1. Introduction

The start of proton-proton collisions at the Large Hadron Collider (LHC) in 2010 opened up a new era of exploration at the high energy frontier. With proton-proton collisions at $\sqrt{s} = 7$ TeV and instantaneous luminosities higher than $10^{33} \text{cm}^{-2}\text{s}^{-1}$ the LHC is a real discovery machine, in particular extending sensitivity for new physics into mass scales above a TeV and set to dominate the high energy physics scene for years to come. During 2011 the LHC definitely entered real physics running with almost routine delivery of integrated luminosities larger than 50 pb$^{-1}$ per day and yearly total of more than 5 fb$^{-1}$.

Both in the Standard Model and many of its possible extension, such as Supersymmetry $[1]-[7]$, the third generation of quarks, i.e. the top and bottom ($b$) quarks, play an important role due to their relatively large mass. The $b$-quark is also important as one of the main decay channels for the proposed Higgs boson and top quark production is one of the major backgrounds to many new physics physics searches.

2. The ATLAS $b$-Jet Trigger

The identification of jets originating from $b$-quarks ($b$-jets) is a central piece in the rich physics program of the ATLAS detector at the LHC. The large (approximately 40 m long and 25 m in diameter) multi-purpose ATLAS detector $[8]$ has a hermetic design with a large muon spectrometer surrounding electromagnetic- and hadronic calorimeters and an inner detector using three different technologies to track charged particles up to $|\eta| = 2.5$. Crucial for $b$-jet identification, the innermost pixel detector provides three space point measurements with $50 \times 400 \mu\text{m}$ pixels, where the innermost layer is located only 5 cm from the beam. Tracking is extended through the large area silicon micro-strip detector with four double-layered sensors (80 $\mu\text{m}$ pitch) and the straw tube transition radiation tracker up to a radius of about 111 cm.

A challenge for the LHC experiments is the large interaction rate and multiplicities. The rate of events collected for further offline analysis needs to be reduced from the initial proton-proton bunch collision rate of 40 MHz, with more than 10 interactions per bunch-crossing, to $< 400$ Hz while keeping the interesting events for further study. The ATLAS trigger system $[9]$ is a 3-tiered structure built around an initial custom made hardware trigger, Level 1 (LVL1), and two software-based levels collectively called the High Level Trigger (HLT), see Fig. 1. The LVL1 trigger builds trigger decisions using fast analog information from hits in the three-layered muon spectrometer and energy deposits in the calorimeter cells to identify signatures of high-$p_T$ muons, electrons/photons, $\tau$-leptons and jets. The ATLAS trigger system relies to a large extent on the so called Regions of Interest (ROIs) which are regions in the detector identified in the LVL1 trigger associated to a specific type of physics.
of signature. These ROIs later form the basis for a more detailed reconstruction at the HLT, effectively restricting the amount of data needed to be shipped from the detector readout buffers. Since the $b$-jet trigger relies on information from the inner detector, the identification of $b$-jets can only start at the HLT. This makes the LVL1 jet reconstruction particularly important and an integral part of any $b$-tagging at the trigger level as it provides the seed ROI in which the inner detector tracking algorithms and subsequent $b$-tagging algorithms are executed. The LVL1 jet trigger is a fixed-size sliding window algorithm that sums energy in projective towers of size $\Delta \eta \times \Delta \phi = 0.4 \times 0.4$. The maximum event rate accepted at LVL1 is $\sim 75$ kHz and the detector readout buffers need to receive the trigger decision no later than approximately 2.5 $\mu$s after the relevant bunch crossing.

The HLT is a farm of mostly commercial computers and networking technology providing a fully configurable two-tiered trigger system seeded by the ROIs. The Level 2 (LVL2) trigger accesses the full detector granularity and precision from the muon system, calorimeters and inner detector within the ROI and is optimized for speed to meet the maximum execution time of $\sim 40$ ms. The HLT manages and steers the event during the LVL2 algorithm sequence execution and assigns data from accepted events to the final event building step. With an event building rate of about 3.5 kHz and a latency up to several seconds the Event Filter can run algorithms which are nearly identical to those used in offline event reconstruction and can limit the final output rate to below 400 Hz.

2.1. The $b$-Jet Trigger Menu

The $b$-jet trigger was actively selecting events during 2011. It consists not only of physics triggers to select signal events but also special triggers for monitoring and calibration purposes, including trigger efficiency measurements. The physics triggers were designed to cover a wide range of generic signals; a multi-jet trigger with one or more $b$-tags and a dijet trigger with two or more $b$-tagged jets. Typical rates at each trigger level can be seen in Fig. 2 [11].

2.2. The $b$-Tagging Algorithm

The most natural choice in building a discriminating variable between $b$- and light jets\(^1\) is to exploit the transverse impact parameter, $d_0$, defined as the distance of closest approach between the particle track and the primary vertex. The finite lifetime of $B$ hadrons ($\tau \approx 1.6$ ps, $c\tau \approx 490$ $\mu$m) allow them to typically travel a few mm before decaying. This, together with their relatively large mass produce tracks with an average large impact parameter compared to tracks originating from light jets (see Fig. 3). Normally also the measured uncertainty $\sigma(d_0)$ is used to define the impact parameter significance, $S(d_0)=d_0/\sigma(d_0)$, to better judge the likelihood of the track displacement.

