The ATLAS Jet Trigger for LHC Run 2

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The new centre of mass energy and high luminosity conditions expected for Run 2 at the Large Hadron Collider impose more demanding constraints on the ATLAS online trigger than ever before. An immense rate of proton-proton collisions must be reduced from the bunch-crossing rate of 40 MHz to approximately 1 kHz before data can be written on disk for offline analysis. The ATLAS trigger system performs real-time reconstruction and selection of these events in order to achieve this reduction. The selection of events containing jets is uniquely challenging at a hadron collider where nearly every event contains significant hadronic activity. It is, however, of crucial importance to exploit the incoming data in many physics topics in the new kinematic regime, ranging from early Standard Model measurements to searches for New Physics.

Following the very successful first LHC run in 2010/12, the ATLAS trigger was much improved, including a new hardware at Level 1 and the restructuring of the High Level Trigger system, which merges two previously separated software-based processing levels. After summarising the design choices used in the jet trigger for Run 2, expected capabilities will be reviewed. The expected performance of upgraded jet trigger will be described and compared with the first trigger performance results from initial Run 2 data.

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1. Introduction

ATLAS [1] is a multipurpose experiment at the Large Hadron Collider (LHC) [2], the proton-proton (pp) collider under operation at CERN in Geneva. The ATLAS detector is designed to cover a wide range of physics topics [3]. These include precision measurements of Standard Model (SM) processes, the understanding of electroweak symmetry breaking and searches for new physics beyond the SM (BSM). ATLAS looks for new physics either via direct observation of new TeV-scale particles or via indirect measurements of anomalies in already well established signals.

The first operational period of the LHC, Run 1, lasted from early 2010 until early 2013. During Run 1 the LHC collided proton bunches at a rate of 20MHz (bunch spacing of 50 ns). In 2010–2011 the LHC provided pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV, with an highest instantaneous luminosity of $L_{\text{inst}} = 3.65 \times 10^{33}$ cm^{-2}s^{-1} and mean pile-up[1] reaching a maximum value of $\langle \mu \rangle \sim 20$. In 2012–2013 the LHC operated at $\sqrt{s} = 8$ TeV, with peak $L_{\text{inst}} = 7.73 \times 10^{33}$ cm^{-2}s^{-1} and peak $\langle \mu \rangle \sim 40$. This allowed the ATLAS experiment to record a total integrated luminosity of ~ 5 fb^{-1} at 7 TeV and ~ 20 fb^{-1} at 8 TeV. The success of Run 1 culminated with the discovery of the Higgs boson and initial measurement of its properties [4].

After Run 1, the LHC went through a first long shutdown (LS1) for two years of maintenance and upgrades. Run 2, the second operational period of the LHC, has started in 2015 and is scheduled to last until 2018. During Run 2 the LHC will collide proton bunches at a rate of 40MHz (bunch spacing of 25 ns) at $\sqrt{s} = 13$ TeV, with highest expected values of peak $L_{\text{inst}} = 2 \times 10^{34}$ cm^{-2}s^{-1} and of peak $\langle \mu \rangle \sim 54$, for a total integrated luminosity of 100–150 fb^{-1}. LHC commissioning progressed well, starting on April 5th with the first protons circulating in the ring. On June 3rd, the first stable beam collisions where produced at 13 TeV. The transition from 50ns to 25ns bunch spacing was made and data taking proceeds at a regular pace since August.

The ATLAS experiment has a cylindrical shape aligned with the beam pipe and centred on the nominal interaction point (IP)[2]. It has 46m length and 25m diameter, and is made of layered sub-components with different purposes: an inner tracking detector surrounded by a superconducting solenoid magnet, electromagnetic (EM) and hadronic (Had) calorimeters, and a muon spectrometer within a toroidal magnet. The 10^8 electronic channels of the detector are read out every 25 ns (synchronously with the LHC clock), resulting in events with an average size of 1.6 MB. The total data rate of 64 TB/s is too large to be recorded.

