b-jet triggering in ATLAS

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Abstract. The online event selection is crucial to reject most of the events containing uninteresting background collisions while preserving as much as possible the interesting physics signals. The $b$-jet selection is part of the trigger strategy of the ATLAS experiment and a set of dedicated triggers is in place from the beginning of the 2011 data-taking period and is contributing to keep the total bandwidth to an acceptable rate. These triggers are used in many physics analyses, especially those with topologies containing more than one $b$-jet where higher rejection factors are achieved that benefit from requesting this trigger to be fired. An overview of the $b$-jet trigger menu and the performance on data is presented in this contribution.

1. Introduction

The 2011 Large Hadron Collider (LHC) run was tremendously successful. The peak instantaneous luminosity increased over the year and reaching its maximum at $3.65 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$. The high collision rate required an efficient trigger system to select only a few hundred events per second. The ability to identify and tag jets originating from $b$-quarks online in proton-proton collisions facilitates many important physics analyses. Due to the large multi-jet production rate at the LHC it is challenging to study signatures without relying on leptons to trigger the event. The $b$-jets trigger offers an advantage compared to calorimeter-based jet triggers because it makes use of precision track information to identify $b$-jets.

2. LHC and the ATLAS Detector

The ATLAS detector [1] is a multi-purpose detector with a forward-backward symmetric cylindrical geometry, divided in different subsystems (see Fig.1):

- The inner detector (ID) reconstructs charged particle trajectories and measures their momentum. It consists of three sub-parts immersed in a 2T solenoid magnetic field. Closest to the beam line is the pixel detector with approximately 80 million silicon pixels arranged in three layers. A silicon micro-strip detector (SCT) arranged in four nested cylindrical layers surrounds the pixel detector with a stereoscopic geometry for three-dimensional hit position measurements. The outermost part of the ID consists of layers of straw tubes (TRT) providing $R-\phi$ ($z-\phi$ in the end cap) measurements in the barrel out to a radius of about 111 cm from the beam line. The ID is designed to reconstruct tracks with a precision of $O(10 \mu \text{m})$ in the transverse plane, to reconstruct masses of unstable particles, to identify...
the primary vertex among multiple pile-up interactions and to find secondary vertices and displaced tracks to tag jets originating from b-quarks (b-tagging).

- The calorimeters: the electromagnetic calorimeter identifies and measures the electrons and photons. The hadronic calorimeter identifies jets formed by the hadronization of quarks.
- The muon system consists of a combination of drift tubes for precision hit measurements and resistive plate chambers for fast trigger information.

3. Online Trigger

The ATLAS trigger system [2] is aimed at reducing the initial collision rate of 40 MHz to a manageable data rate for permanent storage of around 200 Hz. This is achieved by a three-level system: a hardware-based Level 1 and a combined software-based Level 2 and Event Filter. A schematic overview of the ATLAS Trigger System is shown in Fig. 2.

The Level 1 (L1) trigger is a hardware trigger implemented in custom-built electronics. It uses coarse-granularity information from the muon chambers, calorimeters with an overall latency of less than 2.5 μs. It reduces the event rate to about 75 kHz.

The High Level Trigger (HLT) is a software based trigger, running on a large computer cluster. It is subdivided into the Level 2 (L2) trigger and Event Filter (EF), and is used to refine the L1 decision to select interesting events in order to reduce the 75 kHz input event rate to 200 Hz. L2 is seeded by L1 Regions of Interest (RoIs), which are $\eta - \phi$ regions of the detector associated with a L1 object (electron/photon, muon, and jet). RoIs are widely used in the L2 to restrict the amount of data read from the detector readout buffers while accessing the most important part of the event in full granularity. Within each RoI, L2 executes fast reconstruction algorithms that use detector information not available at L1. It has a nominal average processing time of 40 μs and reduces the output rate to around 3 kHz. This data is then passed to the EF where optimized offline algorithms are run in a custom online framework. The EF further reduces the event rate to below 200 Hz with an average processing time of roughly 4 seconds per event.

