A First-Level Track Trigger Architecture for Super-CMS

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Abstract

We present an architectural concept for a first-level hardware track trigger for CMS at SLHC. The design of such a system is challenging. A primary constraint on implementation will be power consumption within the detector, in turn driven by the transmission bandwidth to off-detector electronics. We therefore emphasise the minimisation of the data flow through local filtering of track stubs on the detector. The architecture does not comprise a stand-alone track trigger, but uses muon and calorimeter trigger objects to seed track-matching within an integrated first-level system.

I. SUPERLHC AND SUPERCMS

A. *SuperLHC*

SuperLHC (SLHC) refers to a proposed luminosity upgrade of the LHC machine, envisaged for around 2015 [1]. SLHC would improve upon LHC design luminosity by a factor of ten, delivering a total of around 3000pb^{-1} to CMS. The definition of an SLHC physics programme awaits results from the LHC. Nevertheless, it is clear that in many scenarios, there will remain significant areas of study that will be made accessible by the greatly improved statistics offered by an upgraded machine. Generically, these include:

- High-statistics precision measurement of standard model or BSM parameters (e.g. Higgs couplings, tan β)
- Extension of discovery reach (e.g. Z', extra dimensions)
- The search for extremely rare processes (e.g. multi-gauge boson production, H-pair)

The basic technical parameters of the upgraded machine are still under debate; in particular, several different options for an altered bunch-crossing frequency have been discussed. In this study, we assume a machine with similar characteristics to the baseline LHC from the detector point of view, but with the reduced bunch-crossing rate of 20MHz. This implies a corresponding factor of 20 increase in bunch luminosity; around 350 inelastic events per crossing are expected in such a scenario, generating around 20000 charged tracks within the CMS acceptance of ten units of rapidity.

B. *SuperCMS*

1) Detector Challenges

The increased integrated and instantaneous luminosity available at SLHC presents challenges for CMS subdetectors designed for LHC [2], and which will have already sustained seven or more years of operation by that time.

Around ~400 inelastic collision events are expected in each SLHC bunch-crossing. The *pileup* of secondary particles from unrelated events will degrade the performance of all subdetectors. The calorimeter energy resolution for electromagnetic and hadronic objects will be affected by an increased level of background deposits. Tracking detectors will have greatly increased higher occupancy, complicating pattern-recognition.

Radiation dose and dose rate will increase, affecting the reliability and performance of both detector elements and electronic systems.

The change in *bunch-crossing frequency* will necessitate changes to, or re-optimisation of, detector readout systems and offline algorithms used to interpret the recorded signals. We note that the 20MHz SLHC scenario is much less demanding than a frequency increase compared to LHC.

Trigger rates and readout volumes will increase with luminosity, possibly worse than linearly due to poorer performance of event selection algorithms.

2) CMS Upgrade

Initial studies of the upgrade of the existing CMS subdetectors for 'SuperCMS' have been carried out [3]. The work required varies considerably across the subdetectors.

Major changes to the barrel calorimeters are not proposed, since the technologies chosen were designed for for much larger radiation doses encountered in the endcaps. The detector granularity and readout electronics appear to be sufficient for 20MHz SLHC use. Endcap calorimetry upgrades require further study. Likewise, the muon detectors are expected to withstand the radiation dose, and be capable of operation at SLHC, except perhaps at the highest eta range; however, the on- and off-detector electronics are likely to require an upgrade.

On the other hand, the inner tracking detectors will not be adequate for SLHC operation, in terms of the granularity required at much greater track densities, and of resistance to radiation damage. A complete replacement of the silicon tracker and pixel detector is therefore envisaged. The trigger and DAQ systems will require upgrade and re-optimisation to deal with the increased luminosity and detector occupancy, and to take advantage of the expected improvements in electronics performance by 2015.

II. LEVEL-1 TRIGGERING

A. *CMS Level-1 Trigger*

Both the LHC and SLHC programmes will be characterised by the search for rare phenomena involving high-mass objects, set against an overwhelming background of QCD scattering. The purpose of the CMS trigger system is to efficiently select bunch-crossings containing events of interest, whilst strongly limiting the recorded rate of soft QCD events. The main approach is therefore the identification of leptons, photons and jets with large tranverse momentum (p_t).

