DESY Summer Student Programme 2011

Studies of "Frozen Showers" - Calorimeter Fast Simulation Method

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Abstract

This report discusses studies of frozen showers- a fast simulation method used in the ATLAS calorimeters. New frozen shower libraries were created for EMB, using a continuous energy storage method rather than binning in energy and pseudorapidity, η, used in production libraries. These new libraries were validated and found to reduce CPU times to about 15% of the full simulation time. Close agreement is seen between full simulation with GEANT4 and fast simulation with frozen showers, even on the first validation with no tuning to the library. The results are similar to the current libraries which have undergone tuning of 1-2% in some regions. More tuning and larger data samples are required to test the new libraries further.

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Contents

1 Introduction

1.1 ATLAS detector

The Large Hadron Collider (LHC) has been built at CERN in Geneva, Switzerland in the underground tunnel previously used to collide electrons and positrons in the LEP collider. ATLAS (A Toroidal LHC ApparatuS) is one of two general purpose LHC detectors which records proton-proton interactions for later analysis. The collider has been designed to provide proton collisions with a centre of mass energy of 14 TeV and luminosity of 10^{34} cm^{-2}s^{-1} leading to 40 million collisions per second in the detector.

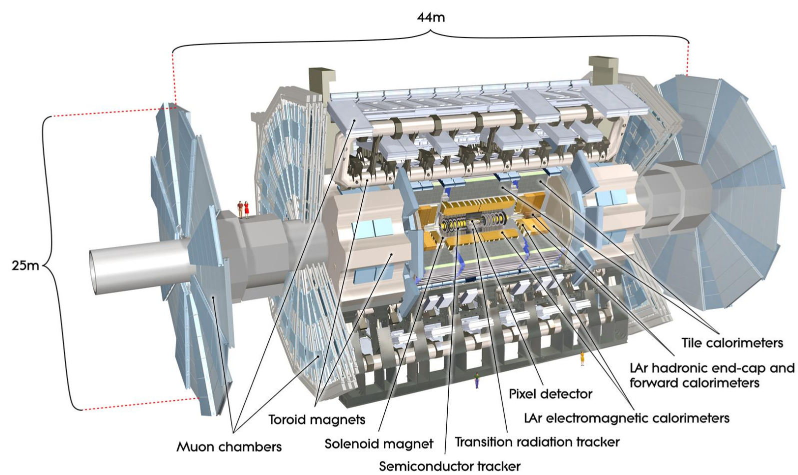

Figure 1: Cut-away view of the ATLAS detector at the LHC. It is the largest of its type in the world, with a length of 44m, diameter of 25m and mass of 7000 tonnes. The magnetic field in the detector is generated using an eight coil toroid around the central region. [1]

Figure 1 shows the roughly cylindrical shape of the detector with the proton beams passing in from left and right to meet at the interaction point in the centre of the detector. Produced particles pass through the trackers which measure their momenta, before travelling into the calorimeters where most particles are stopped and their energy is measured. Muon chambers measure the momenta and track the paths of muons which pass through the rest of the detector unstopped. Magnets ensure that charged particles move in curved trajectories to further aid particle identification.

1.2 LAr EM Calorimeters

Figure 2 shows the inner part of the calorimeter, the sampling electromagnetic (EM) calorimeter, designed to measure the energy of particles which interact electromagnetically. A single charged electron or photon entering the calorimeter creates a cascade of many more electrons and photons. Electrons scatter and emit x-ray wavelength photons by bremsstrahlung radiation, while photons

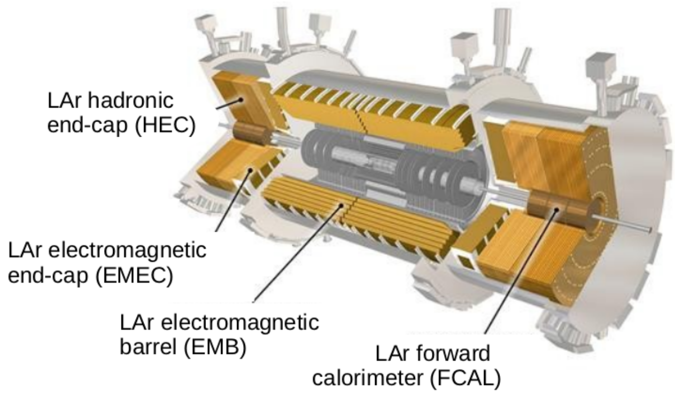

Figure 2: A cut-away view of the ATLAS EM calorimeter. [1]

create an electron and positron by pair production. Energy continues to be lost until the photons are absorbed by atoms, bringing an end to each branch of the shower.

