Online b-tagging selection for the ATLAS experiment at the LHC

Andreas Kootz, Jenny Böhme, Peter Mättig, Anca Siebel, *Bergische Universität Wuppertal*
Mario Cervetto, Fabrizio Parodi, Carlo Schiavi, *Universita degli Studi di Genova*

***Abstract*— The second level trigger system (LVL2) of the ATLAS experiment at the CERN LHC is required to reduce the trigger rate from 100kHz to about 1kHz. The trigger decision has to be taken on average in 10ms.**

The ability of identifying b-quark jets at trigger level opens many interesting physics opportunities, especially in the top quark and higgs sectors. Additionally the acceptance for several supersymmetric channels is increased.

Here we present two methods of tagging b-quark jets at trigger level. One is based on impact parameters, the other one on secondary vertex reconstruction. The algorithms and their performances are described and compared.

***Index Terms*— ATLAS, trigger, b-tagging.**

I. INTRODUCTION

THE LHC will be a proton-proton collider with a center-of-mass energy of 14 TeV. It is expected to run for three years at low luminosity of $10^{33} cm^{-2} s^{-1}$ and later with its design luminosity of $10^{34} cm^{-2} s^{-1}$ The bunches will cross every 25 ns (40 MHz). The data size of one event is approximately 1-2 MB, making it impossible to record all events. The ATLAS trigger system is designed to select only interesting events.

The use of b-jet selection at the second level trigger and the event filter (LVL2/EF) would improve the flexibility of the High Level Trigger (HLT) [1] scheme and its physics performance. In particular, for topologies with several b-jets, the ability to separate b-jets from light quark or gluon jets would increase the acceptance for signal events and reduce the background (and hence the rate) for events containing b-jets that have already been selected by other triggers.

The study presented in this contribution describes b-jet selection methods for the LVL2 trigger based on information of the inner detector. In the first section the ATLAS trigger system is explained. In the second part the algorithms and there performances are discussed.

ak
October 20, 2004

II. THE ATLAS TRIGGER SYSTEM

The ATLAS trigger system is shown in figure 1. It consists of three levels. The task of the system is to reduce the initial rate down to approximately 100 Hz which can be finally recorded. The first level uses the calorimeters and the muon chambers. It identifies high energetic clusters in the calorimeter and muons which have a large transverse momentum. At level 1 the data rate will be reduced to a maximum of 100kHz in a maximal latency of $2.5\mu s$.

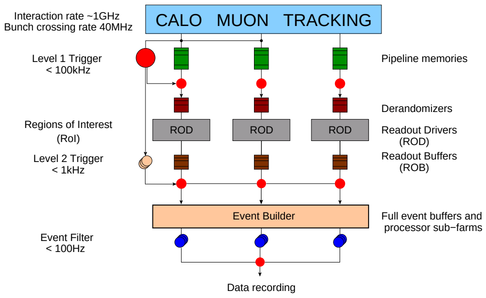

Fig. 1. The ATLAS trigger system is based on three levels. It reduces the data rate by a factor of approximately 4×10^5 [1].

The combination of level 2 trigger and the event filter are called the high level trigger (HLT). The second level trigger will reduce the rate to 1 kHz in an average time of 10 ms. Dedicated algorithms have been developed, which fulfill the high requirements on this trigger stage. LVL2 will use information from all subdetectors in a region of interest (RoI), predefined by the level 1 trigger. It is characterized by a direction and width in pseudorapidity $\eta = -ln\left(tan\left(\Theta/2\right)\right)$ and azimuthal angle ϕ.

Events accepted by LVL2 will be build up by the event builder and send to the event filter. The EF partially uses offline code to fully reconstruct the event in order to decrease the data rate to the finally acceptable rate of 100 Hz. The decision time for the event filter is in the order of seconds.

A. Jet Trigger

The ATLAS trigger system is based on selection procedures for jets, leptons, missing energy etcetera. The algorithms described in this study make use of the long lifetime of B-hadrons (see III). This implies that only the jet triggers are of interest for this study. The energy thresholds of the jet triggers depend on the trigger level. Table I shows the different threshold for events with 1, 2, 3 and 4 jets.

