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L1 Track Triggering at CMS for High Luminosity LHC

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Abstract

The High Luminosity LHC (HL-LHC) is expected to deliver luminosities of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, with an average number of overlapping proton-proton collisions per bunch crossing (pileup) of about 140. These extreme pileup conditions place stringent requirements on the experiments' trigger systems to cope with the resulting event rates. For the CMS experiment, a key component of the detector upgrade for the HL-LHC is a track-trigger system which would identify tracks with transverse momentum above 2 GeV already at the first-level (L1) trigger. Here, a proposal for implementing L1 tracking using "tracklets" is presented. The expected performance of the L1 tracking from simulation studies and the use of L1 tracks to define trigger objects are discussed.

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L1 Track Triggering at CMS for High Luminosity LHC

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ABSTRACT: The High Luminosity LHC (HL-LHC) is expected to deliver luminosities of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, with an average number of overlapping proton-proton collisions per bunch crossing (pileup) of about 140. These extreme pileup conditions place stringent requirements on the experiments' trigger systems to cope with the resulting event rates. For the CMS experiment, a key component of the detector upgrade for the HL-LHC is a track-trigger system which would identify tracks with transverse momentum above 2 GeV already at the first-level (L1) trigger. Here, a proposal for implementing L1 tracking using "tracklets" is presented. The expected performance of the L1 tracking from simulation studies and the use of L1 tracks to define trigger objects are discussed.

KEYWORDS: Trigger concepts and systems (hardware and software); Performance of High Energy Physics Detectors; Data reduction methods.

*For the CMS collaboration

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1. Introduction

The upgrade to the High Luminosity LHC (HL-LHC) is foreseen for Long Shutdown 3 during 2023–2025. The resulting peak luminosity will be about $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with a goal to collect 3000 fb^{-1} over a ten year period [1]. The high luminosity is predicted to result in an average of 140 overlapping proton-proton collisions per bunch crossing (pileup) - a challenging environment for the LHC experiments. With the HL-LHC, trigger rates at the first-level (L1) trigger for single muons, electrons, and jets would exceed 100 kHz. Significantly increasing the trigger thresholds would restrict the physics potential and would alone not be sufficient. The key goal for the CMS experiment [2] is to maintain similar physics performance as for the 2012 operation. To achieve this goal, a critical component of the upgraded CMS detector for the HL-LHC is a new tracker with triggering capabilities [3]. The new tracker would allow to perform tracking already in the L1 trigger to maintain high efficiencies and keep event rates under control for L1 trigger objects.

Different approaches are under study for how to perform track finding at the L1 trigger. One approach is the so called tracklet-based method [4]. The tracklet-based approach is an algorithmic method which relies on commercial FPGA technology. These proceedings describe the basic concept of the tracklet-based method, studies its expected performance, and illustrates the use of tracks in the L1 trigger.

2. Track Trigger Concept

CMS plans to use a self-seeded L1 track trigger which relies on local transverse momentum (p_T) reconstruction. The aim is to reconstruct tracks with $p_T > 2$ GeV and to identify the track z position with ~ 1 mm precision, similar to the average vertex separation at pileup (PU) of 140.

Momentum discrimination is provided by p_T modules through hit correlations between closely spaced sensors. Low- p_T tracks are discriminated from high- p_T tracks based on their different bending in the 3.8 T CMS magnetic field, using the distance between hits in two nearby layers as illustrated in Figure 1. Correlated pairs of clusters, referred to as *stubs*, are selected if they are consistent with a ≥ 2 GeV track. This pre-selection is highly powerful as in minimum bias events about 95% of all tracks have $p_T < 2$ GeV. Stubs are then used as input to the L1 track finding.

Figure 1. Schematic illustration of stubs passing or failing the momentum discrimination. Trajectories of low- p_T particles bend in the magnetic field and produce hits which are not consistent with a high- p_T particle coming from the interaction point.

2.1 Tracker Geometry

The baseline geometry for the upgraded CMS outer tracker consists of a central barrel and two endcaps, each with five disks. Two types of p_T modules are used: 2S modules in the three outer layers and PS modules in the three inner layers. The 2S modules consist of 10×10 cm² strip sensors: 2×5 cm long strips with $90 \mu\text{m}$ pitch. The PS modules have a top sensor with 2×25 mm strips with $100 \mu\text{m}$ pitch and a bottom sensor with $1.5 \text{ mm} \times 100 \mu\text{m}$ pixels. Figure 2 shows the geometry for the outer tracker [5]. Also shown is the inner pixel detector which, however, will not be used for tracking at L1.