At the LHC only a small fraction of the collisions produce events with a significant interest for physics studies. ATLAS uses a sophisticated trigger system to select in real-time (online) the physically relevant events and reduce the data rate. Given the high collision rate and large number of interactions per bunch crossing, the trigger system has to be highly flexible in order to provide high-efficiency unbiased selections for a wide variety of physics analyses and a fast rejection of uninteresting events. The ATLAS trigger system does this by selecting generic high transverse momentum (p_{T}) objects like muons, electrons, photons, jets, taus and large missing transverse

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[1]Pile-up (μ) is defined as the number of collisions per bunch crossing.

[2]ATLAS uses a right-handed coordinate system with its origin at the IP and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

momentum (E_T^{miss}) accounting for high p_T neutrinos. The trigger checks these objects against a menu of interesting physics signatures containing a list of conditions to be fulfilled for an event to be accepted for recording. The ATLAS trigger achieves a reduction of the data volume to be recorded by a factor of 10^5, from 20 MHz to 400 Hz (600 MB/s) in Run 1 and from 40 MHz to 1 kHz (1500 MB/s) in Run 2.

Jets are narrow collimated clusters of stable particles (mainly hadrons) that leave energy depositions in both calorimeters (EM and Had). They are produced by the fragmentation of a hard (high-p_T) partons (quarks or gluons). Jets probe the parton substructure and the highest p_T transfers, thus they test Quantum Chromodynamics (QCD) through a wide energy range and are the best handles on searches for new physics. Jets are signatures and also background for many SM and BSM processes, and are the most common hard objects produced at the LHC.

The inclusive rate from jet events is very high, with a steeply falling spectrum in the p_T distribution. The event reconstruction is uniquely challenging at an hadron collider, where a large fraction of events have significant jet activity. Excellent p_T discrimination is critical for jet trigger performance. A trigger that reaches full efficiency close to its p_T threshold, said to have a steep turn-on curve, is therefore important for the jet trigger to manage this huge incoming rate of events.

2. The ATLAS Trigger system

The ATLAS trigger system achieved excellent performance during Run 1 [5]. However, for Run 2, rates are expected to globally increase five times: factor 2 due to the $\sqrt{s}$ increase (higher for high-p_T jets) and factor 2–3 due to the rise in luminosity. During LS1, the ATLAS trigger system went through major upgrades. The trigger will deal with the higher rates using more sophisticated and flexible algorithms, both in hardware and software. The Run 2 trigger system consists of two levels, the hardware-only Level-1 (L1) and the software-based High Level Trigger (HLT). During Run 1, the HLT was further divided in Level-2 (L2) and Event Filter (EF), but these have been merged for Run 2.

The L1 uses custom designed processors to take a decision within a latency of 2.5 μs. It applies a simple and fast reconstruction, over a coarse granularity readout of the calorimeter and muon spectrometer, to find Regions of Interest (RoIs) where high transverse energy (E_T) objects are found. The rate of L1 accepted events reached 70 kHz (100 GB/s) during Run 1. For Run 2 the system has been improved to handle a L1 output rate of 100 kHz (160 GB/s). However the event rate will increase by a higher factor, so improved and tighter selections are required. This is achieved with new calorimeter hardware.

For jet finding at L1 [6], the EM and Had calorimeters are segmented and combined in trigger towers (TTs) with projective geometry and a size of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The energy is digitized at the EM scale, bunch crossing identification is done, pedestal subtraction is performed and a noise suppression threshold is applied. Jet elements (JEs) are then constructed from 2×2 TTs. The L1 jet algorithm uses a sliding window with a size of 2×2, 3×3 or 4×4 JEs to identify a local E_T maximum. A RoI is created if the jet E_T is above a chosen threshold. Updates for Run 2 include the Multi-Chip Module (MCM), the Common Merger eXtended (CMX) and the L1 Topological processor (L1Topo) [7]. The MCM digitizes the analogue calorimeter signals, applies a dynamic pedestal subtraction (event-by-event pile-up subtraction) and a specific jet energy

calibration. The CMX merges candidates counts and energy sums. It transfers data to the new L1 Topo and provides higher throughput. The L1 Topo will allow to apply geometrical selection criteria on the L1 identified objects.

