

Fast shower simulation in the ATLAS calorimeter

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Abstract. The time to simulate pp collisions in the ATLAS detector is largely dominated by the showering of electromagnetic particles in the heavy parts of the detector, especially the electromagnetic barrel and endcap calorimeters. Two procedures have been developed to accelerate the processing time of electromagnetic particles in these regions: (1) a fast shower parameterisation and (2) a frozen shower library. Both work by generating the response of the calorimeter to electrons and positrons with Geant 4, and then reintroduce the response into the simulation at runtime.

In the fast shower parameterisation technique, a parameterisation is tuned to single electrons and used later by simulation. In the frozen shower technique, actual showers from low-energy particles are used in the simulation. Full Geant 4 simulation is used to develop showers down to ~ 1 GeV, at which point the shower is terminated by substituting a frozen shower. Judicious use of both techniques over the entire electromagnetic portion of the ATLAS calorimeter produces an important improvement of CPU time. We discuss the algorithms and their performance in this paper.

1. Introduction

On average 10 minutes of CPU time on a modern processor are needed to simulate the response of the ATLAS detector (excluding digitisation) to a typical 14 TeV pp collision event. Table 1 shows the simulation time for a specific selection of physics processes. The large simulation time is due to the scale and complexity of ATLAS, as well as the energies and multiplicities of the

generated particles. Approaches to simulation which reduces this CPU time without sacrificing quality are worthwhile because they reduce the load on scarce CPU resources at tier 2 centres, which mostly function as Monte Carlo production farms.

For a typical physics event most of the simulation time ($\sim 70\%$) is spent in the calorimeters, mainly in the endcap and forward regions. The breakdown of the simulation time by subdetectors for a selection of physics processes is also given in table 1.

Simulation of high energy electrons and photons is known to require large computing time. One solution to this problem is a parametrisation of the longitudinal and transverse shower profile, which is already described in the literature [1]. But due to the high amount of material in front of the active part of the electromagnetic (EM) calorimeters (as shown in figure 1), most of the electrons and photons start to shower well in advance of the calorimeter. The energy profile of particles entering the active calorimeter coming from an 100 GeV electron starting at the interaction point is shown in figure 2. Hardly any high energy electrons are left over and the distribution is strongly peaked at very low energies. Therefore different approaches to decrease the CPU time are considered, each optimised and adjusted for a certain energy range. For high energy electrons (above ~ 10 GeV), a fast shower parameterisation based on a functional parametrisation of the longitudinal and transverse shower profile is used. For low energy electrons (below a few GeV) the electron shower is described using previously stored hits from a library. The latter approach is called frozen showers. For very low energy electrons (below ~ 10 MeV) a simple “kill” model is applied, where the energy of the electron is dumped locally.

An overview of the ATLAS calorimeters is given in section 2. The two acceleration methods are discussed in detail in sections 3 and 4. Results of the combined simulation strategy for the ATLAS calorimeters (as described in section 5) for CPU timing and shower description are given in section 6.

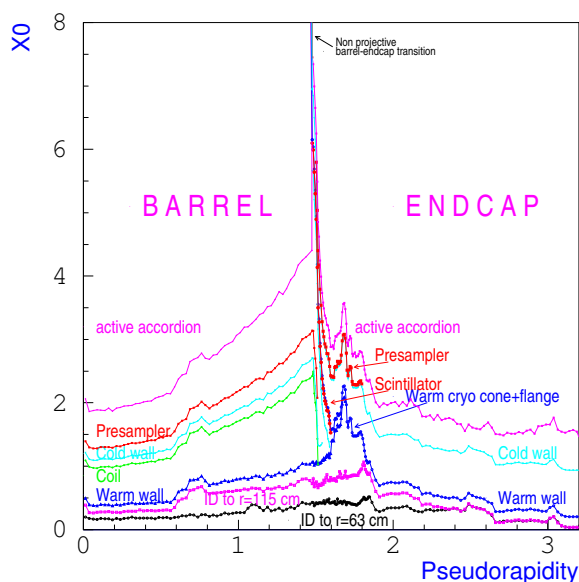


Figure 1. Breakdown of the material distribution in front of the EM calorimeter [2].