2.2 Tracklet Method for Tracking at L1

The tracklet-based approach relies on commercial FPGA technology to perform tracking at L1. The track finding is conceptually done in four main steps, starting from stubs. In the first step, tracks are seeded by forming tracklets from pairs of stubs in neighboring layers. A rough estimate of the tracklet parameters are extracted from the two stubs plus a constraint to the beamspot. The tracklet must be consistent with a track with $p_T > 2$ GeV and a z position $|z_0| < 15 \text{ cm}$ ¹. The seeding is

¹CMS uses a right-handed coordinate system with the origin at the center of the detector, the x -axis pointing to the center of the LHC ring, the y -axis pointing up, and the z -axis along the anticlockwise-beam direction. The azimuthal

Figure 2. Baseline geometry for the upgraded CMS tracker detector.

done multiple times between different layers and disks to ensure high efficiency. Next, tracklets are projected, both outside-in and inside-out, to other layers and disks to search for matching stubs. From the stubs that are matched to the trajectory of the tracklet, a track fit is performed. The fit is a linearized χ^2 fit and gives the final track parameters: transverse momentum (p_T), pseudorapidity (η), the azimuthal angle at the point of closest approach in the R - z plane (ϕ_0), the track z position at the point of closest approach (z_0), and optionally the transverse impact parameter (d_0). In the following, tracks are constrained to come from the interaction point in the x - y plane, i.e. d_0 is fixed to zero. Since a given track can be found many times due to seeding in multiple pairs of layers, a removal step eliminates duplicates based on χ^2 .

3. L1 Tracking Performance

The estimated L1 tracking performance is studied using Monte Carlo simulations. Although the tracking algorithm must eventually be implemented on FPGAs using integer operations [6], results are here shown for a floating-point implementation of the algorithm. Samples with single muons (μ^+/μ^-), pions (π^+/π^-), and electrons (e^+/e^-), overlaid with an average pileup of 140 and 25 ns bunch spacing are generated. The samples are produced with uniform η , ϕ , and p_T spectrum with Gaussian distributed d_0 and z_0 according to the expected LHC beam envelope. Tracks are required to have $p_T > 2$ GeV and $|\eta| < 2.5$, as well as to fulfill basic track quality criteria: $\chi^2 < 100$ and minimum 4 stubs.

3.1 Efficiency

The L1 tracking efficiency as function of η and p_T are shown in Figure 3 for single muons, pions, and electrons in events with $\langle \text{PU} \rangle = 140$. The efficiency is defined with respect to truth tracks corresponding to the single-gun particles. Muons have a sharp turn-on at 2 GeV and an overall high efficiency across all η . Pions have a somewhat lower efficiency due to their higher interaction rate. Electrons are affected by brehmsstrahlung, resulting in a slower turn-on curve and overall

angle ϕ is defined relative to the x -axis in the x - y plane and the polar angle θ is defined relative to the positive z -axis. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

lower efficiency. For $|\eta| < 1.0$ and $p_T > 2$ GeV, the estimated efficiency for muons, pions, and electrons is $>99\%$, 95% , and 87% , respectively.

Figure 3. L1 tracking efficiency as function of p_T (left) and η (right) for single muons, electrons, and pions with $p_T > 2$ GeV and $|\eta| < 2.5$ in events with $\langle PU \rangle = 140$.

3.2 Resolutions

The L1 track parameter resolutions are studied for single muons. Figure 4 shows the estimated z_0 and relative p_T resolutions as function of $|\eta|$ for three ranges of p_T . Despite the large extrapolation distance (the first layer is at 25 cm), the z_0 resolution is about 1 mm for a wide range of η , similar to the average separation of pileup vertices, thanks to the PS modules. The relative p_T resolution is about 1% at central η for high- p_T tracks. The precise z resolution is important to allow selecting tracks that originate from the same vertex for use in the trigger algorithms and the good p_T resolution allows to have sharp muon trigger thresholds.

Figure 4. Resolution of the L1 track z_0 (left) and relative p_T (right) for single muons in events with $\langle PU \rangle = 140$. The resolutions are shown as function of $|\eta|$ for three ranges of p_T .

4. Using L1 Tracks in the Trigger

To take advantage of the L1 track information, the tracks must be combined with L1 trigger ob-

jects. This is done for leptons by matching L1 muon or calorimeter information with L1 tracks to derive improved muon momentum measurements or provide electron identification, to determine z positions for electrons, muons and taus, and by defining track isolation variables. L1 tracks are also used to reconstruct the primary vertex of an event, and to perform vertex association for jets used in hadronic triggers.

4.1 Lepton Triggers

The trigger rates for single muons using the drift tube trigger primitives (DTTF) [7] alone flatten as the threshold is increased. Matching DTTFs to L1 tracks can bring this rate down by a factor of 10 or more for p_T thresholds above ~ 14 GeV, as shown in Figure 5 (left). For electrons, L1 e/γ objects using either the current (5×5 crystal) L1 calorimeter granularity or single crystal-level position resolution are matched to track stubs in the central region [8]. For a working point corresponding to a 90% signal efficiency, single e/γ rates are reduced by a factor of ~ 10 (~ 6) for single (5×5) crystal granularity for $p_T > 20$ GeV, shown in Figure 5 (right).

Figure 5. Single muon trigger rates for the barrel region, normalized to the present trigger at 10 GeV (left) and single electron rate reductions, also for the central region, using single or 5×5 crystal granularity (right).