The HLT architecture has been restructured for Run 2, with the L2, Event Builder and EF farms merged into an unique HLT farm for simplification and dynamic resource sharing. The unified network and farm decrease the data transfer by a factor 2.5, allow for the increase to 100 kHz throughput and provide an output of 1 kHz with an average processing time per event of 0.2 s. The maximum total output rate has been increased from 600 Hz to 1.5 kHz at peak luminosity. The new HLT farm allows the use of sophisticated offline reconstruction algorithms in the HLT. Most important for jets, the new HLT architecture together with large improvements in the speed of calorimeter readout during LS1, means that jet reconstruction can access a Full Scan (FS) of the entire calorimeter. FS jet reconstruction is faster in environments with many jets and does not produce (fake) duplicate jets. FS can run after non-jet triggers on L1, which is useful for low energy threshold triggers which have too high rate at L1. FS allows the use of jets with larger distance parameter and the application of jet area based methods for pile-up subtraction. Jets reconstructed with FS achieve the closest performance to offline, having the full calorimeter granularity and acceptance. FS can be clearly used in the total allocated bandwidth for jets of around 20 kHz. It is also possible to use a Partial Scan (PS) which groups just the RoIs recognised at L1.

For jet finding in the HLT, as in offline, the inputs for jet reconstruction are topoclusters [8] (TCs). TCs are 3D groups of topologically connected calorimeter cells, selected using the energy significance of a cell $|E|/\sigma$, where σ is the cell total noise from the electronics and from pile-up. TCs include seed cells with $|E| > 4s$, surrounding cells with $|E| > 2s$, and all immediate neighbour cells, ensuring built-in noise suppression. Local hadronic calibration [9] can be performed, starting at EM scale, identifying the hadronic clusters by their longitudinal depth and energy density, and applying weights for hadronic response. The calibrated clusters are at the Local Cell Weighting (LCW) scale. Either EM or LCW clusters can be inputs for jet building. performed by the anti-k_T algorithm [10], with distance parameters of $R = 0.4$ and $R = 1.0$ being used in the HLT. After jet finding, the fraction of the jet p_T arising from pile-up can be subtracted on an event-by-event basis. This is done using the median energy density of the event within $|\eta| < 2$ (computed during FS) and the area of each jet (computed by the jet algorithm). The estimated E_T of reconstructed jets may be further refined by applying a jet energy scale (JES) calibration factor dependent on jet η and p_T and extracted from Monte Carlo simulation. The JES correction differs for jets built from EM or LCW clusters. Both the pile-up subtraction and JES correction are applied using offline tools within the HLT framework.

3. Jet Trigger Performance

The excellent performance of the ATLAS jet trigger during Run 1 of the LHC has been well documented [11, 12, 13]. The jet trigger has been allocated about 20% of the total bandwidth of the ATLAS trigger. The steeply decaying jet p_T spectrum means that the jet trigger rate at low p_T must be controlled using prescales. This scheme is still valid for Run 2.