The CMS Level-1 trigger [4] is a hardware system which accepts a fraction of detector data for each bunch-crossing, and flags events of interest at a rate no larger than ~100kHz. Heavily-reduced information from the calorimeter and muon systems is separately analysed using a series of algorithms implemented in pipelined digital logic, in order to identify candidate muon, electron / photon, jet and hadronic-tau objects. A fixed number of objects, along with coarse-grained estimate of position and p_t, are transferred to a global trigger system that forms a trigger decision based upon the number of objects passing a set of p_t thresholds. A schematic diagram of the Level-1 trigger is shown in Figure 1.

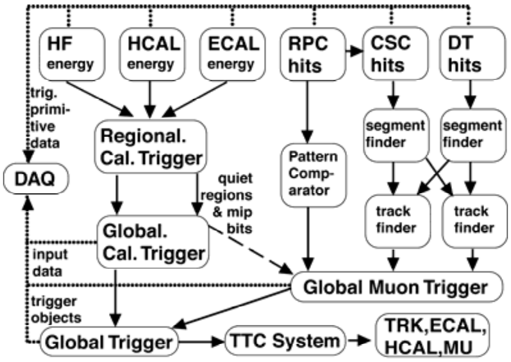

Figure 1: CMS Baseline Level-1 Trigger [4]

No information from the inner tracking is used in the Level-1 trigger. Tracking information is introduced progressively into the trigger decision made by the software Higher-Level Trigger (HLT), beginning with the use of space hit information from the pixel detector at 'Level-2', and followed by use of full tracker information in the final decision [5].

The current Level-1 trigger strategy can be naively extended to the SLHC. The trigger rate may be controlled by raising of thresholds, since the jet cross-section, and hence the rate of fake trigger objects, falls rapidly with p_t. However, this approach will also impact upon physics acceptance due to the 'natural scale' set by W / Z / t mass in many channels.

The performance of the trigger algorithms will also be degraded at SLHC by increased hadronic background in the calorimeters, and noise / punch-through in the muon system. In addition, multiple scattering and other effects in the muon system provide a large rate of fake high-p_t candidates, which cannot be suppressed by a simple p_t cut (see Figure 2).

Increased use of exclusive triggers, using correlations between trigger objects at Level-1, will be of benefit in preserving efficiency for all channels of interest whilst allowing increased inclusive object p_t thresholds; however, this approach will require more detailed information on object kinematics than the current hardware provides.

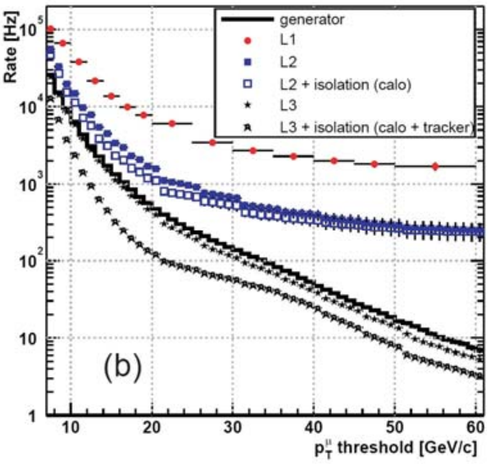

Figure 2: Single muon trigger rate at L1, L2, L3 [5]

Given the substantially increased event size at SLHC (largely due to a very high granularity inner tracker), it would be imprudent to assume that a substantial increase in Level-1 accept rate could be tolerated. A natural, though demanding, target for the Level-1 upgrade is therefore to preserve a maximum ~100kHz accept rate whilst preserving current levels of efficiency for the key LHC physics channels.

B. *Track Triggering*

At 'Level-2', the HLT system achieves further rate reduction beyond that at Level-1 in two principal ways: firstly, by making use of finer-granularity and higher-precision information from the calorimeter and muon systems; and secondly, by incorporation of information from the inner tracker into the trigger decision. It can be assumed that any Level-1 calo / muon trigger upgrade will take advantage of developments in electronics to provide trigger objects with the full resolution allowed by the available detector information. Whilst this allows performance improvement, it is still the case that only aggregated information from the calorimeter and muon systems will be available unless a completely replacement of on-detector electronics is carried out.

It is therefore relevant to consider how the upgraded Level-1 trigger might make use of inner tracking information. The natural starting point for such studies is the current HLT algorithms. However, we note that the constraints imposed by the tracker readout architecture may be quite different in the upgraded detector; that the tracking information may need to be used differently if constraints on information sharing across detector regions are to be respected; and that the challenges of rate reduction at SLHC, under much worse background conditions, may be quite different to those at LHC.