Track-based isolation is another way in which lepton trigger rates can be reduced. An example for electrons is here discussed, where a L1 e/γ object with transverse energy E_T is first matched to a central L1 track. A relative isolation variable is then defined as $\sum p_T^{\text{track}}/E_T$, where the sum runs over tracks with $p_T > 2$ GeV in an annulus of $0.02 < \Delta R < 0.2$ around the matched electron track². The isolation variable is defined with or without requiring a δz cut between the electron track and tracks used for the isolation variable. Figure 6 shows the isolation efficiency for signal (single electron events with $\langle \text{PU} \rangle = 140$) versus background ($\langle \text{PU} \rangle = 140$ sample) for events in which a L1 track-electron candidate with $E_T > 20$ GeV was found. A factor of two in rate reduction can be achieved for a 99% signal efficiency when applying a δz cut.

² $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, where $\Delta\eta$ ($\Delta\phi$) is the distance in η (ϕ) between the matched electron track and other tracks.

Figure 6. Signal efficiency vs background efficiency for events in which a L1 track-electron candidate with $E_T > 20$ GeV was found, defining the isolation variable with or without applying a δz cut.

4.2 Hadronic Triggers

Hadronic triggers benefit from L1 track information by using the tracks to measure jet z positions and thereby be able to reject jets from pileup interactions. The jet vertex is measured by associating the L1 jet object to nearby L1 tracks. When defining hadronic triggers, jets are required to originate from the same vertex through $\Delta z < 1$ cm, illustrated in Figure 7.

Figure 7. Illustration of vertex consistency requirement for hadronic triggers.

For multijet triggers, n jets are required to have $\Delta z < 1$ cm with respect to the z position of the leading jet. H_T triggers are defined with and without vertex association as:

$$\text{No vertex association : } H_T = \sum p_T(\text{jet})$$

$$\text{With vertex association : } H_T = \sum p_T(\text{jet}) \text{ for jets with } |z(\text{jet}) - z_{EVT}| < 1 \text{ cm}$$

where the sum is over jets with $p_T > 15$ GeV and $|\eta| < 2.0$, and the "event vertex" z_{EVT} is the z position of the leading jet in the event. Missing H_T triggers are defined similarly with and without vertex association through the vectorial sum of the p_T of jets.

The jet vertex performance is studied using all-hadronic $t\bar{t}$ events with $\langle \text{PU} \rangle = 140$. Figure 8 (left) shows the efficiency of accurately measuring the jet z position, here defined as $|z(\text{jet}) - z_{true}| < 1$ cm, as function of jet p_T . The efficiency is above 95% for jets with $p_T > 50$ GeV. Figure 8 (right) shows the resolution of the measured z position, which is about 1 mm.

To assess the performance of including track information for hadronic triggers, an example supersymmetry signal point is used. The scenario considered is stop-quark pair production with

Figure 8. Jet vertex performance showing the efficiency to accurately measure the jet z position (left) and the resulting resolution (right), evaluated using all-hadronic $t\bar{t}$ events with $\langle\text{PU}\rangle=140$.

hadronic top decays ($\tilde{t} \rightarrow t\tilde{\chi}_1^0$), where the stop mass is $m(\tilde{t}) = 775$ GeV and the neutralino mass $m(\tilde{\chi}_1^0) = 550$ GeV. Figure 9 shows the trigger rate versus signal efficiency for different missing transverse energy and missing H_T triggers: missing E_T defined using calorimeter information only (CALOmet), missing H_T determined with or without vertex association for two calorimeter-based L1 jet algorithms which differ in the PU subtraction methods used, and track-based missing transverse energy (TKmet). The track-based missing transverse energy variable is calculated using L1 tracks coming from the primary vertex, where the primary vertex is determined using z_0 information from L1 tracks in the event. As shown from the plot, sizable rate reductions are achieved when incorporating the tracking information.

5. Conclusions

For the HL-LHC upgrade, CMS plans to have a new tracker with triggering capabilities to maintain high trigger efficiencies and to keep event rates at manageable levels without large increases in trigger thresholds. One approach to performing tracking in the L1 trigger is the tracklet-based method, where the tracking is implemented in FPGAs. These proceedings presented simulation studies of the performance of the tracklet-based algorithm. The preliminary performance results are very promising, with high track-finding efficiency and precise measurements of L1 track parameters with about $\sigma(z_0) \sim 1$ mm and $\sigma(p_T)/p_T \sim 1\%$ for a wide range of η .

Incorporating L1 track information to the L1 trigger is important to achieve the necessary rate reductions as driven by the physics. For electron and muon identification, rates can be reduced by a factor of ~ 10 . Adding track isolation gives another factor ~ 2 in rate reduction. For hadronic triggers, large rate reductions can be achieved through determining the z positions of jets and thereby requiring jets used for these triggers to originate from a common vertex.

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Figure 9. Rate as a function of signal efficiency for inclusive missing transverse energy triggers for a supersymmetry scenario. The open symbols show the performance of triggers that do not make use of L1 tracking information with calorimetric missing E_T and missing H_T triggers. The filled symbols show the performance of triggers when adding L1 tracking information by constraining the jets used for missing H_T triggers to originate from a common vertex or when defining a missing transverse energy variable using L1 tracks coming from the primary vertex.

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