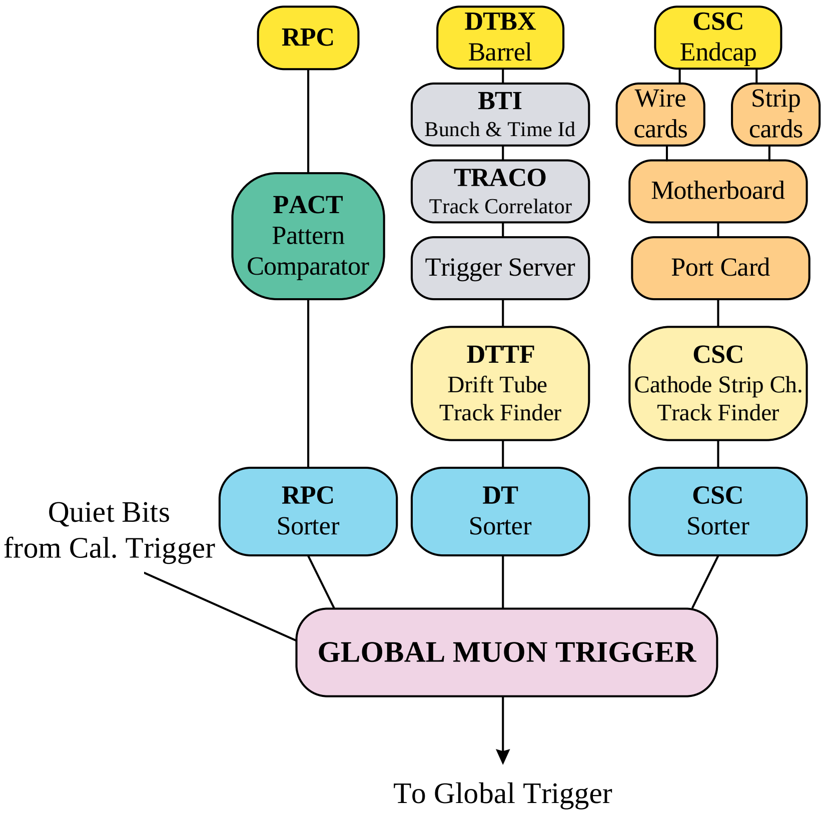

Fig. 13.2: Muon Trigger block diagram.

The logical structure of the Muon Trigger is shown in Fig. 13.2. DT and CSC electronics first process the information from each chamber locally. Therefore they are called *local triggers*. As a result one vector (position and angle) per muon per station is delivered. Vectors from different stations are collected by the Track Finder (TF) which combines them to form a muon track and assigns a transverse momentum value. TF plays the role of a *regional trigger*. Up to 4 best (highest p_T and quality) muon candidates from each system are selected and sent to the Global 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 the barrel and 4 from the endcaps and sends them to the Global Muon Trigger. The Global Muon Trigger compares the information from TF (DT/CSC) and PACT (RPC). 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.

Drift Tube Trigger

The drift chambers deliver data for track reconstruction and triggering on different data paths. The local trigger is based on two SL in the ϕ view of the muon station. The trigger front-end, called the Bunch and Track Identifier (BTI), is used in the ϕ view and the θ view to perform a rough muon track fit in one station measuring position and direction of trigger candidate tracks with at least three hits, in different planes of a Super Layer (SL). The algorithm fits a straight line within programmable angular acceptance. The BTI performs the bunch crossing assignment of every found muon track candidate. The algorithm used in the device is a generalization of the mean-timer method [13.2].

Since this method must foresee alignment tolerances and needs to accept alignments of only three hits, the algorithm can generate false triggers. Hence in the bending plane a system composed by a Track Correlator (TRACO) and a chamber Trigger Server (TS) is used to filter the information of the two ϕ SLs of a chamber in order to lower the trigger noise. The TRACO/TS block selects, at every cycle among the trigger candidates, at most two tracks with the smallest angular distances (i.e. higher p_T) with respect to the radial direction to the vertex.

Track segments found in each station are then transmitted to a regional trigger system called Drift Tube Track Finder (DTTF). The task of the Track Finder is to connect track segments delivered by the stations into a full track and assign a transverse momentum value to the finally resolved muon track. The system is divided in sectors, each of them covering 30° in the ϕ angle. Each Sector Processor is logically divided in three functional units - the Extrapolator Unit (EU), the Track Assembler (TA) and the Assignment Units (AU), as shown in Fig. 13.3.

