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Nuclear Instruments and Methods in Physics Research A 560 (2006) 79–83
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
www.elsevier.com/locate/nima

Vertexing strategy and algorithms at ATLAS

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Available online 28 December 2005

Abstract

The A Toroidal LHC ApparatuS (ATLAS) inner detector consists of three layers of silicon pixels, four double layers of silicon microstrips and a transition radiation tracker (straw tubes). The good performance of the charged track reconstruction and the vertexing possibilities are determined in large part by the small radius, fine pitch and low occupancy of the innermost component: the pixel detector. The strategy for the track and vertex reconstruction, both at trigger level and offline, are reviewed and the most relevant algorithms discussed. Results, from full detector simulation, are presented on track and vertex reconstruction efficiencies and resolutions and on the b-tagging capabilities.

1. Introduction

The A Toroidal LHC ApparatuS (ATLAS) detector will operate at the LHC collider studying *pp* collisions at 14 TeV center of mass energy. The region around the *pp* interaction point will be characterized by a very high density of charged tracks which can be reconstructed only by using high-granularity detectors granting low occupancy.

This article will review the tracking and vertexing algorithms used in the offline and trigger framework to fully exploit the potentialities of the ATLAS precise tracking system. Results, from detector simulation, will be presented for the b-tagging selection.

2. ATLAS

The ATLAS experiment will start taking data in April 2007 at the Large Hadron Collider (LHC), a *pp* collider, currently under construction by the European Organization for Nuclear Research (CERN), characterized by a 14 TeV center of mass energy and a design luminosity of $10^{34}\,cm^{-2}\,s^{-1}$.

ATLAS has been designed as a multipurpose experiment, to be capable both of detecting and measuring new physical phenomena predicted by currently available theories, like evidence for Higgs bosons or supersymmetrical particles, and of performing precision Standard Model (SM) measurements.

To achieve this goal the ATLAS detector is equipped, moving from the inside out, with tracking and particle identification detectors (Pixel, SCT silicon strips and TRT straw tubes) forming the so-called Inner Detector (ID), Liquid Argon (LAr) electromagnetic and Tile hadronic calorimeters, and the outer muon system, designed both for tracking (monitored drift tubes and cathode strip chambers) and trigger purposes (resistive plate and thin gap chambers).

The innermost tracking detector (the Pixel detector) is composed by three layers of silicon pixel detectors positioned at $R = 5.05, 8.85, 12.25\,cm$; the pitch is $50\,\mu m$ in the transverse plane and $400\,\mu m$ along the eam axis. For the initial period of the data taking, a reduced ID layout (lacking the intermediate pixel layer and TRT C wheels at $|\eta| > 1.7$) has been approved for budget reasons.

Operation at LHC means coping, at design luminosity, with ~23 pp interactions every 25 ns; this very high rate obviously poses stringent design demands on both the detectors and the Trigger and Data Acquisition (TDAQ) system.

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0168-9002/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.nima.2005.11.238

3. The ATLAS trigger system

In the ATLAS experiment, reduction of the 1 GHz interaction rate down to the 200 Hz maximum event data storage rate is provided through three different trigger selection layers.

- The hardware-based first level trigger (LVL1) performs a preliminary rejection using only reduced granularity data coming from calorimeters and muon detectors, within a 2 μs fixed latency, producing a maximum output rate of 75 kHz. Further event selection is then performed by software tools running on dedicated commercial processor farms and is divided in two layers, second level trigger (LVL2) and Event Filter (EF), collectively referenced as High Level Triggers (HLT) [1].
- Reconstruction at LVL2, seeded by information collected at LVL1, can exploit full granularity information from all ATLAS subdetectors, processing in parallel data contained inside one or more geometrical regions identified at LVL1, the so-called Regions of Interest (RoI). Event selection is designed in order to provide an output rate below 2 kHz, and must be performed with a mean processing time of 10 ms for each RoI.
- The EF selection, which can be in its turn seeded by results obtained at LVL2, has much looser time constraints, with a 2 s mean execution time, and can thus use reconstruction algorithms with potential access to the entire event data and which are much more similar to the tools used for offline analysis.