A figure of merit of the b-tagging at the second level trigger is derived from simulation studies of events with two bottom quarks. One possible physics channel in which online b-tagging can improve the trigger performance is the fully hadronic decay mode a $t\bar{t}$ pair. The top quark decays almost always into a b

This work was supported by the ATLAS High Level Trigger group

TABLE I

MINIMUM JET E_T FOR DIFFERENT JET MULTIPLICITIES

	LVL1	LVL2
1 Jet with	$>$ 200 GeV	$>$ 400 GeV
2 Jets with	$>$ 170 GeV	$>$ 350 GeV
3 Jets with	$>$ 90 GeV	$>$ 165 GeV
4 Jets with	$>$ 65 GeV	$>$ 110 GeV

quark and a W boson. In the fully hadronic decay mode both W bosons from the t and $\bar{t}$ decay into a $q\bar{q}$ pair. This leads to a total of 6 jets of which two are b-jets. Another interesting physics channel is the decay of a light Higgs boson into a $b\bar{b}$ pair. The knowledge of a jet being a b-tagged jet can reduce the amount of background events (mostly QCD multijet production, W+jet production) and thus increase the efficiency and purity for the signal events.

Figures 2 and 3 show the efficiency, purity and efficiency times purity for tagging $t\bar{t} \rightarrow WbWb \rightarrow jjbjjb$ of the 4 jet trigger as a function of the second level trigger threshold. In Fig. 2 no b-tag information was assumed, while in figure 3 one tagged b-jet (with offline performance: 50% b-efficiency, rejection factor against light jets: 150, rejection factor against c-type jets: 10) was required. The distributions are normalized to the 4 jet trigger with a 110 GeV threshold without b-tag information. These plots show that a reduction of the second level trigger threshold to approximately the LVL1 value would increase efficiency and purity. Also shown is the number of accepted events. Figure 2 shows an increase of a factor 4 for a LVL2 4-jet threshold of 60 GeV. This would result in a four times bigger rate coming from that trigger. Requiring one b-tag reduces the number of triggered events to half times the original rate. The loss in the total rate leads to a gain in efficiency times purity.

The efficiency for tagging a $t\bar{t}$ pair with one of the jet triggers is in total 1.5-2 % with a purity of 0.01%. If b-tagging is required (with offline performance) the efficiency is increased to 5 (15) % when requiring 2 (1) b-tagged jets. At the same time the purity is increased to 22.5 (1.1) %.

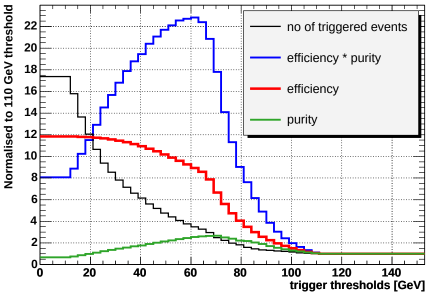

Fig. 2. Performance of the 4 jet trigger menu without b-tag information for triggering $t\bar{t} \rightarrow WbWb \rightarrow jjbjjb$ [3]

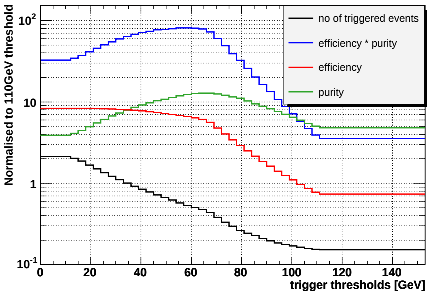

Fig. 3. Performance of the 4 jet trigger menu when requiring 1 b-tagged jet for triggering $t\bar{t} \rightarrow WbWb \rightarrow jjbjjb$

III. B-TAGGING ALGORITHMS

Bottom-quark jets can be identified with several methods. The existence of a soft muon inside a jet is an indicator for a b-quark jet. Another property of B hadrons is their relatively large life time of approximately $1.5 \times 10^{-12}s$. This means that a B hadron can fly a few mm before it decays leading to a secondary vertex. Two different algorithms for b-tagging make use of this large lifetime. One uses the identification of the displaced vertex. Tracks coming from a secondary vertex often have a large tranverse impact parameter giving a further possibility for tagging b-quark jets. Figure 4 shows the impact parameter significance (see III-A) for u- and b-quark jets. It can be seen that b-jets tend to have a bigger impact parameter than u-jets.

