The ATLAS calorimeter simulation FastCaloSim

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Abstract. The FastCaloSim calorimeter simulation was developed to provide a reasonably accurate but still fast simulation of the ATLAS calorimeter system. Parameterizations of electromagnetic and hadronic calorimeter showers are used to deposit particle energies in the detailed calorimeter structure. In the present document a short overview of the fast calorimeter simulation principle is presented. This is followed by a comparison of individual particle signatures and event properties to the full Geant 4 based ATLAS detector simulation.

1. Introduction
The current standard simulation suite for the ATLAS detector [1] is based on a detailed description of the detector geometry and of the simulation of particle interactions in the detector material with Geant 4 [2, 3]. The drawback of such a detailed simulation is a CPU time requirement of several minutes per event, of which more than 90% is spent inside the calorimeter systems. With the rapidly increasing LHC luminosity, this CPU time requirement is a challenge for the production of sufficiently large Monte Carlo samples.

The aim of the FastCaloSim package [4] is to provide a parametrized simulation of the particle energy response and of the energy distribution in the ATLAS calorimeter and hence reduce the calorimeter simulation time to a few seconds per event. In order to evaluate the performance of this calorimeter simulation, a dedicated version of the fast simulation of the ATLAS detector was built (Atlfast-II), where the inner detector and the muon system are simulated with Geant 4, while the FastCaloSim package is used for calorimeter. Atlfast-II reduces the overall simulation time by approximately one order of magnitude. It is also possible to use a combination of the fast calorimeter simulation and of the ATLAS fast track simulation FATRAS [5] for the inner detector and the muon system, called Atlfast-IIIF, which reduces the overall simulation time by another order of magnitude. Table 1 shows the average event simulation time for all tested samples and simulation flavors.

2. Calorimeter simulation model
2.1. Simplifications
The design baseline was to make the simulation algorithm as fast as possible in all areas that cost a large amount of time. Hence the following decisions were taken:

• The simulation uses the reconstruction geometry of the calorimeter that describes calorimeter cells as cuboid in \( \eta, \phi \) and the depth of the calorimeter (forward calorimeter cells are cuboid in \( x,y,z \)).
Table 1. Simulation times per event, in kSI2K seconds, for the full Geant 4 simulation, fast Geant 4 simulation (combination of shower parameterization and shower libraries inside Geant 4), Atlfast-II, Atlfast-IIF [6]. Atlfast-II uses the full simulation for the inner detector and muon system and FastCaloSim in the calorimetry. Atlfast-IIF uses FastCaloSim for the calorimetry and FATRAS for the inner detector and muon system. All times are averaged over 250 events.

| Sample                      | Full G4 Sim | Fast G4 Sim | Atlfast-II | Atlfast-IIF |
|-----------------------------|-------------|-------------|------------|-------------|
| Minimum Bias                | 551.        | 246.        | 31.2       | 2.13        |
| $t\bar{t}$                  | 1990        | 757.        | 101.       | 7.41        |
| Jets                        | 2640        | 832.        | 93.6       | 7.68        |
| Photon and jets             | 2850        | 639.        | 71.4       | 5.67        |
| $W^\pm \to e^\pm \nu_e$    | 1150        | 447.        | 57.0       | 4.09        |
| $W^\pm \to \mu^\pm \nu_\mu$| 1030        | 438.        | 55.1       | 4.13        |

- The simulation of the development of particle showers in the calorimeter takes a large amount of time and is therefore replaced by parameterizations. The fast simulation model reproduces the longitudinal shower properties, including fluctuations and correlations, but only average lateral shower properties and uncorrelated lateral energy fluctuations.
- Only three types of particles are parametrized and used for the simulation: photons, electrons and charged pions. The charged pion parameterization is used for all hadrons (neutral and charged).

2.2. Longitudinal shower shape parameterization

The total energy deposition and the longitudinal shower development are parametrized as a function of the longitudinal shower depth (the energy weighted distance of depositions from the calorimeter surface). The calibration constants are fitted individually for all particle energy and $|\eta|$ points to ensure an average response of unity and a true resolution.