![Figure 1. The ATLAS Detector.](image1)

![Figure 2. Schematic overview of the trigger and data acquisition systems in ATLAS.](image2)
4. $b$-jet Trigger

The identification of jets originating from the hadronization of $b$-quarks ($b$-jets) is experimentally possible because of $b$-quark decay properties:

- the relatively long lifetime of $B$ hadrons (of the order of 1.5 ps) means they travel several millimeters before decaying, therefore producing an observable secondary vertex,
- the fragmentation process is hard and the $B$ hadron retains about 70% of the original $b$-quark momentum
- the $B$ hadron mass is relatively high ($>5$ GeV).

For these reasons, the larger impact parameter of the reconstructed tracks and the presence of a secondary vertex and its associated properties are all good discriminators between jets coming from the hadronization of $b$ quarks and jets coming from light quarks or gluons. Using these features of tracks near a jet we can tag those jets which are likely to have originated from $b$ quarks.

The $b$-jet selection is part of the trigger strategy of the ATLAS experiment and a set of dedicated triggers was put in place for the 2011 data-taking period. The reconstruction at HLT starts from the RoIs selected by a calorimeter-based jet trigger at L1. The L1 jet trigger is a fixed-size sliding window algorithm that sums energy in projective towers of size $\Delta\eta \times \Delta\Phi = 0.4 \times 0.4$.

At the HLT, the sequence of algorithms for $b$-jet triggers consists of two major steps: the calorimeter jet reconstruction and the $b$-jet identification. Three main features must be evaluated to perform the $b$-jet selection: reconstruct tracks of charged particles, measure the primary interaction vertex and estimate the $b$-tagging discriminant variables. This scheme is repeated at both L2 and EF.

The online track reconstruction starts at L2 where track candidates are fitted using a fast Kalman Filter algorithm. At EF, offline reconstruction software is used, slightly adapted to fulfil the trigger requirements. In order to reduce the processing time, the tracking in $b$-jet triggers is performed in a smaller RoI, half the size in $\eta$ and $\phi$ compared to the corresponding L1 jet RoI. A dedicated tuning optimized to efficiently reconstruct tracks with a transverse momentum larger than 1 GeV and with a transverse impact parameter up to 3 mm was used in 2011.

Figure 3. Signed transverse impact parameter significance of the tracks found by the EF. From [3].

Figure 4. Data/MC comparison of the transverse momenta of tracks at the Event Filter. From [3].
The online $b$-tagging is based on the transverse impact parameter of the these reconstructed tracks. The signed impact parameter significance is calculated for each track fulfilling the following selection criteria: minimum transverse momentum of 1 GeV/c, maximum $d_0$ of 1 mm and $z_0 - z_{PV}$ not exceeding 2 mm. The sign is positive if the track intersects the jet direction in the transverse plane projection. As a consequence, most of the tracks produced from decays of particles with a long lifetime, such as $B$ hadrons, have positive sign, as can be seen in Fig. 3. In the significance calculation, the transverse impact parameter ($d_0$) is corrected using the beamspot information and its uncertainty using the measured transverse width of the beamspot, 

$$\sigma = \sqrt{(\sigma_{d_0}^2 + \sigma_{BS}^2)}.$$ 

The jet probability method [4], also called JetProb, is the technique adopted in ATLAS for the online event selection in 2011. It computes the probability for a jet to originate from the primary vertex based on the transverse impact parameter significance of tracks near the jet. The probability is computed comparing the signed impact parameter significance with a resolution function $R$ for prompt tracks, which can be directly measured from experimental data, using the negative side of the signed impact parameter distribution in a light-jet dominated sample:

$$P_{\text{track}} = \int_{-\infty}^{-|d_0/\sigma_{d_0}|} R(x)dx.$$ 

Fig. 3-4 shows the signed transverse impact parameters and track $p_T$ at the EF. A good agreement between data and simulation is obtained. In particular, the $b$-jet enrichment in the positive tail of the transverse impact parameter distribution is evident.