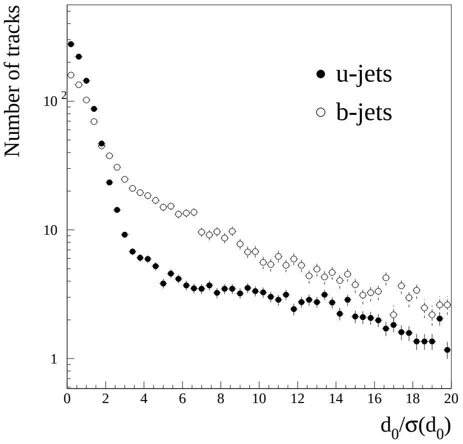

Fig. 4. Impact parameter significance for u-jets and b-jets reconstructed with SiTrack. Tracks in b-jets have more often a larger value than tracks in u-jets [4].

In the ATLAS experiment both lifetime based algorithms, the impact parameter and the secondary vertex based algorithm, are examined for their use in the second level trigger. Both described in this section.

A. b-jet selection using impact parameter

The impact parameter b-tag algorithm is based on the SiTrack tracking algorithm [3] for the ATLAS second level trigger. SiTrack uses triplets of space points in the pixel and silicon strip detector SCT to build tracks. It is applied in the b-tagging algorithm because of its good impact parameter resolution [4].

In an older version of SiTrack - PixTrig [2] - only the pixel detector was used. The geometry of the pixel detector with respect to the initial layout was changed. Especially the inner radius was increased from 4 to 5 cm leading to a reduction in the impact parameter resolution (see Fig. 5). Due to the larger lever arm coming from the use of the strip detector in addition to the pixel detector the resolution can be reduced to the old value.

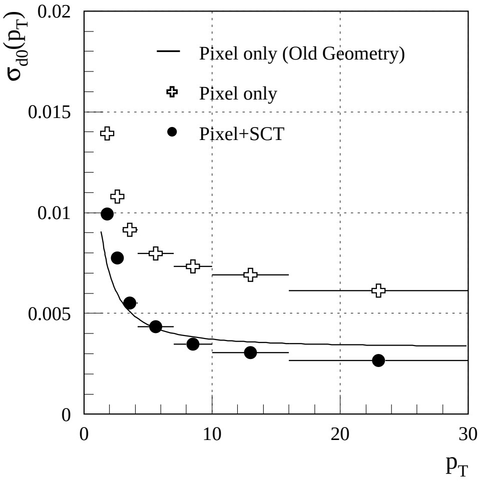

Fig. 5. Impact parameter resolution of SiTrack The line shows the resolution reached with the old geometry in PixTrig. The open crosses show the resolution using SiTrack with the new geometry and using only the pixel detector. The improvement in resolution is shown by the filled circles showing the impact parameter resolution using SiTrack with the new geometry but using the pixel and the SCT detector [4].

For studying the impact parameter based algorithm a sample was used in which a Higgs boson of 120 GeV was produced in association with a W. The Higgs decayed in either two b-jets or into 2 u-jets representing signal and background. The region of interest from the first level trigger was simulated selecting a region $\Delta\phi \times \Delta\eta = 0.4 \times 0.4$ centered around the direction of the quark coming from the Higgs decay.

The first step of the algorithm is the track reconstruction made by SiTrack inside the jet RoI. In the next step the signed transverse impact parameter significance $S = d_0/\sigma(d_0)$ is calculated. The sign of the impact parameter is positive if the vector product of the vector pointing from the primary vertex to the point of closest approach of the track and the vector pointing from the primary to the secondary vertex is positive. Tracks coming from the primary vertex have the same probability for a positive and a negative sign while tracks from a displaced vertex have mostly positive sign. The error on the impact parameter $\sigma(d_0)$ was parameterized with simulated events and is a function of track p_T.

In the next step the b-jet estimator is built. It makes use of the likelihood-ratio method. This is done by calculating the ratio of the probability densities for each track to come from a b-jet or a u-jet: $W_i = f_b(S_i)/f_u(S_i)$. With $W = \prod_i W_i$, the final discriminative variable $X = W/(1 + W)$.

Figure 6 shows the distribution of the final discriminative variable X. Its value peaks at 0 for u-type jets and it has a peak at 1 for b-type jets.