In 2011 the so-called JetProb algorithm was used to select $b$-jets in ATLAS at both LVL2 and Event Filter. This technique was first developed by the ALEPH collaboration [11] and then adopted in experiments at the Large Electron Positron Collider and the Fermilab Tevatron. The JetProb method computes the probability for a jet to originate from the primary vertex using the signed transverse impact parameter significance of tracks associated with the jet. The sign of the impact parameter significance is determined from whether or not the track crosses the jet axis in front of the primary vertex (positive) or behind it (negative). Most of the tracks produced from decays of particles with long lifetime, such as a $B$ hadron, are positive. Due to finite impact parameter resolution, tracks in light jets, even if they originate from the primary vertex, may seem displaced but would have both signs roughly with equal probabilities. Figure 4 shows a comparison of the impact parameter significance for tracks associated to jets classified as $b$-, $c$- or light jets compared to that measured in data [10]. Each track

\(^1\)Light jets are defined here as jets originating from quarks from the two first generations or a gluon.
is assigned a probability, \( P \),

\[
P = \int_{-\infty}^{-|d_0/\sigma(d_0)|} R, \tag{1}
\]

where \( R \) is the parameterization of the negative impact parameter resolution for tracks originating from the primary vertex. The resolution function can be determined from experimental data using the negative side of the signed impact parameter distribution, assuming the contribution from heavy-flavor particles is negligible. The individual track probabilities, \( P_i \), are then combined into a per-jet quantity, \( P_{\text{jet}} \),

\[
P_{\text{jet}} = P_0 \sum_{i=0}^{N_{\text{tracks}}} \frac{(-\ln P_0)^i}{i!} \tag{2}
\]

where \( P_0 = \prod_i P_i \). With the assumption that no long-lived particles contribute to the selected tracks, \( P_{\text{jet}} \) has an expected uniform distribution between zero and one while tracks from jets with a long-lived particle decay tend to give \( P_{\text{jet}} \) closer to zero. This \( b \)-tagging algorithm is considered robust as it relies only on the knowledge of the negative transverse impact parameter distribution of prompt tracks in multi-jet events, rather easily derived from data.

More sophisticated algorithms, such as explicit reconstruction of the secondary decay vertex, show promising improvements but are not yet used to actively select events at the trigger level.

### 2.3. Primary Vertex and Beam Spot

The primary vertex position is a vital ingredient for good \( b \)-tagging performance. A measurement of the primary vertex position depends strongly on the track multiplicity at the vertex. When the \( b \)-tagging algorithm is executed only tracks within the single ROI are available which degrades the primary vertex resolution in the transverse direction. Note that in the longitudinal direction the resolution is less critical for the JetProb algorithm as the longitudinal impact parameter is only used to reject tracks from additional pile-up interactions.

The solution is to exploit the online measurement of the relatively small beam spot every few minutes during data taking. Using special prescaled triggers, the per-event vertex position is integrated to measure the average position and shape (width and tilt) of the beam spot in intervals as short as a few minutes. The width of the beam spot (typically around 25 \( \mu \)m at the end of 2011) is estimated using a split vertex method [12] online that exploits the measured distance between two fitted vertices, each reconstructed with half of the tracks used in the original vertex fit. Figure 5 shows an example of the distribution of primary vertices used in the extraction of the beamspot parameters [12]. The transverse beam spot position and tilt in the longitudinal direction is used to correct the track coordinates and the measured transverse width, \( \sigma(BS) \), to correct the track impact parameter uncertainty used in Eq. (1) \[ \sigma'(d_0) = \sqrt{\sigma(d_0)^2 + \sigma(BS)^2} \]. The measured beam spot parameters are continuously monitored and updated whenever a significant change is detected.

### 3. Bias On Offline \( b \)-Tagging

One important aspect for physics analyses is to understand potential biases arising from trigger inefficiencies. For the \( b \)-jet trigger, the high rejection required together with the algorithm choice induces a non-negligible bias with respect to the offline \( b \)-tagging algorithms. Figure 6 shows the bias on the offline JetProb weight distribution from three different operat-
Figure 6: The measured offline JetProb distribution for jets $b$-tagged at the HLT at three different operating points.

4. Conclusions and Outlook

The $b$-jet trigger in ATLAS has been commissioned and actively rejecting events during 2011. Exploiting $b$-tagging information at the trigger level allows for the lowering of trigger thresholds for jets and missing energy. This leads to an increased selection efficiency for final states including $b$-jets, something which is used to improve the sensitivity in many physics analyses in progress.

To use the $b$-jet triggers together with an offline $b$-tagging requirement in physics analyses detailed measurements of the combined trigger and offline $b$-tagging efficiency and mistag rate are needed. This will properly take into account correlations between the trigger and offline requirements and correct for aspects which are not accurately described by the simulation of the trigger and the offline reconstruction.

For 2012 many improvements are expected to be deployed to further improve the $b$-jet trigger performance. New $b$-tagging algorithms based on explicit reconstruction of secondary vertices will be used to improve light jet rejection. The improved jet measurements at the HLT compared with LVL1 will be used to refine the ROI direction and reduce the load on the data acquisition. Studies comparing new primary vertex algorithms at the trigger level may allow the usage of the an event-based primary vertex instead of the beamspot.

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