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FATRAS - the ATLAS Fast Track Simulation project

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Abstract. The Monte Carlo simulation of the detector response is an integral component of any analysis performed with data from the LHC experiments. As these simulated data sets must be both large and precise, their production is a CPU-intensive task. ATLAS has developed full and fast detector simulation techniques to achieve this goal within the computing limits of the collaboration. At the current early stages of data-taking, it is necessary to reprocess the Monte Carlo event samples continuously, while integrating adaptations to the simulation modules in order to improve the agreement with data taken by means of the detector itself. FATRAS is a fast track simulation engine which produces a Monte Carlo simulation based on modules and the geometry of the standard ATLAS track reconstruction algorithm. It can be combined with a fast parametrized-response simulation of the calorimeters. This approach shows a high level of agreement with the full simulation, while achieving a relative timing gain of two orders of magnitude. FATRAS was designed to provide a fast feedback cycle for tuning the MC simulation with real data: this includes the material distribution inside the detector, the integration of misalignment and current conditions, as well as calibration at the hit level. We present the updated and calibrated version of FATRAS based on the first LHC data. Extensive comparisons of the fast track simulation with the full simulation and data at 900 GeV are shown.

1. Introduction

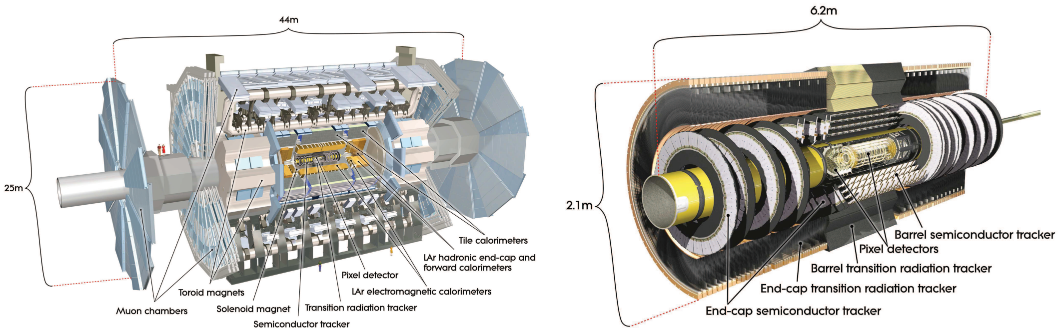
Modeling the elementary physics processes and simulating the interactions of particles with the detection apparatus is an ever-growing complex field in contemporary high-energy physics. The tiny cross-sections of the signatures of new physics with respect to background processes require a large number of events to be generated for Monte Carlo studies. The major fraction of dedicated computing time can be accounted to the simulation of interactions with the active and passive material of the detector and in particular the determination of the detector response.

With the construction and commissioning of the ATLAS experiment [1] at CERN a new era began: it is the largest volume particle detector ever constructed so far. Many different sub-detectors, such as tracking devices and calorimeters, together with cabling and cooling infrastructure, as well as two magnet systems form an immensely complicated apparatus weighing about 7000 tonnes.

Estimating the response of the system as a whole is traditionally done in the most accurate way, modeling small structures which could affect traversing particles from the interaction point in the center of the detector. However, this approach is not always feasible. Some analyses require a large number of collision events to be simulated which can only be done using a simplified approach of modeling the detector material and the response of active detector elements.

2. The ATLAS Experiment

About one hundred meters below the surface of the French and Swiss countryside close to CERN, the Large Hadron Collider (LHC) is delivering streams of protons to four particle detectors since its start-up in 2008. ATLAS (Figure 1a) is a "multi-purpose" detector with a primary focus on the search for new physics, such as Supersymmetry or the Higgs Boson. The apparatus can be divided into three main parts: inner detector, calorimeters and the muon system. The former and the latter are tracking systems, responsible for precisely measuring the momenta of charged particles. The calorimeters are used for determining the energies of traversing particles. The inner detector (Figure 1b) consists of three subsystems: closest to the LHC beam line are the pixel detectors with very high granularity for determining the origin of the hard scattering process and the position of secondary vertices from longer-lived unstable particles. The Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT) provide additional precision hits for reconstructing tracks of charged particles.



