

Trigger selection software for beauty physics in ATLAS

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Abstract. The unprecedented rate of beauty production at the LHC will yield high statistics for measurements such as CP violation and B_s oscillations and will provide the opportunity to search for and study very rare decays, such as $B \rightarrow \mu\mu$. The trigger is a vital component for this work and must select events containing the channels of interest from a huge background in order to reduce the 40 MHz bunch crossing rate down to 100-200 Hz for recording, of which only a part will be assigned to B-physics. Requiring a single or di-muon trigger provides the first stage of the B-trigger selection. Track reconstruction is then performed in the Inner Detector, either using the full detector, at initial luminosity, or within Regions of Interest identified by the first level trigger at higher luminosities. Based on invariant mass, combinations of tracks are selected as likely decay products of the channel of interest and secondary vertex fits are performed. Events are selected based on properties such as fit quality and invariant mass. We present fast vertex reconstruction algorithms suitable for use in the second level trigger and event filter (level three). We discuss the selection software and the flexible trigger strategies that will enable ATLAS to pursue a B-physics programme from the first running at a luminosity of about $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ through to the design luminosity running at $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

1. Introduction

ATLAS is one of two general-purpose experiments currently being built at the Large Hadron Collider (LHC) in CERN [1]. The LHC is a proton-proton machine with a centre-of-mass energy $\sqrt{s} = 14$ TeV scheduled to start up in 2008. From 2008 an initial "low-luminosity" running period is foreseen with a luminosity starting at about $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ and rising to $2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. After that the LHC will run at the design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

ATLAS has a three level trigger system [2] which reduces the initial 40 MHz rate to about 200 Hz of events to be recorded. The first level trigger (LVL1) is a hardware-based trigger which makes a fast decision (with latency $2.5 \mu\text{s}$) as to which events are of interest for further processing. The LVL1 reduces the trigger rate to below 75 kHz and identifies regions of the detector ("Regions of Interest", RoIs) which contain interesting signals (e.g. electrons, muons or jets). The LVL1 RoIs are used in the subsequent trigger levels to guide the reconstruction.

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The High Level Trigger (HLT) is software-based and consists of two levels. At Level 2 (LVL2) the full granularity of the detector is used to confirm the LVL1 results and then to combine information from various sub-detectors within the LVL1 RoIs. This stage of event selection employs fast reconstruction algorithms and has a time budget of about 40 ms. The LVL2 output rate is about 1-2 kHz. Finally at the Event Filter (EF), “offline-like” algorithms are used along with the full alignment and calibration information to produce a final decision about whether or not an event is accepted. With an execution time of about 4 s, the rate is reduced to 200 Hz.

The ATLAS has a well-defined B-physics programme which includes CP violation (in $B_d^0 \rightarrow J/\psi K_S^0$ and $B_s^0 \rightarrow J/\psi \phi$, B_s^0 oscillations (using the $B_s^0 \rightarrow D_s \pi/a_1$ channels), and a search for rare decays (e.g. $B_{s,d}^0 \rightarrow \mu^+ \mu^- (X)$ and radiative decays $B_s^0 \rightarrow \phi \gamma$, $B_d^0 \rightarrow K^* \gamma$). Since at the LHC design energy the cross-section for $b\bar{b}$ is relatively high (1% of pp collisions will contain a $b\bar{b}$ pair) the challenge for the B-physics trigger is to select the events of interest from a background of non- $b\bar{b}$ and other $b\bar{b}$ events. ATLAS is a general-purpose experiment with an emphasis on high- p_T physics and as such has only a limited bandwidth (about 5-10 %) for the B-physics events. Thus accommodating the B-physics programme requires a highly selective trigger with exclusive or semi-inclusive reconstruction of decays.

This paper discusses flexible luminosity-dependent strategies for the ATLAS B-physics trigger and focusses on software tools for B-physics event selection, in particular, a fast vertex fitting tool specially developed for the LVL2 B-physics trigger.