In order to preserve the correlation between the calibrated energy response and the shower depth, a 2-dimensional histogram of both properties is used as a basis of the parameterization. Figure 1 shows this correlation for photons of 200 GeV energy in the range $0.20 < \eta < 0.25$.

![Figure 1. Correlation of the calibrated energy response and the longitudinal shower depth for simulated photons of 200 GeV energy in the range $0.20 < \eta < 0.25$. The color of a given point shows the relative probability density in a linear color scale from blue (low probability) to red (high probability). The black bars indicate the mean and width of a Gaussian fit in each bin of the shower depth.](image)

In a similar way, the energy in each calorimeter layer is stored as 2D histograms of the energy fraction in this layer versus the shower depth. Finally, in order to preserve the correlation between the different energy fractions (the sum of all fractions should be unity), one correlation matrix of the energy fractions in each calorimeter layer is built for each bin in the shower depth.
2.3. Lateral shower shape parameterization

The basic parameterization ansatz for the lateral energy distribution is a radial symmetric function centered on the expected impact point of a particle into a calorimeter layer. Cell energies are simulated by integrating the shape function within the area of a calorimeter cell and then adding fluctuations according to the intrinsic energy resolution of the calorimeter technology. Figure 2 shows the ratio between simulated cell energies and the parametrized shape function for photons of 200 GeV energy in the second electromagnetic barrel calorimeter layer.

![Figure 2. Average ratio of Lateral energy distribution of simulated photons of 200 GeV energy in the range 0.20 < \eta < 0.25 in the second electromagnetic calorimeter layer between the simulated cell energies and the cell energies calculated from the parametrized lateral shower shape as function of the distance in (r \cdot \Delta \eta, r \cdot \Delta \phi) of the cell from the expected photon impact point into the calorimeter layer.](image)

3. Validation of the fast simulation with electrons and photons

The first step in the validation of the FastCaloSim performance for electromagnetic energy depositions is to compare the response of single photons and electrons to that obtained with the full Geant 4 simulation.

Figure 3 compares the FastCaloSim and Geant 4 response for the total energy deposited in the EM calorimeter for photons 1.00 < \eta < 1.05. Three metrics are used to test the consistency: the mean value of the distribution, the RMS of the distribution and a Kolmogorov-Smirnov (K-S) test between the distributions obtained with FastCaloSim and the full Geant 4 simulation.

![Figure 3. Comparison of the total energy response E_{TOT} in the EM calorimeter for Atlfast-II and the full Geant 4 simulation for photons with a true energy of 20 GeV in the pseudorapidity range 1.00 < \eta < 1.05.](image)

|                  | Mean(GeV) | RMS(GeV) |
|------------------|-----------|----------|
| Full Simulation  | 19.35     | 0.418    |
| FastCaloSim      | 19.37     | 0.446    |
| K-S test         |           | 0.86     |

These tests have been performed for a range of energies and pseudorapidities. Figure 4 summarizes the results for the mean and RMS for photons generated with an energy of 20 GeV.
In general, FastCaloSim reproduces the full simulation well, except for the calorimeter transition region near $|\eta| = 1.5$. At the lowest probed energy of 1 GeV discrepancies are also visible at $|\eta| > 3.5$. For the highest energies ($\geq 50$ GeV) the RMS responses differ by more than $3\sigma$ for some points in the range $|\eta| < 0.7$.

![Graphs showing comparison between Atlfast-II and the full Geant 4 simulation](image1)

**Figure 4.** Comparison between Atlfast-II and the full Geant 4 simulation of the mean value (left) and RMS (right) of the total energy response $E_{TOT}$ in the EM calorimeter for photons of 20 GeV energy in the whole pseudorapidity range covered by the ATLAS calorimeter system.