The individual track probabilities are then combined in a single probability for the whole jet, which is uniform between zero and one for jets containing tracks compatible with the resolution function $R$ and is peaked at zero when highly-displaced tracks are reconstructed in the RoI. Only jets with JetProb values close to zero are selected, with the exact cut being dependent on the algorithm instance.

A key challenge in $b$-jet triggering is to run using lower $E_T$ thresholds while keeping the output rate low enough for stable data taking. For 2011, three working points were defined corresponding to roughly 90%, 70% and 50% $b$-jet efficiency (loose, medium and tight respectively) on a simulated top quark sample.

Figure 5 shows the distribution of the offline JetProb tagger (same algorithm as online but offline tracking) in data and a Pythia generated MC simulation of QCD events. The red, blue and green points show the distribution after different cuts at the value of the trigger JetProb. It can be seen that jets tagged with the $b$-jet trigger have an enhanced fraction of heavy flavour (since JetProb has high values for $b$-jets), using the Offline tagger as a reference.

5. $b$-jet trigger in 2012

For the 2012 run several improvements have been implemented in the $b$-jet triggers:

- **Secondary vertex reconstruction at the HLT**: in 2011 secondary vertex reconstruction was used only at EF but not used in the trigger selection. Now the secondary vertex reconstruction is used both at L2 and EF.

- **Tagging Method**: the default tagging method changed from JetProb to a likelihood ratio approach that exploits information from both track’s impact parameters and properties of secondary vertices.


Figure 5. Offline JetProb distribution in data and simulation and the same distribution in data when a b-jet requirement is added at the trigger level. From [3].

Figure 6. Resolution for the primary vertex Z position estimate as a function of the number of online tracks at L2 and EF. The z coordinate of the primary vertex (PV) is calculated by histogramming the $z_0$ of all selected tracks in the event and using a sliding window algorithm to select the largest local maximum. From [3].

- **Per-event primary vertex**: the knowledge of the primary vertex position is an essential ingredient in b-jets identification. A fast algorithm, that exploits a simple histogramming method based on a sliding window, has been found to be efficient in finding the true primary vertex position along the beam line with a resolution of about 120 $\mu$m (100 $\mu$m) at LVL2 (EF). There is no direct attempt in determining the primary vertex position in the transverse plane as a consequence of reconstructing tracks only in particular Rols (the primary vertex resolution is strongly correlated with the track multiplicity of the vertex which is relatively low in each Rol). For the 2012 run, a new algorithm has been added that selects all the tracks in the event to reconstruct the $z_0$ of the primary vertex. The resolution of the $z_0$ estimate of the primary vertex as a function of the track multiplicity is shown in Fig. 6. It shows that there is a 25% gain in resolution at EF when using more tracks in the event. Having a better resolution on the $z$ of the PV directly translates into better selection of the tracks originating from the primary vertex and therefore less spurious tracks in the b-jet.

6. Conclusion

ATLAS used online b-jet trigger for the full 5 fb$^{-1}$ of the 2011 LHC run. Various triggers have been designed for different event topologies and are now being used for physics analyses. Several improvements have been considered and among those the per-event primary vertex estimation has been implemented for the 2012 data-taking period. Future improvements will include exploiting the access to more tracks to estimate the vertex position also in the transverse plane which has a direct impact on the b-tagging performance.

References
[1] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.
[2] ATLAS Collaboration, Performance of the ATLAS Trigger System in 2010, submitted to EPJC, 2011. (http://arxiv.org/abs/1110.1530)
[3] ATLAS Collaboration, Public $b$-jet Trigger Plots for Collision Data  
   (https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BJetTriggerPublicResults)  
[4] ALEPH Collaboration, Physics Letters B, 313, 535 (1993)