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Implementation and performance of the ATLAS second level jet trigger

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Abstract. ATLAS is one of the four major LHC experiments, designed to cover a wide range of physics topics. In order to cope with a rate of 40 MHz and 25 interactions per bunch crossing, the ATLAS trigger system is divided in three different levels. The jet selection starts at first level with dedicated processors that search for high E_T hadronic energy depositions. At the LVL2, the jet signatures are verified with the execution of a dedicated, fast jet reconstruction algorithm, followed by a calibration algorithm. Three possible granularities have been proposed and are being evaluated: cell based (standard), energy sums calculated at each Front-End Board and the use of the LVL1 Trigger Towers. In this presentation, the design and implementation of the jet trigger of ATLAS will be discussed in detail, emphasazing the major difficulties of each selection step. The performance of the jet algorithm, including timing, efficiencies and rates will also be shown, with detailed comparisons of the different unpacking modes.

1. Introduction

ATLAS is one of the LHC multipurpose experiments that will start operation in 2008. At the design luminosity of the LHC, $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and with a bunch crossing rate of 40 MHz the interaction rate will be of the order of 1 GHz, imposing strong demands on the trigger system, that has to be efficient to select the interesting events while rejecting most of the interactions. The trigger system has to be very flexible, prepared to select both, expected and unexpected interesting physics events. It does so by selecting high p_T[1] objects like muons, electrons, photons, taus, jets and/or large missing transverse energy[2].

[1] Momentum relative to the beam axis.
[2] Energy imbalance in the calorimeter, measured in the plane transverse to the proton beam direction.

The ATLAS trigger system was organized in three levels. LVL1 (first level) is hardware based, with coarse granularity and a maximum latency of 2 μs. Using only the information from the muon system and the calorimeters, it does a fast search for high p_T objects, reducing the rate from 40 MHz to about 75 kHz. The High Level Trigger (HLT) formed by the Second Level Trigger (LVL2) and the Event Filter (EF) is software based. LVL2 uses the information provided by LVL1 about the position of the high transverse energy energy deposition (seeds) to start the search for interesting signatures. It is run before the event is built and therefore it asks for the event fragments to the Read-Out Buffers (ROB). To save time it only reconstructs a region of the detector around the seed provided by LVL1, that is known as Region of Interest (RoI). It uses the full granularity of the subdetectors and has a maximum processing time of the order of 40 ms in a 1.8 GHz processor, reducing the rate by a factor 100, approximately. The EF may run in seeded mode, receiving the seeds from LVL2, or in full event access. It runs more sophisticated algorithms and has access to better calibration constants, improving the selection done in the previous steps. It has to reduce the rate to about 200 Hz.

The EF uses an offline-like environment and algorithms, while LVL2 has fast, dedicated algorithms that have to run in a multi-threaded environment. In both levels, a sequence of algorithms is run in order to verify or reject as fast as possible a given signature [1].

2. The ATLAS Jet Trigger

At the HLT, jets with high p_T are selected by running a sequence of algorithms. At LVL2, the first one is a feature extraction algorithm, called TrigT2CaloJet, that uses a basic cone algorithm to reconstruct a jet in the RoI. After that, a hypothesis algorithm is run in order to verify if the p_T of the jet is over the threshold. At the EF, offline-like algorithms are used. Typically, a more sophisticated cone algorithm is run, although there is the possibility to choose also k_T or other offline available algorithms.

TrigT2CaloJet is an iterative algorithm that starts by requesting to the Read-Out Buffers the event fragments in a region around the seed provided by LVL1. It receives the data in a bytestream format that has to be unpacked (translated into the C++ objects that the algorithm uses). This is one of the most time consuming parts of the algorithms. To be able to reduce the unpacking time, three possible granularities are being considered:

- Cells: the standard one. Each cell in the RoI is unpacked.
- FEBs: the energy sums of all the cells belonging to a Front End Board (FEB) are calculated at the Read-Out Driver (ROD) and sent directly to LVL2, that unpacks only the information corresponding to the FEB energy sums. For the electromagnetic calorimeter, each FEB contains 128 cells, reducing considerably the amount of data transfered and unpacked.
- The possibility of using the information of LVL1 Trigger Towers is also under consideration but its feasibility is not yet demonstrated.