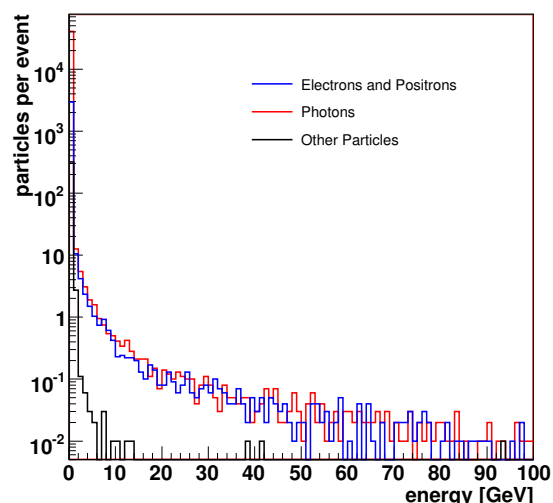


Figure 2. Energy profile of particles entering the active part of the barrel calorimeter coming from 100 GeV electrons starting at the interaction point.

2. The ATLAS Calorimeters

The ATLAS detector has dedicated calorimeters for EM and hadronic interactions. The EM calorimeters in the barrel and endcap region are based on liquid argon as active material and lead as absorber. The electrodes are accordion shaped ensuring continuity in azimuth. The barrel calorimeter consists of two half barrels. The endcap calorimeter consists of two dedicated parts, the outer and inner wheel. In addition the first part of the forward calorimeter is a dedicated EM calorimeter also using liquid argon as active material and copper as absorber. In contrast to the other two EM calorimeters the forward calorimeter consists of a metal matrix with regularly spaced longitudinal channels filled with concentric rods and tubes. For the barrel calorimeter the acceptance in terms of the pseudo rapidity $|\eta|$ is 1.4. The endcap ranges from 1.4 to 3.2. The transition from the outer to the inner wheel is at 2.5. The forward calorimeter extends the acceptance of the calorimeter system from 3.0 up to 4.9. For more details see the liquid argon calorimeter technical design report [2].

3. Fast Shower Parameterisation

For high energetic electrons in a homogeneous calorimeter the average longitudinal and transverse shower profile can be described by simple functions [1]. The average longitudinal energy profile is described by a gamma function:

$$\left\langle \frac{1}{E} \frac{dE(t)}{dt} \right\rangle = \frac{(\beta t)^{\alpha-1} \beta e^{-\beta t}}{\Gamma(\alpha)}, \quad (1)$$

where t is the shower depth in units of the radiation length X_0 and E is the shower energy scaled by the critical energy E_c . The depth of the shower's longitudinal maximum, in units of X_0 , is $T = (\alpha - 1)/\beta$, where α is the shape parameter and β the scale parameter of the profile. T and α are directly related to a combination of profile moments, which are extracted from fully simulated EM showers. In general the free parameters are functions of the kinematics of the incoming particle. In this case the parameters depend only on the energy E and the pseudo rapidity η . Because of the azimuthal symmetry of the calorimeter there is no ϕ dependence. In the fit $\ln T$ and $\ln \alpha$ as functions of $\ln E/E_c$ and η are extracted because they are described by a normal distribution. Figure 3 shows the fitted parameters and their widths at discrete energies and their interpolated form.

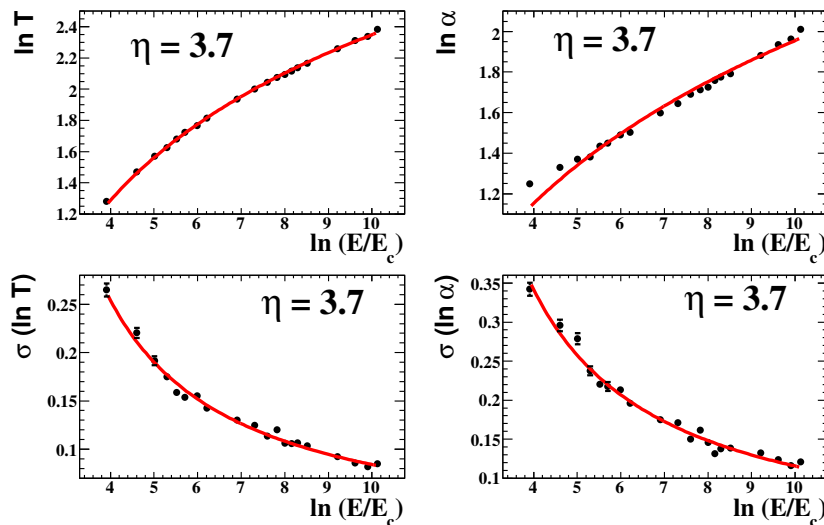


Figure 3. The fitted values for the longitudinal profile parameters $\ln T$ and $\ln \alpha$ and their widths are shown as a function of $\ln E/E_c$. In addition the interpolation function for each variable is shown (red line).