The jet trigger exhibited good performance from the start of Run 2. Figure 1 shows a comparison of per-event trigger efficiency turn-on curves between data and simulation for three rep-
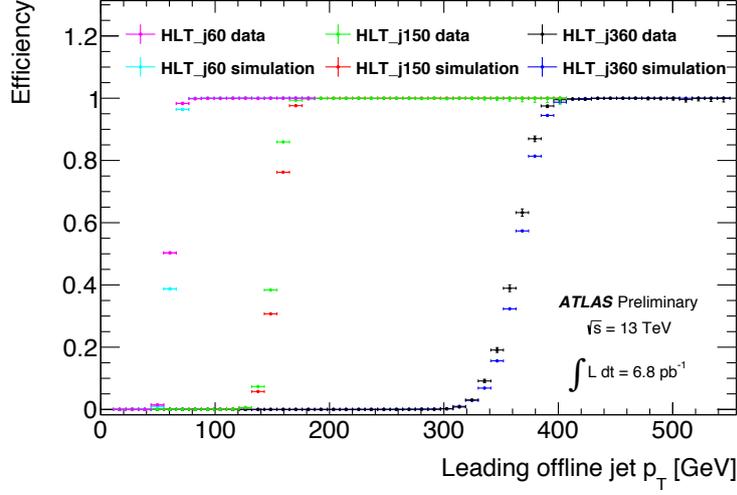
Figure 1: Jet trigger efficiency in bins of p_T of the leading jet for the HLT_j60, HLT_j150 and HLT_j360 chains. Data and PYTHIA 8 [14] simulation are compared [15].
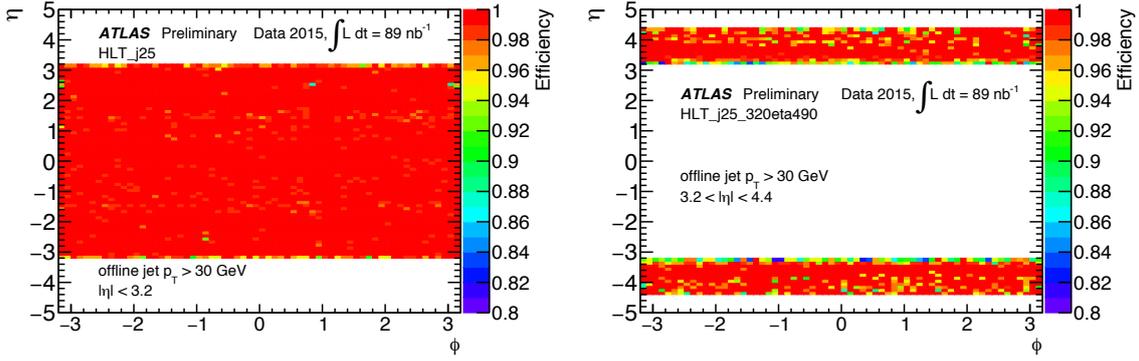
Figure 2: Jet trigger efficiency in bins of (η, ϕ) of the leading jet for the HLT_j25 chain in the central region (left) and in the forward region (right). Offline jets have $p_T > 30$ GeV [15].

resentative thresholds (60, 150 and 360 GeV) in data from June 2015. HLT jets are formed from topoclusters at the electromagnetic energy scale. The HLT jets are then calibrated to the hadronic scale by first applying a jet-by-jet area subtraction procedure followed by a jet energy scale weighting that is dependent on the HLT jet p_T and η. The calibrated jets are used for HLT selection. Each efficiency is determined using events retained with a lower threshold trigger that is found to be fully efficient in the phase space of interest. Already at this early stage, the turn-on curves are sharp and well defined, showing that the jet trigger is performing an efficient selection. Agreement between data and simulation is good.

Figure 2 shows the (η, ϕ) map of the per-jet trigger efficiency for the HLT jet chain with a threshold of 25 GeV in both the central ($|\eta| < 3.2$) and forward ($3.2 < |\eta| < 4.4$) regions. The efficiency is evaluated for an offline jet p_T selection of 30 GeV. The efficiency is uniformly high in the entire range, showing that the jet trigger and the detector infrastructure are working well in the

full spacial extension.

4. Conclusions

The large increase in the jet rates expected during Run 2 of the LHC poses a challenge for the ATLAS jet Trigger. New hardware at L1, a new architecture of the HLT and improvements in calorimeter readout allow the use of more sophisticated algorithms that are able to refine the selection and control the jet trigger rate. The HLT now uses offline algorithms to prepare the jet inputs (calorimeter clusters), build and calibrate the jets, including pile-up subtraction. First results at $\sqrt{s} = 13$ TeV show that the jet trigger behaves as expected and it is ready to support the ATLAS jet-based analyses.

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