2. ATLAS B-physics trigger strategy

2.1. LVL1 trigger

Triggering B-physics events in ATLAS is initiated by the LVL1 muon trigger. Although the branching ratio for $b \rightarrow \mu$ is only 10 %, this channel provides a clean signature already at the LVL1 and allows for flavour tagging. The main background is due to real muons from π and K in-flight decays. This background is reduced at the LVL2 trigger by matching track parameters of muon candidates with those of tracks reconstructed in Inner Detector.

For initial running at about $10^{31} \text{cm}^{-2} \text{s}^{-1}$ events will be triggered by a single LVL1 muon candidate with a p_T threshold of about 4 GeV rising to 6-8 GeV at a luminosity of $2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$. At design luminosity only a di-muon LVL1 trigger will be used. This strategy keeps the trigger rate within allocated budget and provides sufficient bandwidth for rare B decays with two muons in the final state ($B_{s,d}^0 \rightarrow \mu^+ \mu^- (X)$).

At lower luminosities ($< 2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$) additional LVL1 RoIs will be used to facilitate the HLT reconstruction of hadronic (using Jet RoI) or radiative (using electromagnetic (EM) RoI) decays of the other b quark.

2.2. High Level Trigger

At LVL2 the muon candidates identified at LVL1 will be confirmed firstly in the muon detector (using tracking based on the precision muon chambers) and then by matching muon tracks with tracks reconstructed in the Inner Detector (ID). The track reconstruction in the ID and Muon detector uses special-purpose fast algorithms customized for the use at LVL2 [3], [4], [5].

During low-luminosity running a single muon trigger will be used at LVL1 with a search for additional features at the HLT. The trigger efficiency for di-muon events can be improved by searching for a second muon below the LVL1 threshold in an enlarged RoI around the confirmed LVL1 muon. This search starts in the ID followed by an extrapolation of the reconstructed tracks into the muon system. This approach has been successfully demonstrated for the $J/\psi \rightarrow \mu^+ \mu^-$ trigger [5].

At lower luminosities additional LVL1 RoIs such as jet or EM will be used by the HLT to select channels containing a $J/\psi \rightarrow e^+ e^-$ or exclusive B-hadron decays. In the case of $J/\psi \rightarrow e^+ e^-$

an EM RoI with E_T threshold of 2 GeV will be used in addition to the muon RoI that triggered the event. As for the di-muon final state, the efficiency for J/ψ can be increased by searching for a second electron, below the LVL1 threshold, in an enlarged RoI. Electron candidates are identified using information from the Transition Radiation Tracker (TRT) and Calorimeter.

In order to increase the trigger efficiency for hadronic and electromagnetic B-decay channels during initial luminosity running an approach based on LVL2 track reconstruction within the entire volume of the Inner Detector ("Fullscan") will be used for events with a single muon trigger [6].

After track reconstruction at the LVL2, event selection is accomplished by a combinatorial search for suitable combinations of tracks, e.g. opposite charge-sign track pairs for $J/\psi \rightarrow \mu^+\mu^-$ or $J/\psi \rightarrow e^+e^-$ or track triplets for $D_s \rightarrow \phi(KK)\pi$. At this stage the vertex fitting algorithms are employed and cuts on invariant mass and vertex fit quality are applied.

The event selection is then refined at the Event Filter where the lower event rates allow the use of more sophisticated offline algorithms to reconstruct the tracks (within RoIs or using the "Fullscan" approach) and find B-decay vertices [7].

3. Example: $D_s \rightarrow \phi(KK)\pi$ selection at low luminosity

This event selection is based on tracks reconstructed within a Jet RoI. Pairs of opposite sign tracks passing a $\phi(K^+K^-)$ mass cut are selected. This selection is followed by a search for a third track to form a triplet $K^+K^-\pi$. A $3\text{-}\sigma$ cut on invariant mass of track combinations is applied for all vertex candidates. Note that, for the moment, vertexing is employed only at the LVL2 stage.