4. Fast tracking at second level trigger

At LVL2, the ID data are available for track reconstruction; the pattern recognition algorithms have to be fast (due to the limited available processing time) and access the smallest amount of the data needed (in order to limit the data transfer).

Since at the LHC design luminosity in every bunch crossing about 23 events are spread along the beam direction by $\sigma(z) = 5.6$ cm, one of the most important tasks for the tracking is the determination of the z coordinate of the primary vertex of the main event (characterized by large transverse energy) allowing the rejection of background hits from other soft interaction vertices.

Two complementary approaches have been implemented to cope with different physics cases:

- An algorithm aiming at the reconstruction of the innermost track segments (emphasis on the precision of the impact parameters).
- An algorithm aiming at the reconstruction of the full track using all the hits in the silicon trackers (optimizing the resolution of the track direction and curvature).

4.1. Seeding algorithm

The algorithm [2], initially based solely on the pixel detector, uses the concept of "logical layer". A logical layer can be defined as a set of detector modules from different physical layers playing the same role during track reconstruction. Logical layers are built examining Monte Carlo tracks that at least produced a space point on the pixel detector layer closest to the interaction point (B-layer), ordering and numbering their hits with increasing r values and finally grouping together the modules containing space points with the same number.

The algorithm consists of three steps.

- *Space point sorting*: The first algorithmic operation is sorting the space points retrieved from the LVL1 RoI putting them in a map according to their physical module address in order to speed up the following data access.
- *Track seeds formation*: Using the sorted map and a Look-Up Table (LUT) linking each module within the B-layer to the ones belonging to second logical layer track seeds are formed by two space points and interpolated with a straight line. The line defined by each seed is extrapolated back to the beam line and the transverse and longitudinal impact parameters are computed; the space point pair is accepted if it has a small impact parameter with respect to the primary vertex in the transverse plane (coincident, with good approximation, with the origin in the transverse plane). The requirement on the value of the transverse impact parameter can be actually used to tune the lowest p_T threshold for the track reconstruction. At this stage the z coordinate of the primary vertex is estimated as the coordinate of the maximum of the histogram filled with the z intersection of the seeds with the beam line. More than one candidate is retained to improve efficiency.
- *Track extension*: Each track seed is extended adding a third space point. The extrapolation is performed using a MC map giving, for each seed, a set of module lists where further hits may lay (road). Space points from the selected modules are used to extend the seed if they are compatible with its linear extrapolation. Ambiguities (tracks having one space point in common) are removed on the basis of the extrapolation quality. The spacepoints triplets are then fitted (circle in the $r-\phi$ plane, line in the $r-z$ plane) and identified as candidate tracks.

4.1.1. Performance

The algorithm reconstructs tracks in jets with an efficiency ranging from 80% to 90% (depending on the luminosity and event topology). Single electrons are reconstructed with an efficiency of about 95% for all the luminosities.

The track resolutions are summarized in Table 1. The results of timing measurements on 2.4 GHz PC using b-jets (signal only) are given in Table 2. The total algorithmic time scales to ~1.4 ms at initial luminosity and ~2.5 ms at design luminosity. The timing performance is well within the LVL2 constraints.

4.1.2. Application: online b-tagging selection

Given the good transverse impact parameter resolution, one of the most natural applications of the fast tracking algorithm previously described is, because of the good transverse impact parameter resolution, the definition of a b-jet selection for LVL2.

The b-tagging selection has been studied on single jets using b-jets as signal sample and u-jets as background representative for the light jets. The sample consists of jets issued from the decay of a Higgs boson produced with a mass of 120 GeV in association with a W.