The Extrapolator Unit attempts to match track segments pairs of distinct stations. Using the spatial coordinate ϕ and the bending angle of the source segment, an extrapolated hit coordinate is calculated. The two best extrapolations per each source are forwarded to the Track Assembler. The Track Assembler attempts to find at most two tracks in a detector sector with the highest rank, i.e. exhibiting the highest number of matching track segments and the highest extrapolation quality.Once the track segment data are available to the Assignment Unit, memory based look up tables are used to determine the transverse momentum, the ϕ and η coordinates, and a track quality.

CSC Trigger

The task of the Cathode Strip Chamber (CSC) Track-Finder is to reconstruct tracks in the CSC endcap muon system and to measure the transverse momentum (p_T), pseudo-rapidity (η), and azimuthal angle (ϕ) of each muon.The measurement of p_T by the CSC trigger uses spatial information from up to three stations to achieve a precision similar to that of the DT Track-Finder despite the reduced magnetic bending in the endcap. The CSC Local Trigger provides high rejection power against these backgrounds by finding muon segments, also referred to as Local

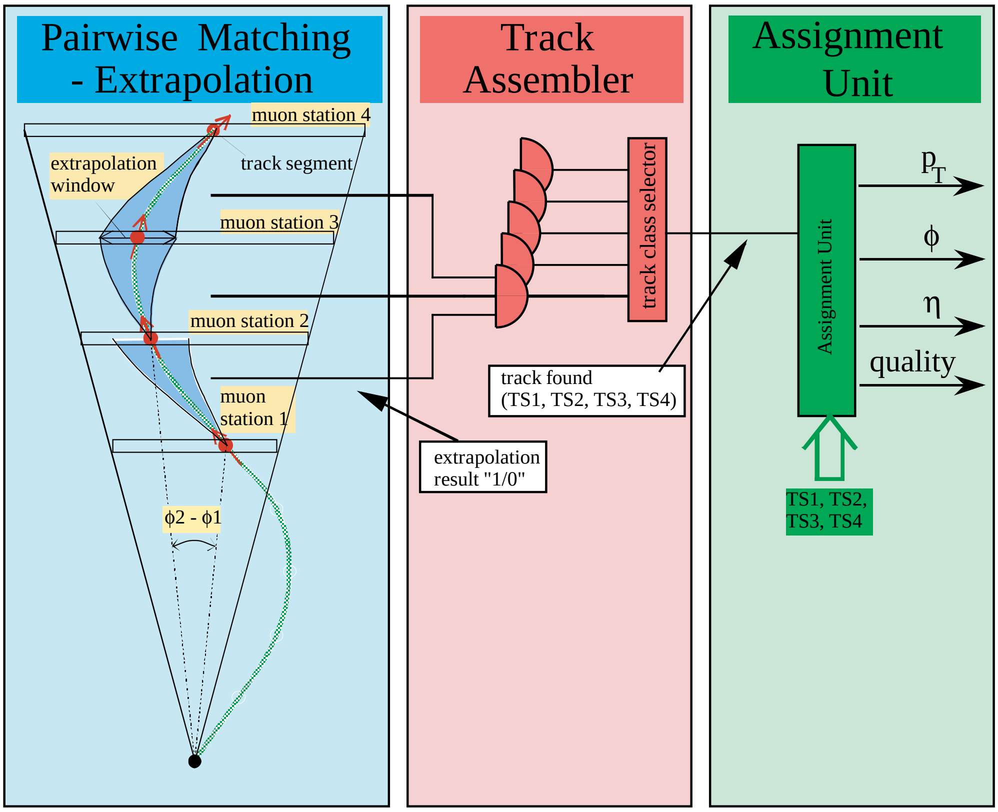

Fig. 13.3: Principle of the Drift Tube track finder algorithm (3-step scheme). On the left side, the pairwise matching algorithm is described. An extrapolated hit coordinate is calculated using the ϕ_1 coordinate and the bending angle of the source segment. The match is considered successful if a target segment is found at the extrapolated coordinate, inside a certain extrapolation window.

Charged Tracks (LCTs), in the 6-layer endcap muon CSC chambers. Muon segments are first found separately by anode and cathode electronics (see Fig. 13.4) and then time correlated, providing precision measurement of the bend coordinate position and angle, approximate measurement of the non-bend angle coordinate, and identification of the correct muon bunch crossing with high probability.

The primary purpose of the CSC anode trigger electronics is to determine the exact muon bunch crossing with high efficiency. Since the drift time can be longer than 50 ns, a multi-layer coincidence technique in the anode "Local Charged Track" (LCT) pattern circuitry is used to identify a muon pattern and find the bunch crossing.