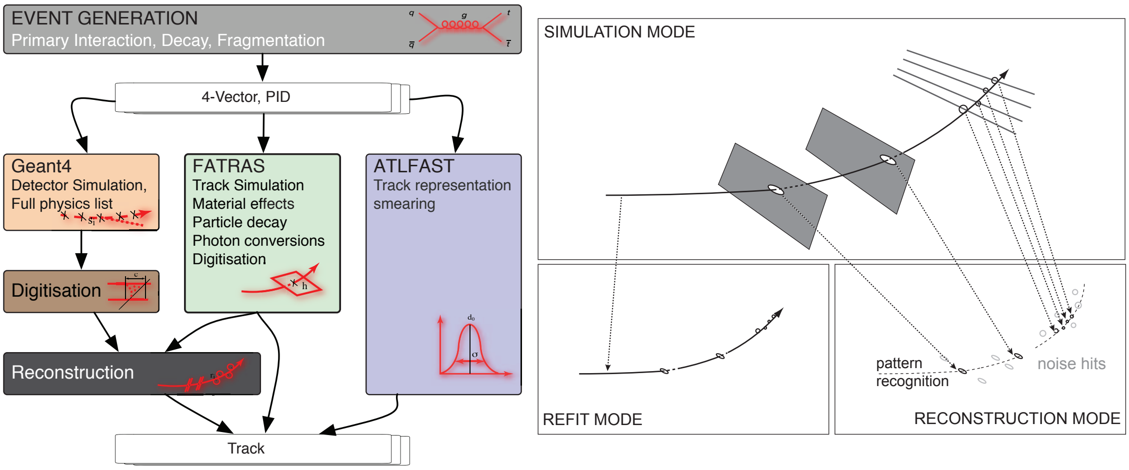
(a) The ATLAS detector

(b) The ATLAS inner detector

Figure 1: The ATLAS detector at the LHC, full overview (a) and an enlarged view of the inner detector (b) which consists of the pixel detector, the semiconductor tracker and the transition radiation tracker.

3. Simulation

In high energy physics, the modeling of the detector response with Monte Carlo methods is an integral component of many studies. Tracking devices like the ATLAS pixel detectors and the SCT are extremely complex instruments that have to be commissioned and fully understood, also with respect to the results of previously conducted simulation efforts. In addition to that, physics analyses often require extensive data sets of simulated physics data for the estimation of systematic effects. The production of those simulated data to the very detail is usually a very CPU-intensive task. The ATLAS collaboration has developed full and fast detector simulation techniques to achieve this goal within the computing limits of the collaboration [2]. At the current stage of data-taking, it is necessary to reprocess the Monte Carlo event samples continuously, while integrating adaptations to the simulation modules in order to improve the agreement with the data taken from the detector itself. FATRAS is a fast track simulation engine of the ATLAS inner detector and muon system. It produces a Monte Carlo simulation based on the software modules and the geometry used by the standard ATLAS track reconstruction algorithms. It can be combined with a fast parametrized-response simulation of the calorimeter. This approach shows a high level of agreement with the Geant4-based full simulation, while reducing the amount of computing time by two orders of magnitude. FATRAS was designed to provide a fast feedback cycle for tuning the MC simulation to real data, including the material distribution inside the detector, the integration of misalignment and current conditions, as well as calibration at the detector hit level. Figure 2 shows an overview of the different ATLAS track simulation strategies and different subtasks done in FATRAS.



(a) Track simulation in ATLAS (b) Track simulation and reconstruction in FATRAS

Figure 2: (a) Overview of the data flow for the full simulation with Geant4, the ATLAS fast track simulation FATRAS and the ATLAS fast simulation framework, ATLFAST. (b) Visualization of the simulation and refit/reconstruction of a track of a charged particle. In all modes, the standard ATLAS reconstruction software is used for navigating the different detector parts in the geometry and the extrapolation of the particle path through the magnetic field. In reconstruction mode, detector effects such as the granularity and noise are taken into account as well.

4. Features of FATRAS

The software takes care of modeling the most dominant effects of the traversed detector material on the particle, such as multiple scattering/ionization loss, bremsstrahlung, hadronic interactions and photon conversions. Also particle decays are simulated for all unstable particle types and their decay products are iteratively processed by the same algorithms. Design details of the detectors (e.g. their granularity and readout methods) are also accounted for, such as for example the cluster creation in the pixel detectors from neighbouring detector elements being hit. As an example, the momentum spectra of photons produced by the bremsstrahlung of electrons is shown in Figure 3a. The simplified detector geometry which is used by FATRAS can be seen in a map of the origins of photon conversions, e.g. in the r/z-plane of the detector as shown in the bottom of Figure 3b, and it can be compared with the corresponding geometry in the Geant4 based simulation, which is shown in the upper part of the same figure. A more extensive description of FATRAS and its features can be found in [3].

5. Timing

Comparison of the simulation time per event in kSI2K seconds for different simulation frameworks used by the ATLAS collaboration show a significant speed gain when using FATRAS combined with a fast calorimeter simulation (ATLFAST-IIF) w.r.t. to the Geant4 full simulation (see Table 1).