After unpacking the data, a grid with the list of detector elements in the RoI is built. The algorithm loops in this grid and calculates the energy weighted η, ϕ[3] position of the detector elements (cells, FEBs) inside a cone with fixed radius[4] around the center of the RoI. The center of the cone is updated and the calculation is iterated few times in order to improve the measurement of the jet center position. Reducing the granularity by using FEB based energy sums has the advantage that the time to loop over the detector elements is shorter, improving even further the algorithm performance.

[3] The ATLAS coordinate system is a right-handed system with the x axis pointing towards the center of the LHC ring, the z axis following the direction of the beam and the y axis pointing upwards. The azimuthal angle, ϕ is measured from the positive x axis and the polar angle θ is measured from the positive z axis. Frequently, the pseudorapidity variable, defined as $\eta = -\log\left(\tan\frac{\theta}{2}\right)$, is used.

[4] The cone radius is measured as a distance in the (η,ϕ) plane, defined as $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

The jet reconstruction at LVL2 finishes with a fast calibration algorithm that sets the hadronic energy scale for the jets. The algorithm used is called the *Sampling* calibration method[2]. The energy is corrected by applying two weights, one to the energy measured in the electromagnetic (EM) calorimeter and another one to the energy measured in the hadronic calorimeter (Had):

$$E_{jet}^{corr} = \omega_1 E_{EM} + \omega_2 E_{Had}$$

The weights have a logarithmic dependence on the total energy of the jet: $\omega_i = a_i + b_i \cdot \log E_{jet}$, where a_i and b_i are two different constants for the EM and hadronic energies, that can have different values for different bins in η. Since the total energy of the jet is not know a priori, the calibration is applied in an iterative procedure that converges in few iterations. The sampling method is fast and uses a negligible amount of time in comparison with the previous steps in the jet reconstruction. The calibration constants are calculated using the Monte Carlo (MC) simulation. This algorithm is simpler and faster than the ones being considered for the offline ATLAS jet reconstruction [3].

The calibration of the jets is one of the most important steps in the jet algorithm given the fact that the main background for the jets are also jets, and therefore the most difficult task is to discriminate the energies that are above the threshold with high efficiency while rejecting most of the jets under the threshold.

3. The Second Level Jet Trigger Performance

3.1. Timing Performance

The timing performance of the algorithm has been measured by running the trigger software on MC simulated fully hadronic $t\bar{t}$ events that were stored in a bytestream format, the same that is expected to be used for the real data once the detector starts operation. Computers with processors of similar speed to the ones that will be used in the LVL2 farm[5] at ATLAS were used. The average processing time per RoI is shown in figure 1 for the two possible granularities studied up to now. For the cell based jets, the average processing time, with the current default reconstruction parameters, is around 30 ms. Taking into account that the average number of RoI's per event is expected to be of the order of 1.6, this average time seems too large. It can, however, be improved by optimizing the reconstruction parameters like the number of iterations that the algorithm executes to determine the center of the jet and the size of the RoI. These two points will be discussed in the next section. By choosing the FEB based granularity the total processing time can be reduced by approximately a factor 3, as seen in figure 1. The physics performance of the FEB based jet reconstruction will be discussed in section 3.3.

3.2. Optimization of the reconstruction parameters

The default parameters used in the reconstruction of the LVL2 jets are summarized in table 1. A detailed study was performed in order to understand if these parameters can be changed to improve the timing performance without loosing precision in the jet energy and position measurements.

The variation of the coordinates of the jet center after each iteration of the jet reconstruction algorithm is shown in figure 2. The largest variaton of η, ϕ happens after the first iteration and thus it has the largest impact on the precision. This suggests that the number of iterations could be reduced to 2 without loosing too much precision on the jet position.

In order to study the effect of the RoI size, the RoI was reduced to 1.0x.1.0 in η, ϕ, that is a bit larger than the diameter of the jet. Notice that the maximum displacement of the center of the RoI is of the order of 0.2 in $\Delta\eta$ or $\Delta\phi$, as it can be seen in figure 2, and therefore an RoI of 1.0x1.0 seems enough for the jet reconstruction. The total time spent by the LVL2

[5] 8 core computers with 1.8 GHz CPU's.