The average transverse energy profile is described by the weighted sum of two rational functions:

$$\left\langle \frac{1}{dE(t)} \frac{dE(t, r)}{dr} \right\rangle = p \frac{2rR_C^2(t)}{(r^2 + R_C^2(t))^2} + (1-p) \frac{2rR_T^2(t)}{(r^2 + R_T^2(t))^2}, \quad (2)$$

with $0 \leq p \leq 1$. Here $R_C(R_T)$ is the median of the core (tail) component and P is a probability giving the relative weight of the core component. As before, the parameters are related to moments of the transverse shower profile and can be estimated from them. For more details see [1].

At simulation time energy spots are generated randomly according to the longitudinal and transverse shower profile. Fluctuations from the sampling resolution or the geometry are included into this process. Figure 4 shows the deposited energy for high energy electrons for three different energies and pseudo rapidities in the forward region. The distribution from full simulation is very well reproduced by the parametrisation.

4. Frozen Shower Library

The idea of the frozen shower library approach is the following: In order to reduce the CPU time spent in simulating a full EM shower, only the high energy part of the shower simulation is performed by Geant 4. If the particles in the shower reach an energy cut-off around a few GeV, they are replaced by previously stored hits from a “frozen shower”. The frozen showers are generated beforehand from fully simulated low energy electrons with discrete energy and pseudo-rapidity values and stored in a library. This approach is similar to the way in which pile-up is introduced into the simulation at LHC experiments. There, a given number of minimum-bias events are overlaid on the hard physics event. Also this approach is taken in computer games to display small details using previously stored animations in contrast to real collision simulation.

4.1. Library Generation

A frozen shower is generated in the following way: The response of EM showers in the calorimeter is simulated for an electron starting at the front of the calorimeter with fixed energy E and position. The position is given by the pseudo rapidity η , the azimuthal angle ϕ at the front of the calorimeter. Only the energy deposits in the sensitive detector are collected. The position of the deposits is transferred into a local coordinate system. The origin of this coordinate system is at the starting point of the primary electron and the z-axis is along its momentum direction.

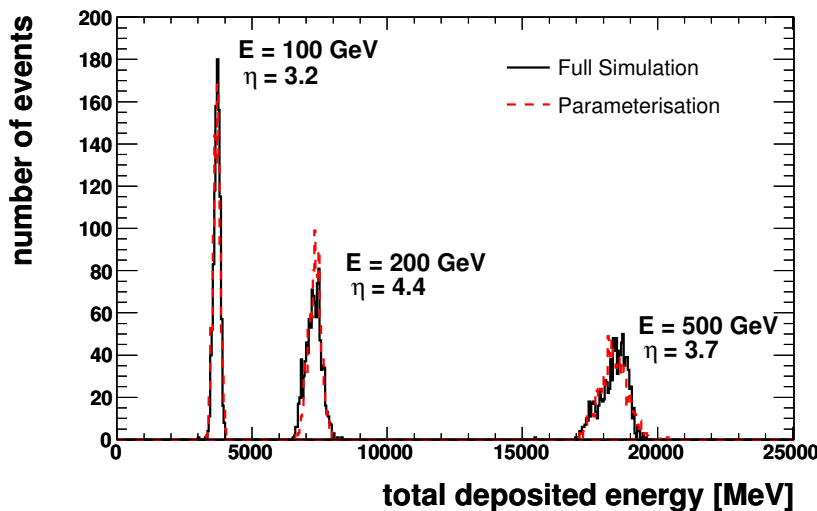


Figure 4. Total deposited energy in the forward calorimeter for electrons of different energies (100, 200, 500 GeV) and pseudo rapidities ($\eta = 3.2, 4.4, 3.7$) for full simulation and parameterisation.

In order to reduce the memory consumption of the shower, the energy deposits are compressed. Details are given in section 4.2.