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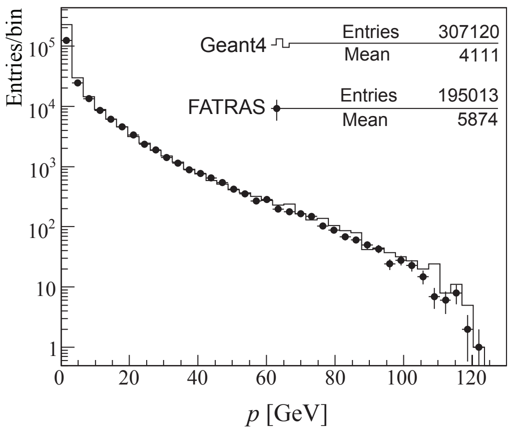
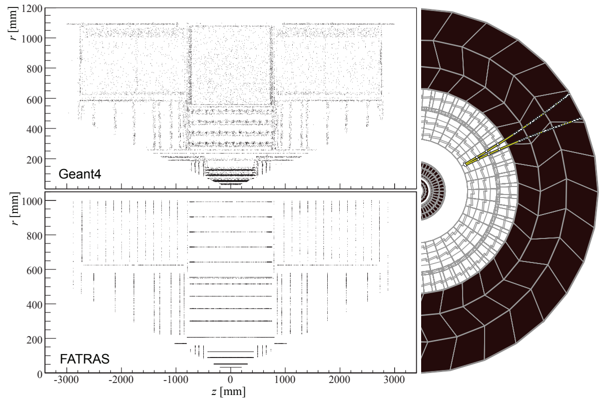


(a) Momentum spectra of Bremsstrahlung photons



(b) Tracker geometries derived from photon conversions

Figure 3: (a) Comparison of momentum spectra of Bremsstrahlung photons simulated with Geant4 (histogram) and FATRAS (points). (b) Simulated image of the ATLAS tracking detectors using photon conversions for the underlying full Geant4 geometry and the simplified ATLAS reconstruction geometry

Table 1: Timing comparison for typical types of physics Monte Carlo events. All numbers are given in kSI2K-seconds per simulated event. The left column contains the times achieved with the full simulation using Geant4. The middle column shows the same information for ATLFAST-II (using Geant4 for tracking and a fast calorimeter simulation). The right column displays the timing of ATLFAST-IIF where FATRAS is used for tracking. An improvement of at least one order of magnitude can be seen between each column to the next for all signatures.

Sample Type	Full Simulation	ATLFAST-II	ATLFAST-IIF
Minimum Bias	551.0	31.2	2.1
$t\bar{t}$	1990.0	101.0	7.4
Jets	2640.0	93.6	7.7
γ + Jets	2850.0	71.4	5.7
$W \to e\nu_e$	1150.0	57.0	4.1
$W \to \mu\nu_\mu$	1030.0	55.1	4.1
Heavy Ion	56000.0	3050.0	203.0

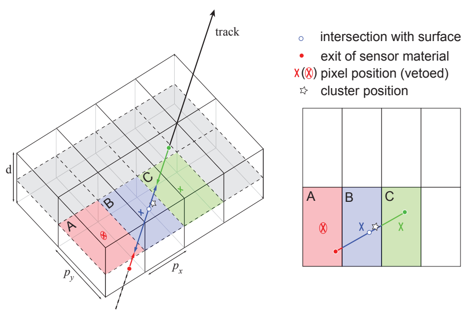
6. Comparison with Experimental Data

Based on data taken at a centre-of-mass energy of 900 GeV, several tracking-specific observables have been compared to the output from FATRAS. The plots shown here concentrate on distributions related to the pixel detectors and the track resolution of the vertex.

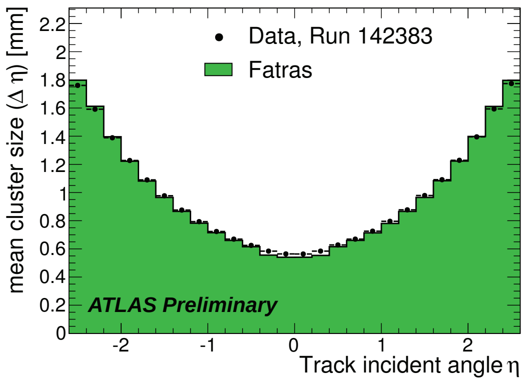
The simple geometrical approach (Figure 4a) for reproducing the proper sizes for neighbouring pixel hits shows an excellent agreement between data and MC (Figure 4b).

The number of hits in the pixel detector in dependence of the pseudorapidity η (Figure 5a) and the azimuthal angle ϕ (Figure 5b) are reproduced to a large extent, the general shape fits very nicely.