The trigger rates after various steps of trigger selection are shown in Table 1 for the low luminosity regime with $L = 10^{33} \text{cm}^{-2} \text{s}^{-1}$.

Table 1. Trigger rates for $D_s \rightarrow \phi(KK)\pi$ selection at $L = 10^{33} \text{cm}^{-2} \text{s}^{-1}$.

Step	LVL1 single μ	LVL2 μ confirmation	LVL2 $D_s \rightarrow \phi\pi$
Rate, kHz	20	5	0.2

4. LVL2 algorithms for B-physics event selection

The selection of B-physics events benefits from fast and efficient track reconstruction algorithms developed for the LVL2 trigger. They include fast pattern recognition algorithms for silicon detectors (Pixel and SCT) with Kalman filter-based track fit [3]. Track reconstruction and particle ID in the TRT is provided by either a stand-alone pattern recognition algorithm or a fast track following algorithm [4] which uses tracks found in the silicon detectors as input. In addition, the algorithm [4] provides a full (i.e. silicon+TRT) track refit thus significantly improving accuracy of track momentum estimation.

The LVL2 Muon tracking features a stand-alone muon reconstruction algorithm, which confirms the muons found at LVL1 using the precision chambers based on monitored drift tubes (MDT) [8]. The better momentum resolution gives a sharper p_T threshold, which significantly reduces the trigger rate. The further rate reduction is achieved by a combined Muon-ID algorithm [9], which matches tracks found by the stand-alone muon reconstruction with tracks reconstructed in the ID. Further details regarding performance of the LVL2 muon algorithms can be found in [10].

The LVL2 ID algorithms have been proved to be highly efficient for low- p_T (about 1 GeV) tracks which are of interest for B-physics. As an example, Table 2 shows track finding efficiency for tracks with $p_T \geq 1.5$ GeV from $D_s \rightarrow \phi(KK)\pi$ decay.

Table 2. LVL2 track finding efficiency for K and π from D_s meson decay.

Tracks	π	K
Efficiency	93 %	94 %

5. A fast vertex fitting algorithm

Vertex finding and fitting is an important part of the B-physics trigger event selection. The LVL2 track reconstruction imposes additional constraints providing input track parameters estimated at perigee points (points of the closest approach to z -axis parallel to the magnetic field) and track parameter errors in the form of covariance (rather than weight) matrices.

In contrast, vertex fitting algorithms described in the literature [11], [12] assume uncertainties of the input track parameters to be described by weight (inverse covariance) matrices. However, if only track covariance matrices are available, these algorithms require them to be inverted beforehand thus giving a substantial computing time overhead.

To alleviate this drawback a fast vertex fitting algorithm capable of using track covariance matrices directly has been developed. The basic idea of the algorithm described below is to decouple position- and momentum-related track parameters in the vertex fit input by selecting "at-perigee" rather than "at-vertex" track momenta as the fit parameters. This choice makes it possible to transform input track parameters into two uncorrelated vectors – measured momentum and its linear combination with measured track position at the perigee. This linear combination comprises a new 2D measurement model while the measured momenta and the corresponding blocks of the input track covariance matrices are used to initialize vertex fit parameters and covariance matrix. This approach provides a mathematically correct and numerically stable initialization of the vertex fit. The reduced-size measurement model makes the proposed Kalman filter very fast and suitable for an application in the trigger. A detailed description of the algorithm can be found in Appendix.

The algorithm has been validated on $B_s \rightarrow J/\psi(\mu^+\mu^-)+\Phi(K^+K^-)$ data produced using a full ATLAS Monte Carlo (MC) simulation. Tracks were reconstructed by the LVL2 algorithms [3],[4]. In order to test the performance of the algorithm for the reconstructed tracks corresponding to the products of the B_s decay, the Monte Carlo truth information was used to identify these tracks which were combined into $J/\psi(\mu^+\mu^-)$ and $B_s(\mu^+\mu^-K^+K^-)$ vertices and fitted using the algorithm described above.