The algorithm is repeated until the given bin is sufficiently filled. The number of entries should be adequate for the expected number of electrons in full simulation, but a precise criterion needs to be developed. For the barrel with wide η bins 1000 showers are used and for the endcap with finer η bins 500 showers. This process is repeated for different pseudo rapidities η and energies E to produce an appropriate grid in η and E .

4.2. Compression

In order to reduce the additional disk and memory consumption of the frozen shower library every single shower is compressed using the following three steps:

Clustering: Two nearest energy deposits in space are identified. If the distance between these deposits is below the cut-off parameter R_{min} , they are merged into one at the energy-weighted centre of the two deposits. This procedure is repeated until the distance between two deposits for all possible combinations is above R_{min} .

Truncation: The running sum of the energy sorted deposits is calculated and deposits corresponding to a fraction f of the total energy are kept.

Rescaling: The remaining total energy is rescaled to the original energy and the radial coordinates are rescaled to preserve the barycentre and the second moment of the true shower.

In the generation process of frozen shower libraries $R_{min} = 5$ mm, motivated by the granularity of the first sampling of the barrel calorimeter, and $f = 95\%$. Figure 5 illustrates the effect of the compression procedure.

4.3. Binning

The binning in the generated energy E is done logarithmically as expected from the exponential cascade of electromagnetic showers. The values used are 10, 20, 50, 100, 200, 500, 1000 MeV.

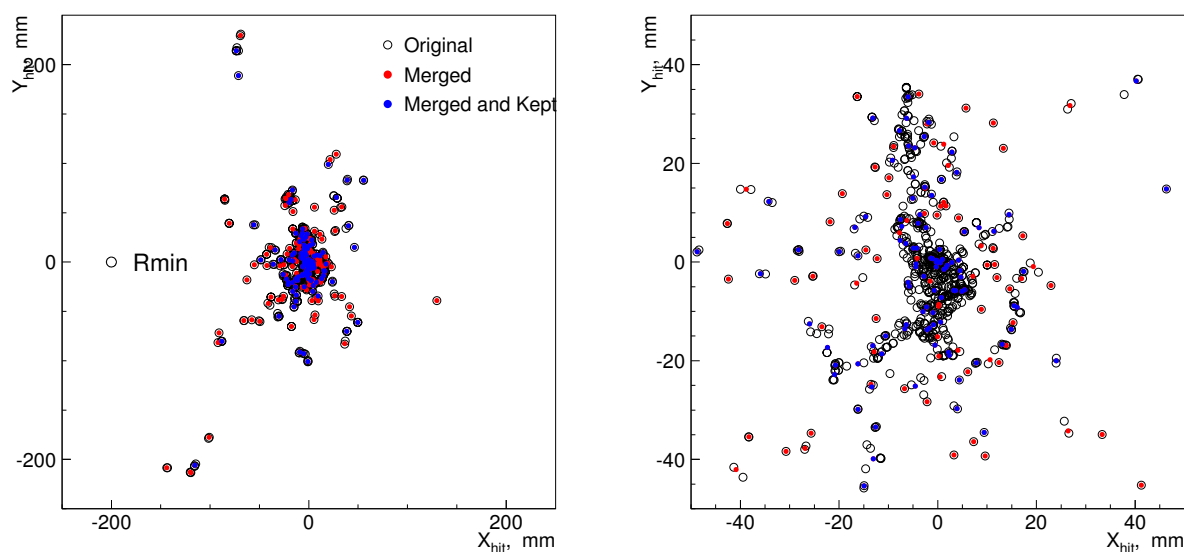


Figure 5. Energy deposits before and after merging and after truncation. The right side shows a zoom of the centre of the left side.

From these discrete points smooth distributions for the number of hits and the deposited energy can be sampled.

The binning in η is not as straightforward as the energy binning and needs to be adjusted to the detector geometry. The layers of active material and absorber are parallel (perpendicular) to the beam axis in the barrel (endcap). Hence the effective radiation length X_0 along the momentum direction for particles from the interaction point varies with η and therefore the shower depths varies also with it. Further the sampling fraction changes in the barrel at $\eta = 0.8$ and in the endcap at $\eta = 2.5$ due to a change in the absorber depths. In the endcap there is an additional sampling fraction variation due to the geometry which is partly compensated by adjusting the high voltage. This together gives a rather complex structure for the total deposited energy as a function of η (see figure 6). The choice for the η bins is motivated by this fact. As an example figure 6 shows the η binning for the endcap calorimeter.