Figure 5 shows the electron reconstruction efficiency for electrons passing the medium quality electron selection [7, 8] and matched to a truth electron within a distance of $dR < 0.1$ using sample of $Z \rightarrow ee$ events generated by the PYTHIA[9] Monte Carlo generator. The selection efficiencies are calculated with respect to truth electrons with a transverse momentum $p_T > 5$ GeV and in the rapidity range $|\eta| < 2.5$. The Atlfast-II simulation reproduces the full Geant 4 simulation within the 5% level or better.

4. **Response of the calorimeter to charged hadrons**

The calorimeter response to charged hadrons is quantified computing the ratio between the energy $E$, deposited by a single isolated charged particle in the calorimeter, and the momentum $p$ of the corresponding track. The ratio $E/p$ is studied following Ref. [10]. For the MC simulation, non diffractive (ND) minimum bias events are generated with PYTHIA [9] and the detector is

![Graphs showing electron identification efficiency](image2)

**Figure 5.** Electron identification efficiency for medium quality electrons [7, 8], with respect to truth electrons, as a function of $p_T$ (left) and pseudorapidity (right). The black points show the full Geant 4 simulation and the red points the Atlfast-II simulation.
simulated with both the standard Geant 4 simulation and with Atlfast-II. The two resulting MC samples consist of 1 million events each.

Figure 6 shows the comparison of full Geant 4 simulation and Atlfast-II. The discrepancies between them are below the level of 10% plus the statistical error. For intermediate values of p the Atlfast-II simulation tends to systematically overestimate \( \langle E/p \rangle \). These indications of a bias in Atlfast-II are currently under investigation.

**Figure 6.** \( \langle E/p \rangle \) as a function of the track momentum, for \( 0.0 < \eta < 0.6 \). The black open circles represent the MC minimum bias Atlfast-II prediction and the green rectangles the Geant 4 simulation prediction. The lower plot shows the ratio between Atlfast-II and the full Geant 4 simulation, with dotted lines placed at ±10% from unity.

5. Comparison of jet and missing transverse energy observables

In this section the Atlfast-II performance for jets and missing transverse energy is compared to the full Geant 4 detector simulation of non-diffractive minimum bias events. Details for the event selection and the analysis of jet observables are described in Ref. [11, 12]. Details for the analysis of the missing transverse energy observables are described in Ref. [13, 14].

Figures 7 show the jet transverse momentum \( (p_T) \) and rapidity \( (y) \) distributions for jets. The jet \( p_T \) distribution is well described by the Atlfast-II simulation, but some discrepancies in the rapidity distributions are seen between Atlfast-II and the full Geant 4 simulation. Further studies show that the discrepancies in Atlfast-II appear for low momentum jets and are related to the shortcomings of the lateral shower model in FastCaloSim.

**Figure 7.** Jet \( p_T \) (left) and rapidity (right) distributions for jets with \( p_T > 30 \) GeV and \( |y| < 2.8 \). The filled histogram shows the full Geant 4 simulation and the open squares with error bars show the Atlfast-II simulation, respectively. The EM+JES calibration is applied. The total numbers of jets are normalized to unity.
Figure 8 shows the distributions of $E_T^{miss}$ reconstructed only from calorimeter cells associated to topological clusters. The Atlfast-II distributions agree sufficiently well with the ones from the full Geant 4 simulation.

![Figure 8](image)

Figure 8. Distributions of $E_T^{miss}$ for events with at least one jet with $p_T > 20$ GeV reconstructed using the EM scale signals for all cells. The filled histogram shows the full Geant 4 simulation and the open squares with error bars show Atlfast-II, respectively.

6. Conclusion
The fast calorimeter simulation FastCaloSim has been developed in order to reduce the simulation time in the ATLAS calorimeter system from several minutes to a few seconds per event, using a parametrization model for the longitudinal and lateral shower development of photons, electrons and charged pions. The fast simulation performance was validated against the full Geant 4 based detector simulation for photons, electrons and isolated charged hadrons.

Finally, the performance for the simulation of jets and the missing transverse energy was compared between Atlfast-II and the full Geant 4 simulation. Overall a good agreement between Atlfast-II and the full Geant 4 simulation is observed except for some regions.

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