The normalized residuals (pulls) of the fitted vertex coordinates and χ^2 -probability distribution for the $J/\psi(\mu^+\mu^-)$ vertices are shown in Fig.1.

The pull distributions in Fig.1 are nearly perfectly Gaussian with a r.m.s close to 1. This indicates that covariance matrices produced by the vertex fit correctly reflect the actual estimation errors of the vertex parameters. The χ^2 -probability distribution is flat. It means that the χ^2 values produced by the vertex fit for the signal vertices are distributed in accordance with the χ^2 law.

The computing time of the vertex fit has been measured on a Xeon 2.4 GHz processor as a function of track multiplicity n . The number of iterations in the vertex fit has been fixed at 5. Average computing time is 0.2 ms and 0.36 ms for $J/\psi(\mu^+\mu^-)$ ($n = 2$) and $B_s(\mu^+\mu^-K^+K^-)$

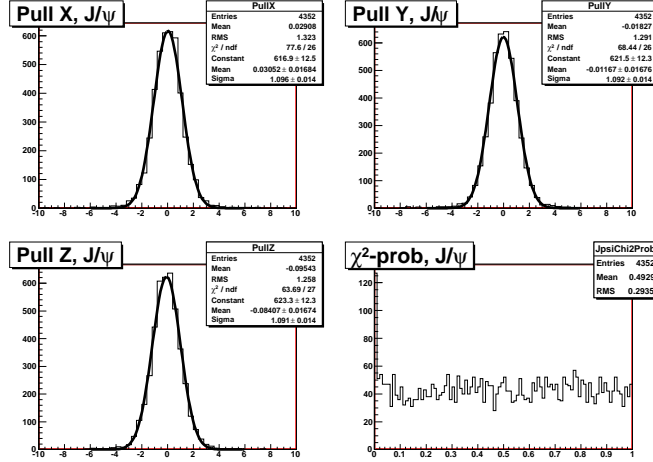


Figure 1. Vertex pulls and χ^2 -probability.

($n = 4$) vertices respectively. The vertex fitting algorithm is very fast and its computing time is negligible with respect to the available LVL2 time budget.

6. Conclusion

We have outlined flexible strategies for the triggering of B-physics events at ATLAS from the initial running to final design luminosities. The trigger software for the B-physics event selection software based on efficient innovative algorithms has been presented. This software has been successfully validated on simulated data and is ready for testing on the first LHC data.

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Appendix A. A fast Kalman filter for vertex fitting

Let a vertex be composed by n tracks with measured track parameters at perigee points m_k and covariance matrices V_k , $k = 1, \dots, n$. A Kalman filter performs vertex fitting progressively, track-by-track, so that after adding k -th track a fit parameter vector X_k is

$$X_k = (R q_1 \dots q_k)^T,$$

where R is a vertex position and q_i , $i = 1, \dots, k$ are "at-perigee" track momenta. This vector is related to the measured track parameters by the following measurement equation

$$m_i = \begin{pmatrix} m_i^r \\ m_i^q \end{pmatrix} = \begin{pmatrix} h(R, q_i) \\ q_i \end{pmatrix} + \epsilon_i, \quad (\text{A.1})$$

where m_i^r , m_i^q are measured track position and momentum, respectively, $h(\cdot, \cdot)$ is a 2D non-linear function, and $\text{cov}(\epsilon_i) = V_i$.

Let \hat{X}_k be an estimate of the vector X_k and $\hat{\Gamma}_k$ be a covariance matrix of this estimate. In the block-matrix notation,

$$\hat{\Gamma}_k = \begin{pmatrix} C_k & E_k^T \\ E_k & D_k \end{pmatrix},$$

where C_k is a 3×3 vertex covariance, D_k is a $3k \times 3k$ joint covariance matrix of the track momenta, and E_k is a $3k \times 3$ matrix of mutual "vertex-track" correlations.