The primary purpose of the CSC cathode trigger electronics is to measure the ϕ coordinate precisely to allow a good muon momentum measurement up to high momentum. The charge collected on an anode wire produces an opposite-sign signal on several strips, and precision track measurement is obtained by charge digitization and precise interpolation of the cathode strip charges. The six layers are then brought into coincidence in LCT pattern circuitry to establish position of the muon to an RMS accuracy of 0.15 strip widths. Strip widths range from 6-16 mm.

Cathode and anode segments are brought into coincidence and sent to CSC Track Finder electronics which links the segments from the endcap muon stations. Each Track Finder unit

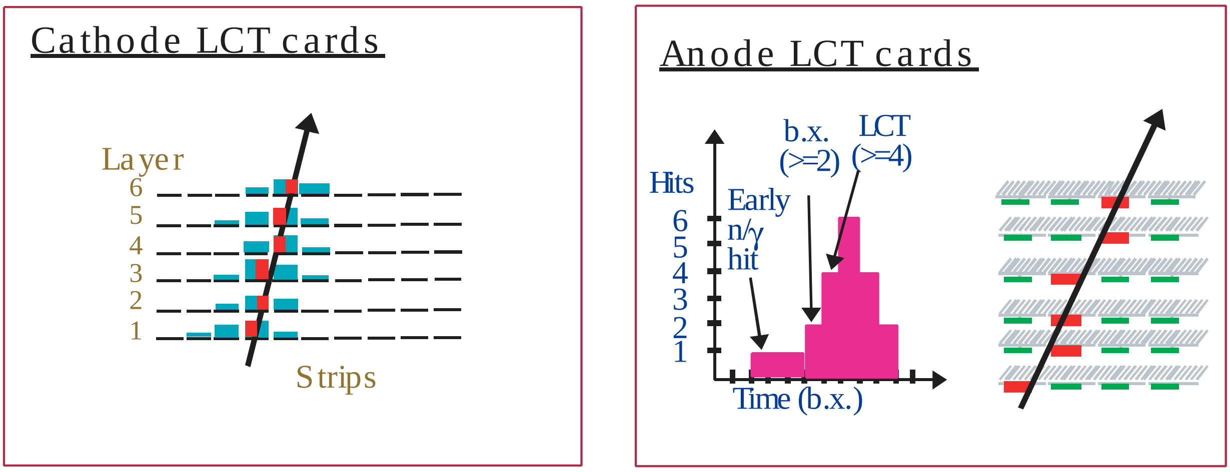

Fig. 13.4: Principle of the CSC Local Trigger.

finds muon tracks in a 60^o sector. A single extrapolation unit forms the core of the Track-Finder trigger logic. It takes the three dimensional spatial information from two track segments in different stations, and tests if those two segments are compatible with a muon originating from the nominal collision vertex with a curvature consistent with the magnetic bending in that region. Each CSC Track Finder can find up to three muon candidates. A CSC muon sorter module selects the four best CSC muon candidates and sends them to the Global Muon Trigger.

RPC Trigger

The RPC pattern Trigger Logic (PACT) is based on the spatial and time coincidence of hits in four RPC muon stations (see Fig. 13.5). Because of energy loss fluctuations and multiple

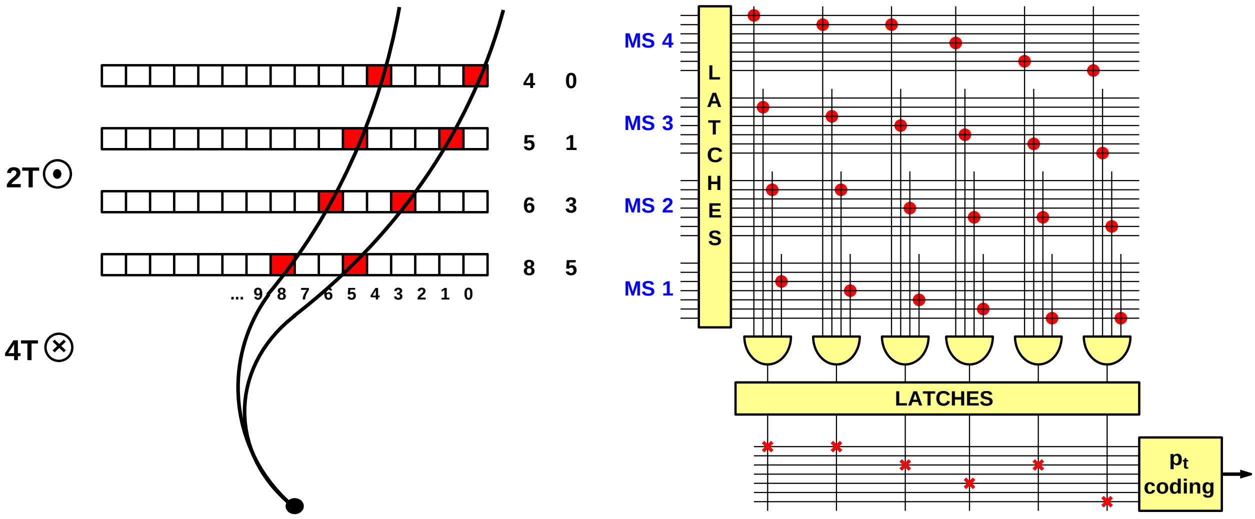

Fig. 13.5: RPC Trigger principle.