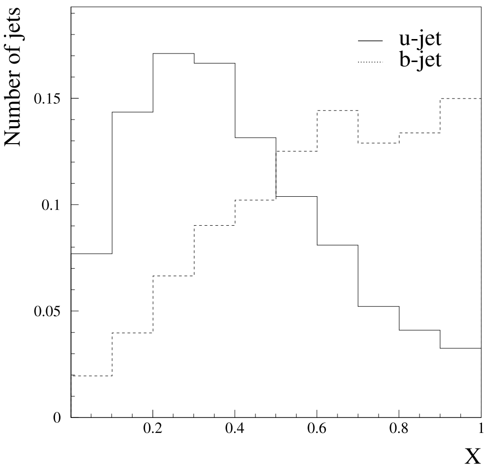

Fig. 6. Distribution of the discriminative variable X for b-jets (full line) and u-jets (dashed line) [4]

The performance of the impact parameter b-tag algorithm is shown in figure 7. It the rejection factor for u-type jets versus the efficiency for b-jets for the case of a 120 GeV Higgs decaying into two u or b-quarks.

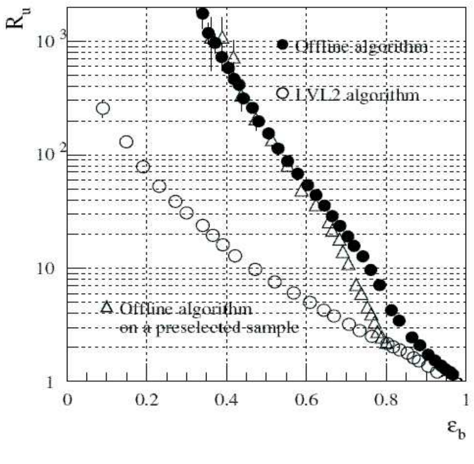

Fig. 7. Comparison between the online impact parameter and the offline b-tag. Shown is the rejection factor versus u-jets versus the efficiency for b-jets for jets coming from the decay of a Higgs boson with a mass of 120 GeV [4].

Table II shows the rejection factor against u-type jets of the impact parameter b-tagging algorithm for different efficiencies at low luminosity. In the central region of the detector the rejection is better than in the forward region. The dependence on the efficiency for b-type jets is also shown. The upper line

TABLE II

REJECTION RATE OF IMPACT PARAMETER ALGORITHM AGAINST U-JETS FOR DIFFERENT EFFICIENCIES - 60% (TOP), 70% (MIDDLE) AND 80% (BOTTOM) AT LOW LUMINOSITY.

	$40\,GeV < E_t$ $< 70\,GeV < 100\,GeV$	$70\,GeV < E_t$	$E_t > 100\,GeV$
$\lvert\eta\rvert < 1.5$	5.9 ± 0.4	5.1 ± 0.6	4.8 ± 0.7
	3.6 ± 0.2	3.9 ± 0.4	3.1 ± 0.4
	2.3 ± 0.1	2.8 ± 0.3	2.4 ± 0.3
$\lvert\eta\rvert > 1.5$	3.7 ± 0.4	4.9 ± 1.0	3.0 ± 0.8
	2.6 ± 0.2	2.9 ± 0.5	2.6 ± 0.6
	1.5 ± 0.1	1.6 ± 0.2	1.7 ± 0.4

shows the rejection for 60 % efficiency, while the middle and bottom show the rejections for efficiencies of 70 % and 80 %.

The processing time of the impact parameter based b-tag algorithm at low luminosity is compatible with the second level trigger latency of at most 10 ms per RoI in average. For b-jet events processing times of approximately 1.5 ms for low and 2.5 ms for high luminosity have been achieved [3].

B. *b-jet selection using secondary vertices*

The possibility of identifying b-quark jets by the existence of a secondary vertex was examined with a fast vertex algorithm using the perigee parameterization for the tracks [5]. This algorithm is implemented in the ATLAS software in a package called TrigWuppVertex. The input to this method are tracks coming from either SiTrack (see III-A) or from any other tracking algorithm like for example IDScan.