If a $k + 1$ -th track is added to the vertex the vector X_k is augmented and its prior estimate (prediction) and predicted covariance $\tilde{\Gamma}_{k+1}$ are

$$\tilde{X}_{k+1} = \left(\hat{X}_k, m_{k+1}^q \right)^T, \quad \tilde{\Gamma}_{k+1} = \begin{pmatrix} \hat{\Gamma}_k & 0 \\ 0 & V_{k+1}^{qq} \end{pmatrix}, \quad (\text{A.2})$$

where V_{k+1}^{qq} is the qq -block of the covariance V_{k+1} .

The Kalman filter updates the prediction as follows

$$\hat{X}_{k+1} = \tilde{X}_{k+1} + K_{k+1} d_{k+1}, \quad (\text{A.3})$$

where K_{k+1} is the Kalman filter gain, d_{k+1} is a 2D residual:

$$d_{k+1} = m_{k+1}^r - h \left(\hat{\mathbf{R}}_k, m_{k+1}^q \right). \quad (\text{A.4})$$

A 2×2 covariance matrix S_{k+1} of the residual (A.4) is given by

$$S_{k+1} = A_{k+1} C_k A_{k+1}^T - B_{k+1} V_{k+1}^{qr} - V_{k+1}^{rq} B_{k+1}^T + B_{k+1} V_{k+1}^{qq} B_{k+1}^T + V_{k+1}^{rr}, \quad (\text{A.5})$$

where A_{k+1} , B_{k+1} are matrices obtained by linearizing the measurement function $h(\cdot, \cdot)$ in the vicinity of the prediction $\tilde{\mathbf{X}}_{k+1}$:

$$A_{k+1} = \left. \frac{\partial h}{\partial \mathbf{R}} \right|_{\hat{\mathbf{R}}_k, m_{k+1}^q}, \quad B_{k+1} = \left. \frac{\partial h}{\partial q} \right|_{\hat{\mathbf{R}}_k, m_{k+1}^q}. \quad (\text{A.6})$$

In turn, the Kalman filter gain is given by

$$K_{k+1} = M_{k+1} S_{k+1}^{-1}, \quad (\text{A.7})$$

where a $(3k + 6) \times 2$ matrix M_{k+1} denotes the following matrix expression

$$M_{k+1} = \begin{pmatrix} C_k A_{k+1}^T \\ E_k A_{k+1}^T \\ V_{k+1}^{qq} B_{k+1}^T - V_{k+1}^{qr} \end{pmatrix}.$$

An updated covariance matrix of the estimate $\hat{\mathbf{X}}_{k+1}$ is

$$\hat{\Gamma}_{k+1} = \tilde{\Gamma}_{k+1} - K_{k+1} M_{k+1}^T. \quad (\text{A.8})$$

Finally, a χ^2 contribution of the $k + 1$ -th track to the total χ^2 of the vertex fit is given by

$$\Delta \chi_{k+1}^2 = d_{k+1}^T S_{k+1}^{-1} d_{k+1}. \quad (\text{A.9})$$

The system (A.2)-(A.9) completely describes a fast vertex fitting algorithm. This algorithm has a number of computational advantages. Due to using the so-called "gain matrix" formalism [12] track covariance matrices V_k , $k = 1, \dots, n$ are utilized directly and as soon as the last track is processed the estimate of the full fit parameters vector \hat{X}_n and its covariance $\hat{\Gamma}_n$ are available immediately. Another advantage is that the only matrices to invert are 2×2 symmetrical matrices S_k , $k = 1, \dots, n$. This feature is especially important since vertex fit is an iterative procedure – after processing all tracks the linearization (A.6) is re-computed using estimated vertex position and the Kalman filter cycle (A.2)-(A.9) is repeated for each track. Typically, a few iterations are required for convergence so that the overall computational cost of the vertex fit can be significantly reduced by using the fast Kalman filter (A.2)-(A.9) in the iteration loop.

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