The b-jet selection is performed using the transverse impact parameter of its tracks. For each reconstructed track, the significance of the transverse impact parameter $S = d_0/\sigma(d_0)$ is computed; the error on the impact parameter $\sigma(d_0)$ is parametrized, using simulated events, as a function of p_T. The b-jet estimator is then built using a likelihood-ratio: for each track (i), the weight $w_t = P_b(S_i)/P_u(S_i)$ is computed; the product W of these weights over all reconstructed tracks in the jet is the final tagging variable. W is expected to be small ($W \ll 1$) for u-jets and large ($W \gg 1$) for b-jets.

4.1.3. b-jet tagging performance

The efficiencies for b-jets (e_b) and rejection factors (R_u) against u-jets (defined as the inverse of the efficiency for u-jets) are given in Fig. 1.

The performance is robust with respect to luminosity and event topology. The rejection, although modest, is still useful to increase the acceptance of multi b-jet events

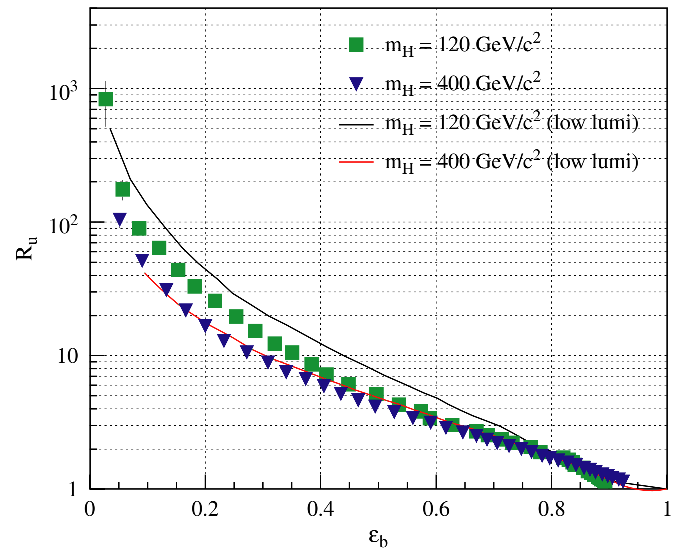

Fig. 1. Rejection for light jets as a function of the efficiency for b-jets for different luminosities and event topologies.

(SUSY channels) and, more generally, to increase the flexibility of the trigger scheme.

Table 1
Track parameters resolution

$\sigma(1/p_T)$ (GeV^{-1})	0.006
$\sigma(\phi)$ (rad)	0.7×10^{-3}
$\sigma(\eta)$	2.2×10^{-2}
$\sigma(z_0)$ (μm)	340
$\sigma(d_0)_{p_T > 10\,\mathrm{GeV}}$ (μm)	30

Table 2
Timing measurements for the different steps of the algorithm

Sorting (ms)	~0.2
Seeding (ms)	~0.5
Extension (ms)	~0.3
Tot. algorithm (ms)	~1

4.2. Histogramming algorithm

An alternative approach [3] for track reconstruction based on a histogramming technique has been developed in ATLAS; it is composed of several sub-algorithms.

- *ZFinder*: Hits are selected in narrow ϕ slices, pairs of hits in each slice are extrapolated back to the beam line entering the z of the intersection in a histogram. The z-value corresponding to the peak of the histogram is taken as that of the primary vertex.
- *HitFilter*: Puts all hits into a histogram binned in ϕ and η. It finds clusters of hits within the histogram and creates group of hits if the cluster contains contributions from more than a given number of layers.
- *GroupCleaner*: Splits hits groups into tracks and removes noise hits from the group. Each triplet of hits forms a potential track, groups of triplets with similar parameters are formed. Track candidates are accepted if a group contains enough hits.
- *TrackFitter*: Verifies track candidates and finds track parameters by using a fast object-oriented implementation of the Kalman filter algorithm.

5. Offline pattern recognition and track reconstruction

In the offline analysis the tracking algorithms can access the full data and calibration and hence to reach the best performance. Two different algorithms of pattern recognition for charged tracks have been used in ATLAS:

- *IPatRec* searches for tracks using the three-dimensional space points in pixels and SCT; candidates are extrapolated to the TRT and drift time hits added using a χ^2 fit;
- *XKalman* searches for tracks in TRT using a fast histogramming of straw hits; candidates are extrapolated to the SCT and pixels and fitted using a Kalman filter, the tracks obtained are then extrapolated back to TRT and drift-time hits added.