4.4. Simulation

At simulation time incoming electrons are checked for containment in the calorimeter and correct energy range. If the frozen shower library approach is applicable, a shower is picked up from the library. First the η bin is chosen randomly from the two adjacent η bins in the library, where the probability $p(\eta)$ for choosing the lower bin (η_l) is given by $p(\eta) = \frac{\eta - \eta_l}{\eta_u - \eta_l}$. Second the energy bin is chosen from the two adjacent E bins. For the energy the random distribution follows a logarithmic distribution. Then the single energy deposits of the frozen shower are transformed into the ATLAS coordinate system. The total deposited energy of the frozen shower is rescaled according to the energy of the replaced electron. The adjusted energy deposits of the frozen shower are put into the simulation using a dedicated hit making algorithm. This is needed as the standard sensitive detector introduces sampling fluctuations and responses, which are already included in the frozen shower library. Frozen showers from one bin are used in linear order and the full bin can be used more than once.

5. Simulation Strategy

The current strategy for simulation is different for the barrel and endcap calorimeters and the forward calorimeter. The purpose of this is to study the different methods and finally to choose an optimal combination of them. In the barrel and endcap region electrons down to 1 GeV are handled by the full simulation. Electrons below 1 GeV are substituted using the frozen shower library. Electrons below 10 MeV are killed and their energy deposited in one spot. In the forward

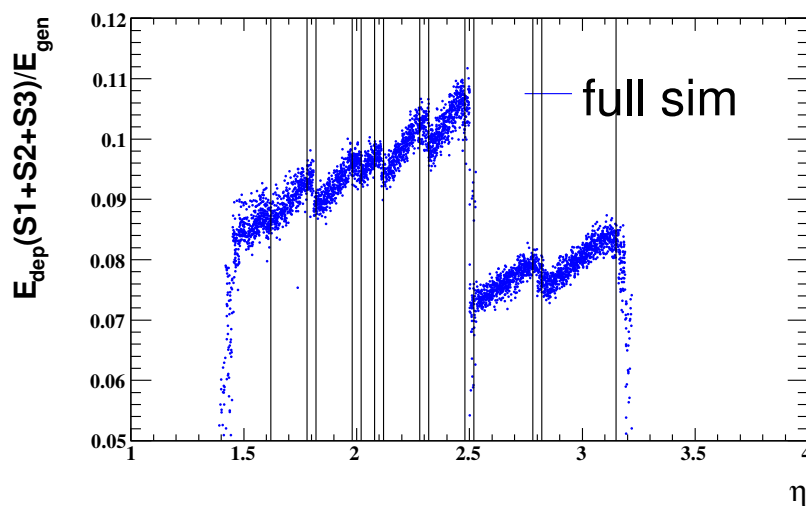


Figure 6. Deposited energy in the endcap calorimeter normalised to the total generated energy. The bins for the frozen shower library are indicated by the black lines.

region electrons down to 500 MeV are handled by the fast shower parameterisation. Between 500 MeV and 10 MeV full simulation is used and below 10 MeV electrons are killed and their energy is deposited in one spot. Photons are not treated separately at the moment, as they are an electron-positron pair after pair production.

6. Results

The average time gain for single electrons/positrons of 50 GeV starting from the interaction point is shown in figure 7. The time is reduced by a factor of ~ 10 for electrons, as long as they are away from cracks and edges ($\eta = 0, 1.4, 2.5, 3.2$). Apparently the parameterisation is not applicable near the cracks and edges because the shower must be fully contained in the calorimeter to be parameterised. Averaging over the different calorimeter regions the time gain in the barrel, endcap and forward calorimeter is 3.3, 4.9 and 2.8, respectively. The average gain in simulation time for a typical physics event is ~ 2 . Still most of the time is spent in the EM calorimeters, although the fraction is reduced to $\sim 40\%$. Other subdetectors as the muon system become more important now and should be considered for optimisation. Detailed numbers for each subdetectors are listed in table 1.