The tracks are described by their perigee parameters ϵ, z_p, θ, ϕ and ρ at the point of closest approach P with respect to the origin. ϵ is the signed distance of P to the origin in the $R-\phi$ plane. Its sign is positive if the origin is on the left side of the tracks trajectory. z_p gives the z-coordinate of P and θ gives the angle of the track at P with respect to the z-axis. The parameters ϕ and ρ describe the direction of the track in the $R-\phi$ plane with respect to the x-axis and the signed curvature of the track. The absolute value of the curvature $|\rho| = 1/R$ (R = bending radius of the track). Its sign is positive if the charge of the track is negative and vice versa.

The algorithm can be separated into three parts. In the first part the track-samples are defined which will be used to search for the primary and secondary vertex. This is done mainly using the transverse impact parameters d_0 of the tracks. In the second part the algorithm searches for the primary vertex of the event and in the last part the b-tag decision is created.

For the primary vertex only tracks with a small impact parameter are used. while for the secondary vertex search only tracks with a large impact parameter are used. The minimum required impact parameter depends on the tracks p_T. The requirements are set up in a way that tracks cannot be used for both vertex searches.

In the next step the three dimensional primary vertex is fitted. This is done by an iterative algorithm [5]. The algorithm fits a helix to all tracks which are consistent with an assumed starting point. The starting point is in the first iteration the origin in the coordinate system. This is a good approximation because the primary vertex is near the beam. We assume that the track parameters are linearly dependent on small variations of the vertex and of the track momenta. Additionally we assume that θ, ϕ and ρ do not change in the vicinity of the expected vertex. With these assumptions the total $\chi^2 = \sum_i \Delta q_i^T W_i \Delta q_i$ is calculated, with q_i representing the track parameters and W_i being the inverse of the covariance matrix. The minimization of χ^2 with respect to the estimated vertex position and to the track momenta gives two equations from which the vertex can be calculated. For the next iteration step this vertex position taken as the starting point. If the new χ^2 is smaller than the smallest χ^2 in previous iterations the new vertex is accepted as the reconstructed vertex. These steps are repeated until the change of χ^2 gets smaller than a preset value or the number of iterations exceeds a predefined value. It is possible to delete a track from the subset of tracks if its χ^2 is too high. The decision whether one track should be deleted is based on a cut on the total χ^2-probability of the vertex fit.

If a primary vertex was reconstructed the same procedure is applied for searching the secondary vertex.

In the last step the b-tag decision is created based on several variables. The algorithm combines probabilities on all variables to one final value on which a simple cut is applied.

In section II the region of interest principle is described. The b-tag algorithms would be called in the experiment only for jet-RoIs. The number of tracks in a jet is used as well as the number of tracks which fit into the secondary vertex. The last variable is the invariant mass of all particles fitting into the secondary vertex. Figure 8 shows the distribution of the invariant vertex mass for light and b-quark jets.

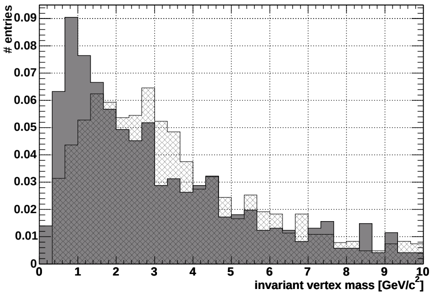

Fig. 8. Invariant Mass of secondary vertex from b-jets (full histogram) and light quark jets (hatched histogram)

Figure 9 shows the distributions of the final cut variable for light quark and b-quark jets. The peak at low values comes from events in which no secondary vertex was found.

Figure 10 shows the actual performance of the algorithm when using smeared generated tracks instead of reconstructed ones. A charged particle with a transverse momentum bigger than 1 GeV is considered as a generated track if there are at least three hits in the pixeldetector associated to this particle.

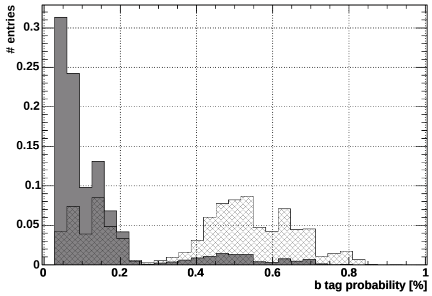

Fig. 9. Final btag probability variable shown for b-jets (hatched histogram) and light quark jets (full histogram)

The track parameters of these particles have been smeared with a gaussian distribution. The width of this distribution was set to the resolution of the tracking algorithms. Shown in figure 10 is the rejection factor against u,d,s and c-quark jets versus the b-tagging efficiency.