The two approaches have different advantages: XKalman is faster because it benefits from the fast histogramming of TRT hits; IPatRec is less sensitive to interactions or bremsstrahlung. The overall performance of the two algorithms turns out to be very similar.

The track efficiency is about 0.95 for single track and 0.90 for tracks in jet. The resolutions for the transverse impact parameter (d_0) and for the transverse momentum (p_T) can be parametrized as

$$\sigma(d_0) = 12 \otimes \left(\frac{107}{p_T}\right) \mu\text{m},$$

$$\sigma\left(\frac{1}{p_T}\right) = 0.6 \otimes \left(\frac{18}{p_T}\right) \text{TeV}^{-1}.$$

5.1. Primary vertex reconstruction

The primary vertex reconstruction starts with a preliminary approximation of the z coordinate performed with a sliding window searching for the maximum number of tracks weighted with p_T. The procedure is iterated removing the tracks already assigned in order to reconstruct more vertices.

The primary vertex position is finally computed using a χ^2 fit by iteratively removing the tracks having the largest contribution to the χ^2.

Typical resolutions in jets are $\sigma_{xy} \simeq 80\,\mu\text{m}$ and $\sigma_z \simeq 300\,\mu\text{m}$ in the transverse and longitudinal plane, respectively.

5.2. Inclusive secondary vertex reconstruction

Inclusive secondary vertex reconstruction (without assumption on the exact topology or multiplicity) is an important tool to identify b-jets.

The search starts with a selection of all the tracks pairs forming a good two-track vertex: in a first stage these vertices are used to reject “bad” tracks coming from secondary interaction or V^0 decays. All the tracks in the two-track vertices are combined into a single effective secondary vertex; if the resulting vertex has unacceptable χ^2 the track with highest contribution to the χ^2 is removed from the “secondary” tracks list and the vertex is refitted. The procedure iterates until receiving a good χ^2 of the vertex fit or the complete disappearance of the tracks from the “secondary” list.

The reconstruction efficiency ranges from 50% to 80% for b-jets while it remains below 10% for u-jets.

5.3. b-tagging strategy

Several methods have been used to discriminate the b-jets from jets issued from lighter quark using the properties of the reconstructed charged tracks:

- significance of transverse impact parameter (2D method: analog to the online method);
- combination of the significance of the transverse and longitudinal impact parameter (3D method);
- combination of several parameters of the secondary vertex (vertex energy fraction, secondary vertex mass, number of vertices). These variables have been chosen trying to minimize the correlation with the impact parameters (in order to ease the overall combination).

The relative weights of the different methods at initial luminosity are summarized in Table 3.

The development of different methods and their continuous improvement have been very useful to compensate various design modification causing a degradation of the performance (increase of the material, staging of the intermediate pixel layer, increase of the z pitch in first pixel layer).

6. Conclusion

Different tracking and vertexing algorithms have been developed in order to maximize the performance of the overall ATLAS reconstruction scheme. Among the other tools, the primary vertex reconstruction is the crucial key, both at online and offline level, to reduce the dependence on the luminosity regime.

Continuous effort on algorithms and the combination of different approaches have proven to be effective and able

Table 3
Light jets rejection at 60% b-jets efficiency for different methods with staged and complete detector

ε_b (%)	Two layers	Three layers
$m_H = 120\,\text{GeV}/c^2$		
2D 60	41 ± 1	50 ± 1
3D 60	57 ± 1	76 ± 1
SV 60	131 ± 3	164 ± 6
$m_H = 400\,\text{GeV}/c^2$		
2D 60	37 ± 1	49 ± 1
3D 60	48 ± 1	66 ± 1
SV 60	170 ± 5	257 ± 10

to compensate for "unfortunate" (but unavoidable) modifications in the detector layout.

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