Figure 8 shows the deposited energy after simulation for the same sample as a function of the pseudo rapidity η . In the forward region there is good agreement between full and fast simulation, while there are some discrepancies in the other two. In the endcap region there are small discrepancies around the transition from the inner to the outer wheel and at the high η edge. In the barrel the shape is very well reproduced by the fast simulation although there is a bias of $\sim 1\%$ below $\eta = 0.8$ and $\sim 2\%$ above it. The deposited energy in the different samplings is described very well by the fast simulation. As examples the deposited energy in the presampler and the first sampling for 50 GeV electrons/positrons with $\eta = 0.25$ is shown in figure 9. Further the resolution in the pseudo rapidity η and azimuthal angle ϕ calculated within the different samplings are also well described except for $\Delta\phi$ in the second sampling. Here some smearing effects from the accordion structure are not taken into account. In the future this will

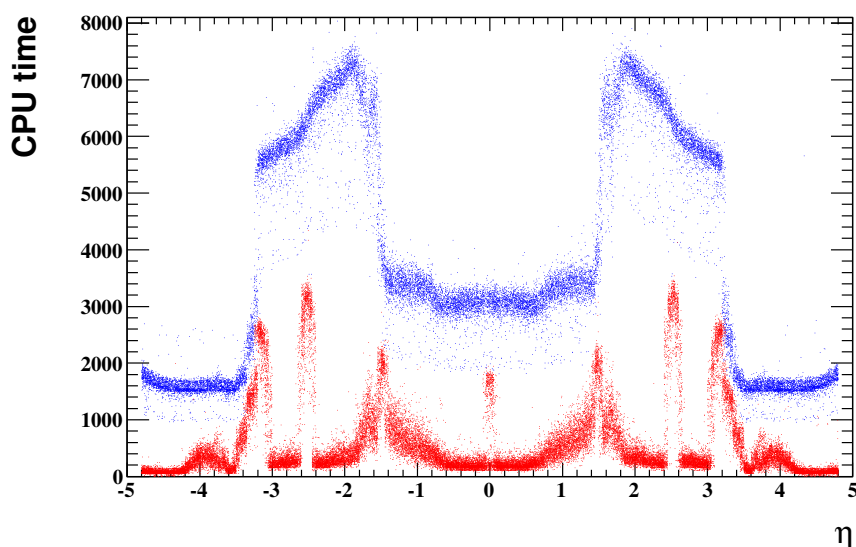


Figure 7. Simulation time in arbitrary units for full (blue) and fast (red) simulation as a function of the pseudo rapidity η .

Table 1. Total time and fraction of time spend in each subdetector for a selection of physics processes and full and fast simulation.

subsystem	$Z \rightarrow e^+e^-$		di-jets		SUSY	
	full	fast	full	fast	full	fast
subsystem	time/event [%]					
tracker	3.7	7.8	3.8	7.2	4.4	8.0
calo - barrel	5.9	6.0	7.3	5.8	11.0	7.7
calo - endcap	32.0	24.0	46.1	27.1	33.9	23.0
calo - forward	33.4	19.0	14.5	10.9	20.6	12.1
calo - hadronic	3.0	5.7	6.6	13.4	4.7	10.3
muon	5.7	13.0	6.4	12.5	8.0	13.9
other	6.5	12.7	6.3	11.1	7.7	12.7
dead material	9.8	11.7	9.0	12.0	9.7	12.3
event	7.7 min	3.3 min	13.6 min	6.5 min	12.8 min	6.3 min

be improved. As examples the resolution in η in the first sampling and ϕ in the second sampling are shown in figure 10.

The same degree of agreement between full and fast simulation is seen also at reconstruction level. Figure 11 shows the reconstructed energy for 50 GeV electrons/positrons with a pseudo rapidity of $\eta = 0.25$. The mean energy from fast simulation is 0.9% below the one from full simulation and the width of the distribution is narrower by 8.6%. As another example figure 12 shows two quantities, which are used for electron/photon identification and fake rejection:

- the shower width $\omega_{3strips}$, which is calculated along the η direction from 3 strips in the first sampling
- the lateral shower shape $R_{\eta(37)}$, which is the ratio of reconstructed energies in the second sampling in a 3x7 and 7x7 cluster

The features of both distribution are reproduced and the agreement between full and fast simulation is good. Further studies on the electron/photon identification are needed to decide if this agreement is sufficient.

In general the agreement between full and fast simulation is quite good for this stage of development. The disagreements that persist can be traced to the crudeness with which the fast simulation is currently implemented, compared to the full simulation. We expect improvement in the coming months, without the need for any sacrifice in CPU performance. By contrast, only a very few fine effects present in the full simulation will be lost by simulating the showering in a separate processing step, due to irreducible features of the frozen shower approach. These include, for example, the modulation of the response vs ϕ which results from the accordion structure.