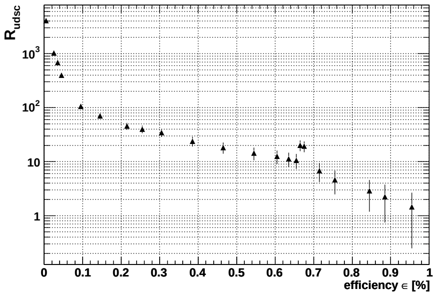

Fig. 10. Performance of the secondary vertex based algorithm. Shown is the rejection factor against u,d,s and c-quark jets versus the b-tagging efficiency.

Another aspect of the algorithm is the average time which is needed. The total second level trigger must decide within 10 ms (see II). This implies that the b-tag algorithm alone (without the tracking algorithm) should not need longer than approximately 1 ms on average. With this number the b-tag algorithm alone should not need longer than approximately 1 ms on average. Figure 11 shows the execution time on a PC with a Pentium III with 933MHz. On this machine the execution time is on average 0.4 ms which is fast enough.

IV. CONCLUSION

Currently the ATLAS high level trigger uses high energy thresholds for jets. The acceptance for events with b-quarks jets can be increased by a b-tag algorithm. Additionally such an algorithm would increase the trigger efficiency for events containing b-jets while retaining the total data rate. This can be achieved by a reduction of the jet trigger thresholds on LVL1 respectively LVL2. Reduction of the LVL1 thresholds would increase the total rate of that level but also gives the opportunity to be much more sensitive on events with multi b-jets. After LVL2 the total rate should not be increased at all.

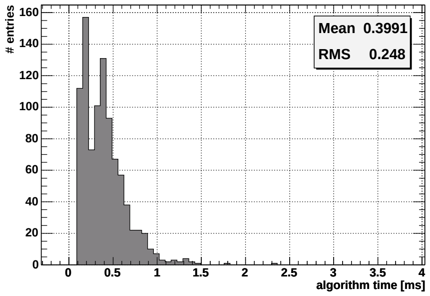

Fig. 11. Time needed for the secondary vertex based b-tag algorithm. The algorithm has a mean execution time of about 0.4 ms.

Two algorithms have been presented. The first one is based on the tranverse impact parameter of the tracks d_0. It makes use of the likelihood-ratio method to calculate a discriminative variable. This algorithm is using tracks reconstructed from SiTrack. It has a rejection factor for u-quark jets of the order of 5 for a b-tag efficiency of 60 %. At 80 % its rejection factor has a value of approximately 2. The second algorithm is based on secondary vertex reconstruction. While the first one was tested with reconstructed tracks coming from SiTrack, this one was tested with smeared generated tracks. Tests with tracks from SiTrack are under investigation. The rejection factor of this algorithm is of the order of 10 at 60% efficiency and it has a value of 3-4 at 80%. The performance with real tracks should decrease the rejection factor at a given efficiency due to fake tracks and other facts like slightly different resolutions for the track parameters and a probably smaller tracking efficiency.

The processing time for both algorithms, which is in average less than 1 ms is compatible with the requirements of the second level trigger.

ACKNOWLEDGMENT

The authors would like to thank the ATLAS High Level trigger community for there support.

REFERENCES

[1] ATLAS HLT/DAQ/DCS Group, *ATLAS High-Level Trigger, Data Acquisition and Controls Technical Design Report*, CERN/LHCC/2003-022.

[2] ATLAS HLT/DAQ/DCS Group, *ATLAS HLT, DAQ and DCS Technical Proposal*, CERN/LHCC/2000-17.

[3] M. Cervetto, F. Parodi, P. Morettini and C. Schiavi, *SiTrack: a LVL2 track reconstruction algorithm based on Silicon detectors*, ATL-COM-DAQ-2000-25 (2003)

[4] M. Cervetto, F. Parodi, P. Morettini and C. Schiavi, *b-tagging Event Selection for the ATLAS High Level Trigger: an update*, ATL-COM-DAQ-2000-34 (2003).

[5] P.Billoir, S.Qian, *Fast vertex fitting with a local parametrization of tracks*, NIM A311 (1992) 139-150.