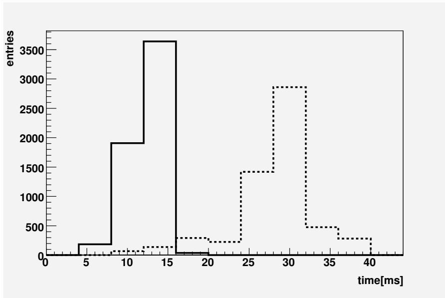

Figure 1. Time spent by the LVL2 jet reconstruction algorithm per RoI for cell granularity with a dashed line and for the FEB granularity with a solid line.

Table 1. Default parameters used in the reconstruction of the ATLAS Second Level Jets.

Parameter	Default value
Cone radius	0.4
Number of iterations	3
RoI size	1.4x1.4 in (η, ϕ)

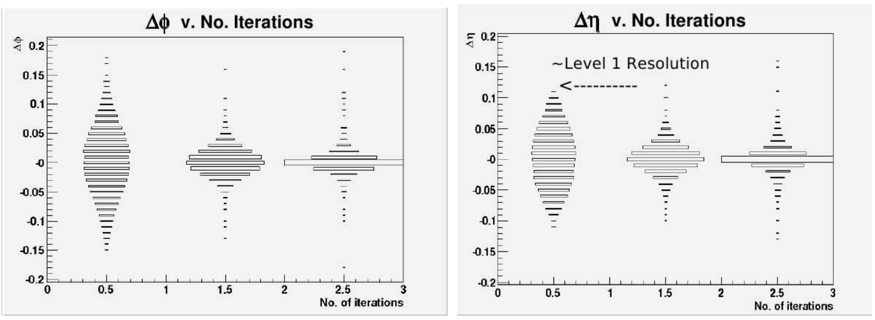

Figure 2. Variation in the ϕ (left) and η (right) position of the jets with the number of iterations run by the LVL2 jet reconstruction algorithm.

jet algorithm, using 3 iterations, is shown in figure 3. The reduction of the RoI size means a considerable reduction of processing time, of the order of 30%. As it will be shown in the next section, the energy reconstruction is not affected by this reduction of the size of the RoI.

3.3. Jet Energy Scale

The ATLAS jet trigger menu will cover a wide range of energies, as it can be seen in tables 2 and 3 for the single jet triggers. In addition to those, there will be multi-jet triggers (di-jet, tri-jet, tetra-jet) and triggers combined with missing transverse energy. The jet energy should therefore be properly calibrated for a large range of transverse energies, from 10 GeV to 400 GeV.

The jet energy scale and resolutions were calculated using the standard reconstruction, based on cells. The calibration constants were previously extracted using di-jet simulated events. The results are shown in figure 4. The energy scale, defined as the LVL2 jet energy divided by

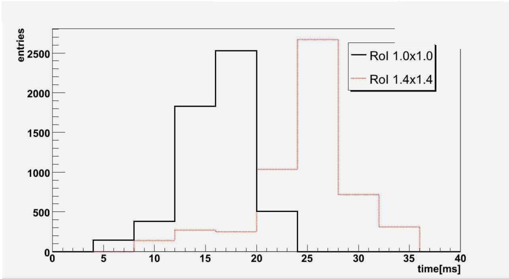

Figure 3. Time spent by the LVL2 jet reconstruction algorithm for two different RoI sizes: 1.4x1.4 (dashed line) and 1.0x1.0 (solid line).

Table 2. Single jet triggers for the design luminosity of the LHC ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$).

Threshold	Prescale factor
25 GeV	17,280,000
35 GeV	5,760,000
50 GeV	1,440,000
65 GeV	360,000
90 GeV	72,000
130 GeV	12,000
170 GeV	3000
300 GeV	200
400 GeV	1

Table 3. Single jet trigger menu for the start-up luminosity ($10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$).

Threshold	Prescale factor
5 GeV	1,000,000
10 GeV	42,000
18 GeV	6,000
23 GeV	2,000
35 GeV	500
42 GeV	50
70 GeV	5
100 GeV	1

the truth jet energy[6], is around 1 for all the η coverage of the LVL2 jet trigger and all the energies studied, demonstrating that the energy is correctly measured within 2%. This is a good precission for LVL2. The jet energy resolution decreases from 12% for the smallest energies to 4% for energies above 1000 GeV. The resolutions were fit with the following expression, that includes an stochastic term convolved with a constant term:

$$\frac{\sigma(E)}{E} = \frac{A(GeV^{1/2})}{\sqrt{E}} \oplus B \tag{1}$$

On the table 4 the results of the fit are shown for all the η bins, before and after calibration. A few percent improvement in the resolution is obtained with the current calibration method. A further improvement can be achieved in future by exploiting the correlation between the fraction of electromagnetic energy and the calibration weights[4].