A key feature of the proposed architecture is that, similarly to the current 'Level-2' HLT, we make use of tracker information only to augment the information provided by the calorimeter and muon systems. The design of a complete stand-alone track trigger system, as implemented in previous hadron collider detectors [6, 7] is not considered here.

III. TRACK TRIGGER ARCHITECTURE

A. *Requirements*

There are many ways in which tracking information could be used at Level-1. However, there are also many constraints from the practical implementation of such a system. In this study, we have attempted to identify the *minimal* implementation that could meet the upgrade requirements; it is possible that more ambitious schemes could offer more robustness and better performance, if they can be shown to be technically viable.

We propose to make use of tracking information in several ways. In each case, the 'track candidates' are identified by matched pairs of directed track stubs, measured in the outer tracker (~1.2m from the interaction point, at the outermost radius of the tracker) and the intermediate region (around 0.6m) respectively. The uses of these candidates include:

- Confirmation of *isolated muon* candidates, and improvement of p_t measurement, by association with a track. This is similar to the algorithm employed in the HLT.
- Confirmation of *isolated electron* candidates by association with a track. This approach differs from that of the HLT, which uses pixel tracks. The use of pixel tracks, however, requires bremsstrahlung clusters to be included in the electron position estimate, which is not possible in the Level-1 trigger.
- Identification of *isolated tau* candidates by tagging hadronic calorimeter clusters with 1- or 3-track signatures.
- Track-based identification of *high-pt jets*, used both for inclusive jet triggers and as a veto for isolated lepton / photon candidates.
- Estimation of *primary vertex z-position* for lepton tracks, allowing the requirement of a vertex match in multi-candidate triggers.

This approach extends previous concepts that focus exclusively on the pixel detector [8]. The addition of information from the outermost tracking layer has several important advantages:

- The track density in the outer tracker is much lower than in the pixel detector, due to the geometric factors and the capture of low-pt background tracks in the CMS 4T field.
- The outermost tracker layer lies around approximately halfway between the interaction point and the innermost muon station, optimising the additional information available to refine muon candidate measurements (along with the beam position constraint).
- The adjacency of the outer tracker to the calorimeter greatly simplifies the correlation of calorimeter trigger candidates and tracks.

B. *Technical Constraints*

The implementation of even a minimal tracking trigger will be challenging. The CMS tracker, and any proposed upgrade, will be a highly integrated electromechanical system, in which any trigger functionality must form a seamless part. Some of the key technical constraints are given here.

- The addition of trigger functionality must not add significantly to the material or power budget of the inner tracker; in both cases, these parameters are already close the acceptable limit in the current CMS detector. This implies that no trigger detectors are possible which do not also add points for track reconstruction.
- The bandwidth required to convey trigger information to the off-detector systems must be reasonable. Very large bandwidth implies both an increased fibre count and increased on-detector power consumption, neither of which could be easily accommodated by the CMS services.
- The trigger algorithms must execute within a few μs latency, since this is dictated by the readout requirements of other subdetectors. Notably, this precludes any approach based upon 'selective readout' of the tracker, since the round-trip delay in conveying a trigger decision to the tracker would consume most of the available latency.
- The processing density, and in particular the communications density, of the off-detector trigger electronics must be kept within reasonable bounds, taking into account the likely capabilities of 2015 electronics. Reduction of data sharing between different parts of the trigger processor is a key lesson from the implementation of the current Level-1 trigger.
- The system must be robust with respect to detector alignment, inefficiency and noise.

The minimisation of on-detector power consumption and services is a key consideration. Along with the data concentration issues in the off-detector system, this dictates an architecture that minimises the bandwidth for transmission of trigger primitives. This in turn places the emphasis on heavy on-detector data reduction. Since very high-speed communication between outer and intermediate tracker layers is ruled out on technically grounds, the solution depends upon the readout of tracking information from two or more independent layers, which is then correlated off detector.

IV. TRACK TRIGGER IMPLEMENTATION

A. *Data Reduction*

A promising concept for a stand-alone track stub measurement using a pair of closely-spaced inner pixel detector planes has previously been studied [8]. The principle is illustrated in Figure 3. Hits on the two layers are correlated within a fixed window to form track stubs; for a detector ('trigger station') at roughly normal orientation to the radial direction, this allows the rejection of low p_t tracks intersecting the detector at a significant angle. The information available from such a detector is, in principle, the position and dual slopes of each identified stub.