7. Conclusions

The fast shower parametrisation and the frozen shower library as two approaches for speeding up the simulation process of electron showers in the calorimeter have been implemented within the ATLAS simulation framework. Switching between these options and full Geant 4 is simple and does not affect output format at all. Tests have shown that both methods achieve significant improvement in simulation time without losing too many details of the shower. The gain in time can be around an order of magnitude for electrons away from cracks and edges. For typical physics events the gain is a factor of 2.

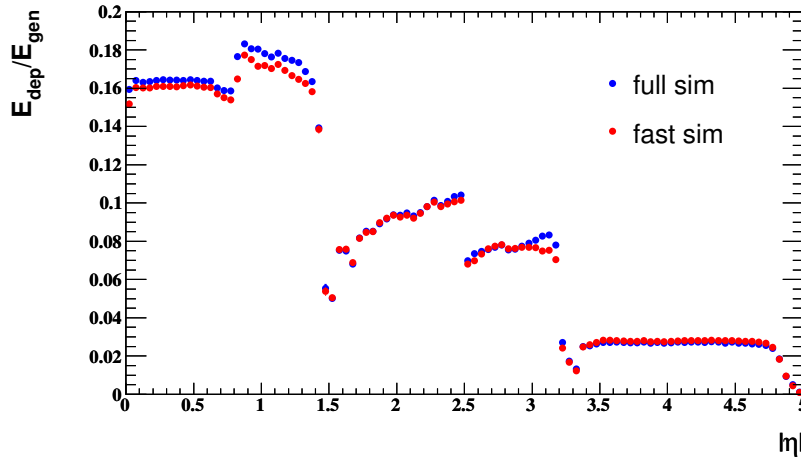


Figure 8. Deposited energy for full and fast simulation as a function of η from 50 GeV electrons/positrons.

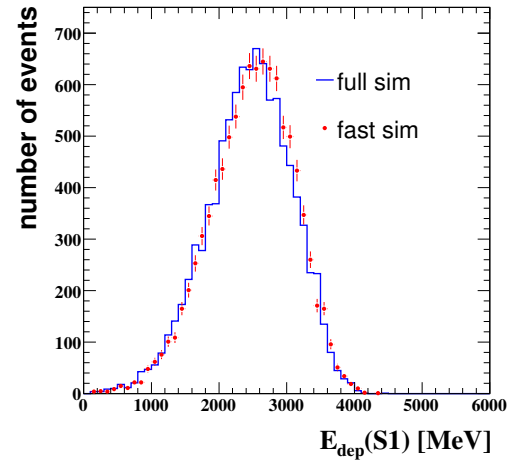
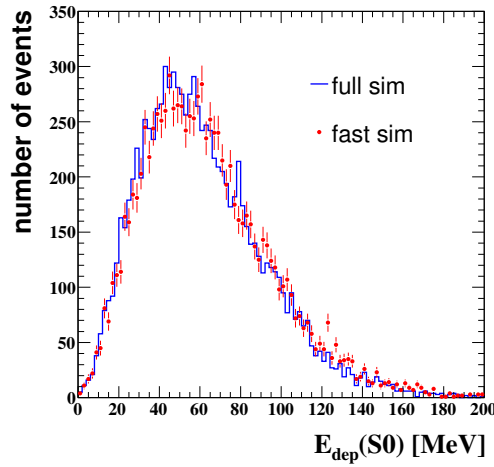


Figure 9. Deposited energy in the presampler (S0) and first sampling (S1) from 50 GeV electrons/positrons with $\eta = 0.25$.