In another study, two different RoI sizes were used in order to study its effect on the jet energy scale and resolution. One of the RoI sizes was chosen to be slightly smaller than the cone diameter (0.7x0.7 in η, ϕ) so some of the energy of the jet was lost outside the RoI. The other one had the default dimensions. The jet energy calibration constants were calculated independently in both cases and the resulting jet energy scale and resolutions were compared. In both cases,

[6] The truth energy of the jet is calculated in the following way: first, jets are reconstructed with the cone algorithm running on the MC-truth particles. The total energy of the jet is calculated by summing up all the energies of the MC-truth particles that fall inside the cone. The MC-truth jet that is closer to the LVL2 reconstructed jet is used to calculate the energy scale.

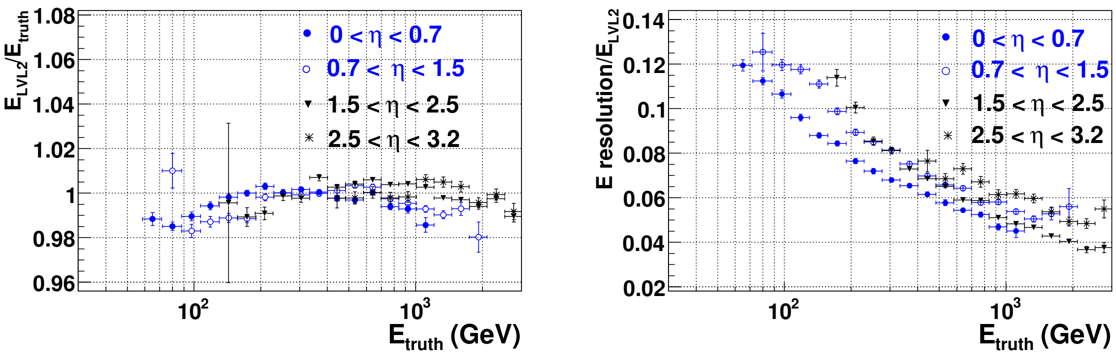

Figure 4. Left: jet energy scale for the LVL2 jets as a function of the truth energy of the jet, for four different bins in η. Right: jet energy resolution as a function of the truth energy of the jet, for four different bins in η.

Table 4. Results of the fit of the jet energy resolution as a function of the jet energy, before and after applying the calibration. The fit was done assuming the expression 1.

η region	Before calib.		After calib.	
	a	b	a	b
(0.0,0.7)	1.03	0.06	0.96	0.04
(0.7,1.5)	1.28	0.06	1.18	0.04
(1.5,2.5)	1.53	0.05	1.37	0.03
(2.5,3.7)	1.86	0.06	1.46	0.04

the jet energy scale was found to be within 2% around 1. The resolution of the jets was also found to be the same. This means that, in case that some small fraction of the jet energy would be lost outside the RoI the calibration algorithm would correct for it. Therefore, using an RoI of 1.0x1.0 will reduce processing time while keeping the same physics performance.

Finally, the jet energy scale and resolution were calculated also for the case when the FEB granularity is used. The results obtained, for both the scale and the resolution, were compatible with the ones obtained for the cell based jets, demonstrating that the FEB granularity fullfills the timing and performance requirements of the ATLAS LVL2 jet selection.

4. Conclusions

The ATLAS Second Level jet trigger uses a cone algorithm to reconstruct the jets and applies a simple calibration procedure. Two possible granularities have been studied up to now: using cell energies and FEB based energy sums. In both cases similar performance in terms of energy measurement and resolution were obtained while the FEB based approach has been proben to be a factor 3 faster, being more addequate for the ATLAS LVL2 trigger. The cell based method can also fullfill the timing requirements provided the reconstruction parameters (like the RoI size or the number of iterations of the jet algorithm) are properly chosen. For the cell based algorithm, the jet energy scale was found to be correct with a 2% accuracy, for all η regions and all the energies. The calibration method improves the jet energy resolution by a few %.

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