The impact parameters z_0 (Figure 6a) and d_0 (Figure 6b) of the reconstructed tracks give

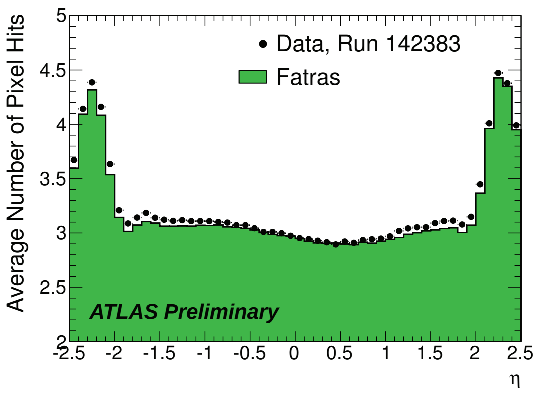


(a) Schematic display of the pixel cluster creation in FATRAS

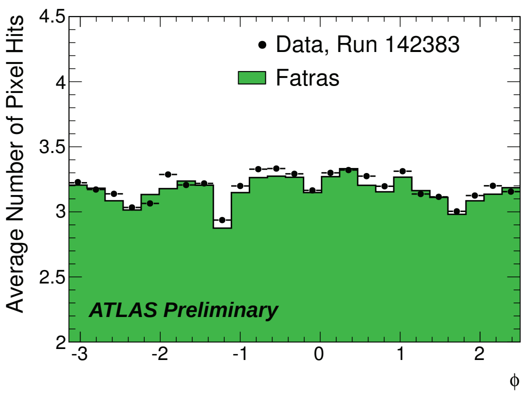


(b) Mean size of pixel clusters versus the η of the associated track

Figure 4: (a) In FATRAS, pixel clusters are created by calculating the relative path length of a track to a pixel volume and counting all pixels as hits where this quantity passes a tunable threshold. (b) Comparison of the mean cluster size in the ATLAS pixel detector in 900 GeV collision data (black points) and MC simulated with FATRAS (shaded histogram). The cluster size $\Delta\eta$ is given in a local coordinate along the global η coordinate.



(a) Number of pixels hits versus η

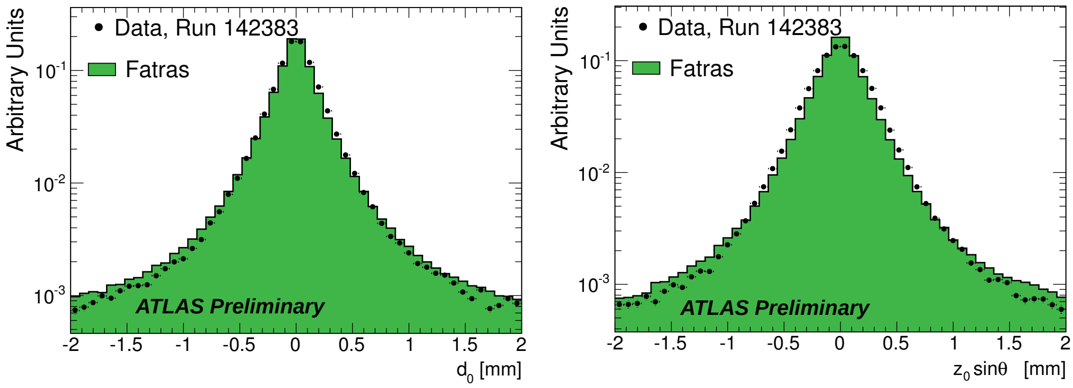


(b) Number of pixels hits versus ϕ

Figure 5: Comparison of the geometric distribution of pixel detector hits in η (a) and ϕ (b) in 900 GeV collision data (black points) and MC simulated with FATRAS (shaded histogram). The distribution is shaped by the existence of inactive pixel modules which are also taken into account by FATRAS.

information about the closest point of approach of a track w.r.t. to the beam line. They are relevant for vertex reconstruction. While the general shape is reproduced sufficiently well by FATRAS, small deviations exist in the tails of the distributions.

7. Summary
Since the development of FATRAS was started, it has proven to be a useful tool, not only for debugging the track reconstruction algorithms and the simplified reconstruction geometry of the ATLAS detector, but also as a fast simulation engine. Comparisons with real collision data show that the description of the physics processes and the material distribution are modeled in



(a) d_0 w.r.t. the primary vertex

(b) z_0 w.r.t. the primary vertex

Figure 6: Comparison of the track impact parameters d_0 (a) and z_0 (b) w.r.t. the primary vertex in 900 GeV collision data (black points) and MC simulated with FATRAS (shaded histogram).

a realistic way. The speed increase with respect to a detailed detector simulation which also uses a much more complex description of the detector is significant. This implies that FATRAS is a perfect tool for investigating questions that are related to tracking and also for simulating alternative geometries. It has already been successfully used for studying different concepts of a potential replacement of the ATLAS inner detector [4].

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