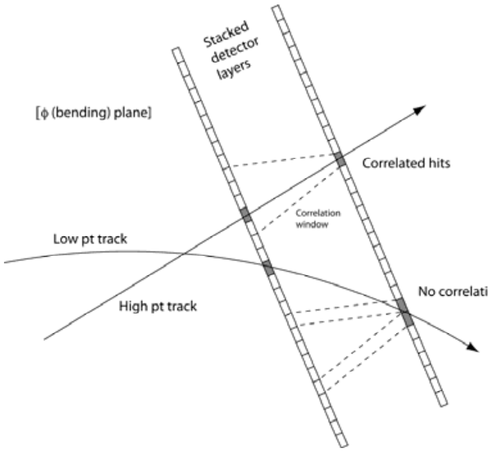

Figure 3: Principle of stacked-layer stub measurement

We propose to extend this concept to the outer tracker; it is likely that the use of true pixels is not feasible for the large-area detectors required in this region, and alternatives based upon macropixels, short strips or stereo strips require study. We do not consider details of the sensor technology further here. However, we note that the use of the stacked-layer concept in outer region substantially alleviates one of the potential technical issues with such a concept, by relaxing the constraint on spacing between the two planes. As previously noted, we assume the use of trigger stations in the barrel at r=1.2m and r=0.6m. The individual sensors within each trigger station are sized to correspond with the existing CMS trigger geometry of 0.0875 x 0.0875 in η-ϕ [4].

A key design parameter is the required p_t cutoff for track stubs, which in turns informs the required sensor resolution and spacing, and the trigger primitives bandwidth. A cut of around 4GeV/c suppresses the soft minimum bias background by a very large factor while maintaining good efficiency for tracks within high-p_t jets, and is substantially below any conceivable Level-1 lepton threshold. A cut at this level also simplifies the data-sharing requirements later in the system.

On-detector data reduction takes place in two steps. In the first stage, digital logic associated with each sensor (presumably as part of a readout ASIC) performs hit correlation, filters the resulting stubs as necessary in order to remove duplicate candidates resulting from multiple closely-spaced hits, and produces a fixed number of track stub candidates. The average number of charged tracks expected per trigger tower due to minimum bias background is predicted from simulation to be less than two at r=0.6m (using the standard CMS minimum bias simulation parameters [5]). An output of four candidates per trigger tower is therefore adequate to guarantee good efficiency for lepton tracks in the presence of background, and also covers the case of very narrow τ 3-track decays. In the case of jet activity, the number of high-p_t track stubs could be greater than four in a single tower. However, the trigger architecture does not demand detailed information on jet tracks, and so a simple flag of high stub count suffices to facilitate a jet veto if required.

Candidate information is then transferred via short-haul data links to a second digital logic stage, which performs zero-suppression on the overall candidate list from a portion of the detector, and transfers this data on longer-haul high bandwidth optical links to the off-detector electronics. Under quiescent conditions of minbias background, the occupancy of the trigger towers is likely to be very low and relatively uniform, and a large data reduction factor is therefore expected.

A simple four-vector level study of occupancies due to minbias background indicates that an average readout bandwidth of less than 1Tb/s is required to read out track stubs with sufficient precision (16b per stub, covering both position and slope information) to support later track correlation. This corresponds to 100 10Gb/s fibre links. However, the trigger primitives readout must be designed to support worst-case occupancy, and this requires further study.

B. Track Correlation

The function of the off-detector electronics is to correlate the stubs from the two trigger stations, and to further correlate the resulting track candidates with calorimeter and muon objects. It is likely that the current CMS Level-1 scheme of regional trigger processing [4], will remain in place for the SLHC upgrade. In order to allow regional correlation of candidates, we assume an architecture in which a single regional trigger processor handles information from muon, calorimeter and tracking systems. A sketch of the overall processing layout is given in Figure 4.