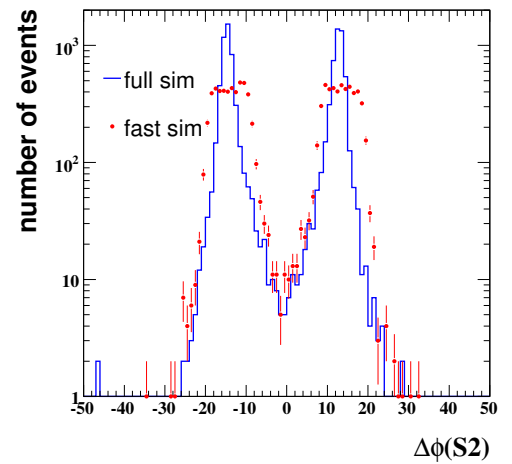
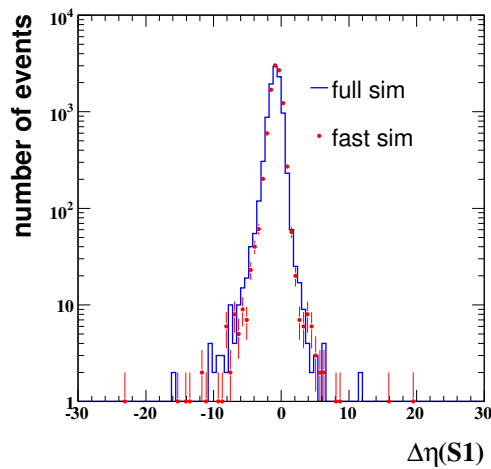


Figure 10. Resolution in η calculated from first sampling (S1) and ϕ calculated from second sampling (S2) from 50 GeV electrons/positrons with $\eta = 0.25$.

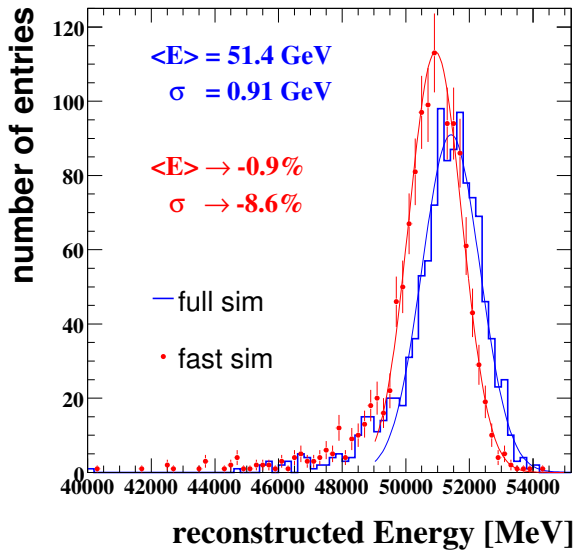


Figure 11. Reconstructed energy for full and fast simulation from 50 GeV electrons/positrons with $\eta = 0.25$.

The fast shower parametrisation gives a good gain in time and good agreement with full simulation for high energy electrons and a homogeneous detector. Both conditions are not very often valid for electrons from typical physics events. Most improvement in time is coming from the usage of frozen shower libraries for low energy electrons. This work has shown that this idea is very suitable for this kind of problem. There are still some minor discrepancies between full and fast simulation, but further studies will help to understand and solve them.

References

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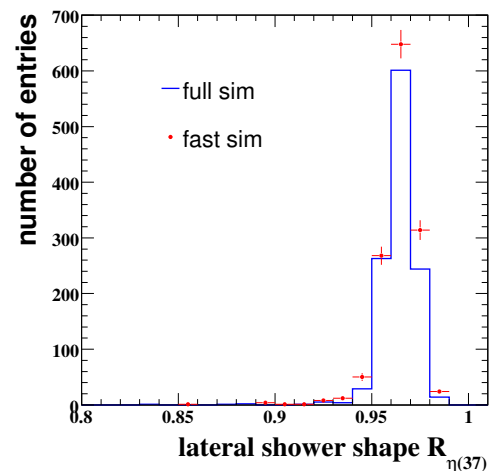
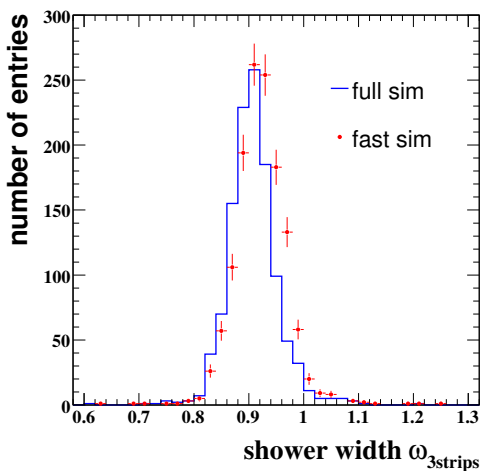


Figure 12. The shower width $\omega_{3strips}$ and the lateral shower shape $R_{\eta(37)}$ for full and fast simulation from 50 GeV electrons/positrons with $\eta = 0.25$.