scattering there are many possible hit patterns in the RPC muon stations for a muon track of defined transverse momentum emitted in a certain direction. Therefore, the PACT should recognize many spatial patterns of hits for a given transverse momentum muon. In order to trigger on a particular hit pattern in the RPCs left by a muon, the PACT electronics performs two functions: requires time coincidence of hits in patterns ranging from 3-out-of-4 muon stations to 4 out of 6 muon stations along a certain road and assigns a p_T value. The coincidence gives the bunch crossing assignment for a candidate track. The candidate track is formed by a pattern of hits that matches with one of many possible patterns pre-defined for muons with defined transverse momenta. The p_T value is thus given. The pre-defined patterns of hits have to be mutually exclusive i.e. a pattern should have a unique transverse momentum assignment. The patterns are divided into classes with a transverse momentum value assigned to each of them. PACT is a threshold trigger; it gives a momentum code if an actual hit pattern is straighter than any of pre-defined patterns with a lower momentum code. The patterns will depend on the direction of a muon i.e. on ϕ and η.

Global Muon Trigger

The Regional Muon Trigger reconstructs muon candidates in both the barrel and the endcap regions out of hits or track segments found at the muon stations. For RPCs this is the Pattern Comparator Trigger (PACT) covering the entire η-region. The DTs and CSCs have separate track finders. The GMT receives the best four barrel DT and the best four endcap CSC muons and combines them with 4+4 muons sent by the RPC PACT. It performs a matching based on the proximity of the candidates in (η,ϕ) space. If two muons are matched their parameters are combined to give optimum precision. If a muon candidate cannot be confirmed by the complementary system quality criteria can be applied to decide whether to forward it. The muon candidates are ranked based on their transverse momentum, quality and to some extent pseudorapidity and the best four muon candidates in the entire CMS detector are sent to the Global Trigger.

The Global Muon Trigger also receives information from the calorimeters. The Regional Calorimeter Trigger sends two bits based on energy measurements representing isolation and compatibility with a minimum ionizing particle in $\Delta\eta \times \Delta\phi = 0.35 \times 0.35$ trigger regions. The GMT extrapolates the muon tracks back to the calorimeter trigger towers and appends the corresponding ISO (isolation) and MIP (minimum ionizing particle) bits to the track data consisting of p_T, sign of the charge, η, ϕ and quality.

13.1.3 Global Trigger

The Global Trigger accepts muon and calorimeter trigger information, synchronizes matching sub-system data arriving at different times and communicates the Level-1 decision to the timing, trigger and control system for distribution to the sub-systems to initiate the readout. The global trigger decision is made using logical combinations of the trigger data from the Calorimeter and Muon Global Triggers.

The CMS L1 system sorts ranked trigger objects, rather than histogramming objects over a fixed threshold. This allows all trigger criteria to be applied and varied at the Global Trigger level rather than earlier in the trigger processing. All trigger objects are accompanied by their coordinates in (η,ϕ) space. This allows the Global Trigger to vary thresholds based on the location of the trigger objects. It also allows the Global Trigger to require trigger objects to be close or opposite from each other. In addition, the presence of the trigger object coordinate data in the trigger data, which is read out first by the DAQ after a L1A, permits a quick determination of the regions of interest where the more detailed HLT analyses should focus. Besides handling physics triggers, the Global Trigger provides for test and calibration runs, not necessarily in phase with the machine, and for prescaled triggers, as this is an essential requirement for checking trigger efficiencies and recording samples of large cross section data.

The Global L1 Trigger transmits a decision to either accept (L1A) or reject each bunch crossing. This decision is transmitted through the Trigger Throttle System (TTS) to the Timing Trigger and Control system (TTC). The TTS allows the reduction by prescaling or shutting off of L1A signals in case the detector readout or DAQ buffers are at risk of overflow.

Reference

[13.1] 1999 Status Report on the RD-12 Project, CERN/LHCC 2000-002, 3 January 2000.

[13.2] F. Gasparini et al, Nucl. Instr. and Meth **A 336** (1993) 91.