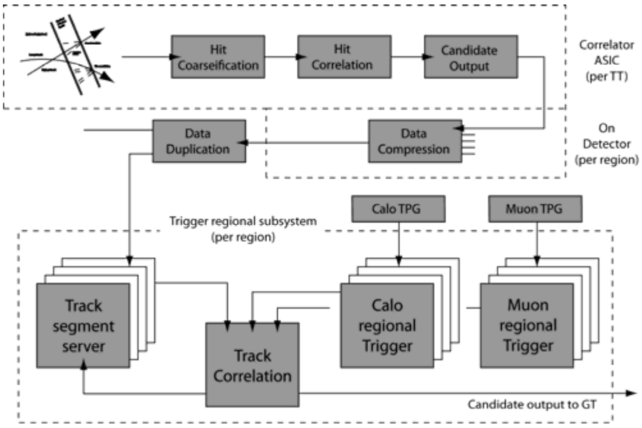

Figure 4: Processing layout of the SLHC Level-1 regional trigger

An exhaustive correlation of stubs from both trigger stations would be extremely logic-intensive. We therefore propose a simpler *seeded correlation* approach. The track correlation process begins once the muon and calorimeter candidates have been identified (it is reasonable to expect that the pipelined logic for these systems takes only a small fraction of the available processing latency in 2015-era technology). A simple geometric match is made between calorimeter or muon candidates, if any, in a given trigger tower, and the track stubs in directly-corresponding outer station sensor. If a preliminary match is found, then the slope of the stubs is projected inwards towards the interaction region to identify regions of interest in the inner station. A match in slope may then be searched for in the stub lists in the corresponding inner sensors. This algorithm is straightforward to implement in pipelined logic; we envisage the use of a 'track segment server' module, separate from the correlation unit, which stores the inner stub lists in FIFO memory, supplies them on demand to the correlator, and also acts as the DAQ readout unit for the track trigger.

Since, at 4GeV/c p_t, a track is stiff enough so that the sagitta encompasses only one trigger tower's breadth in ϕ at r=0.6m, the region of interest to be searched is rather small, and is dictated by the resolution on the track stub slope in the η direction in the outer station. This effect also strongly limits the amount of data required to be duplicated at input to the correlator system to cover geometric overlap of adjacent detector regions.

One a match with a track has been made, additional information may be added to the existing trigger candidates: enhanced p_t or quality flag for muons; charge assignment for electrons; and z-vertex position estimate in both cases. Further logic will be required to identify high-p_t jets, which are likely to span an area greater than one trigger region; to correlate them with calorimeter jet candidates; and to potentially classify them as τ candidates. The full list of candidates is then forwarded to the global trigger, as in the current system.

A four-vector level study of the required sensor resolutions in outer and inner trigger stations indicates that relatively modest performance is required. The resolution in ϕ is dictated by the requirements of stub matching between stations, with a resolution of 500μm providing adequate performance, assuming a layer separation of 10mm. In the z-direction (corresponding to the η-angle) the resolution is dictated by the requirements of vertex z-resolution; given the average vertex separation between two uncorrelated events of ~70mm, a sensor resolution of 2mm is adequate. These numbers are purely indicative, and have not been optimised; however, they demonstrate that the ϕ resolution is well within the capabilities of strip sensors, whereas the z-resolution is better than short strips can provide; work is therefore needed to identify a sensor that could meet these requirements without recourse to very high granularity detectors. We note that the presence in the outer tracking detector at two radii of sensors capable of giving a space point probably obviates the need for separate stereo strip layers for track reconstruction.

The implementation of all components of the regional trigger system using a single generic processing module is an attractive concept. Concepts for such a module, based upon FPGA and fast optical link technology, have been proposed [9, 10], and the requirements described here appear to lie well within the technical capabilities of such modules.

C. *Topics for Further Study*

The conceptual architecture presented has many promising features. However, much further study is required in order to demonstrate the robustness of such an architecture in the face of realistic detector performance, and to optimise its parameters. In particular, the following areas require attention:

- The ideas presented relate only to the barrel section of the detector. While there is no reason why the endcaps cannot employ the same basic principles, the data sharing between trigger regions, particularly in the barrel/endcap overlap region, may be more complex.
- The alignment of planes within stacked sensors can be assumed to be mechanically robust, but the sensitivity of the trigger to alignment between stations must be ascertained.
- Sensor inefficiency and geometric acceptance will reduce the efficiency of a track trigger; the architecture as presented involves no tracking redundancy. It is possible that a third trigger station may be required in order to add robustness, and there is no reason why the architecture cannot accommodate this if required.

In order to address these questions, a realistic simulation of an upgraded detector and trigger system is under way.

V. CONCLUSIONS

We have presented an architectural concept which allows tracking information to be incorporated into the Level-1 trigger decision of an upgraded CMS detector for SLHC. There are several motivations for the use of tracking information in support of the calorimeter and muon trigger systems, many of which draw upon algorithms currently implemented in software in the CMS higher-level trigger. The architecture emphasises heavy on-detector data reduction along with a seeded correlation approach for the identification of track candidates. It appears to make realistic demands on sensor resolutions, trigger primitive readout bandwidth, and off-detector processing. Further simulation study is required to validate and optimise the architecture under realistic conditions and technical constraints.

VI. REFERENCES

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