Liquid Argon (LAr) is used as the active medium throughout the EM calorimeter, though the design varies for different regions. The barrel (EMB) and end caps (EMEC) use accordion-shaped lead electrodes as absorbers. The layout ensures continuity in the azimuth (ϕ) to minimise cracks. The forward calorimeter (FCAL) lies close to the beam pipe so has a high particle flux. In this region the LAr lies between longitudinally placed copper rod absorbers [2].

With pseudorapidity defined as $\eta = -\ln[\tan(\theta/2)]$; the acceptance of EMB is $|\eta| \leq 1.5$, that of EMEC is $1.4 \leq |\eta| \leq 3.2$ and FCAL covers the very forward region of $3.2 \leq |\eta| \leq 4.9$ [1].

1.3 Fast Simulation Techniques

Simulations are widely used in HEP to study physics processes and develop data analysis techniques for real results. ATLAS events are simulated in detail with GEANT4. The complexity of the detector and the high energies and numbers of particles produced mean that these "full simulations" can take about 10 minutes to compute (excluding digitization and reconstruction). Up to 70% of this time is spent on particles in the calorimeters and most of this in their electromagnetic layer [2]. Several methods have been developed to decrease the time to simulate EM showers in the calorimeters without reducing the overall accuracy. These are fast simulation techniques [3].

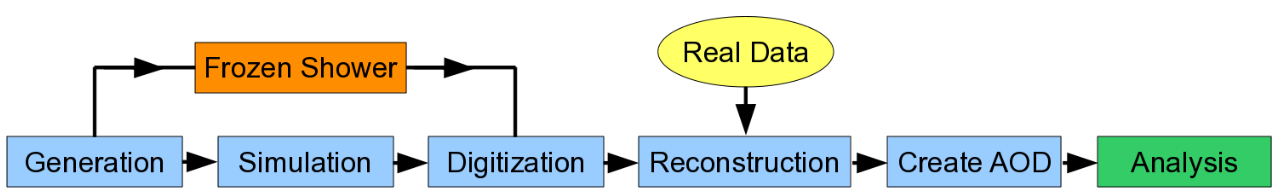

Figure 3: The Monte Carlo simulation chain.

To save CPU time, showers are stopped when a particle has an energy less than 10 MeV and the particle is replaced by a "spot" with the same energy. This can be called the "killing" method.

At energies less than 1 GeV the "frozen shower" method is utilised. At this point the simulation is terminated and the initial EM particle is replaced by a pre-simulated shower from a file library [4]. This method is considered in more detail in this project. For particles with energy greater than 10 GeV a "parametrisation" method can be used which uses parametrised functions to describe the longitudinal and transverse distributions of energy within the EM showers. (More detail can be found in the literature [4, 5])

2 Frozen Showers

2.1 Current Method of Generating Frozen Shower Libraries

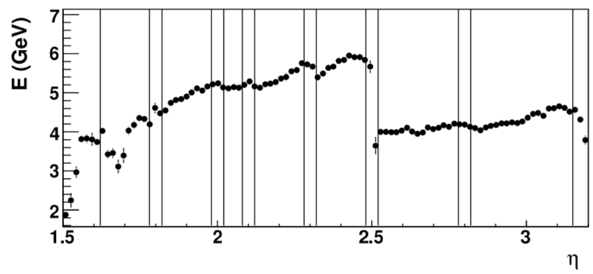

Figure 4: The energy deposited by 64 GeV electrons in EMEC. The library bins in η are shown as vertical lines. [4]

Current frozen shower libraries are generated with EM particles started from just inside the calorimeter. A value of ϕ is randomly chosen and the particle energy and η values are fixed. This creates a library which is binned in energy and position. The same values are used for the energy bins in all calorimeters: 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000 MeV, while position binning varies by calorimeter. Libraries for EMB and EMEC are binned in η as a result of their accordion geometry. FCAL binning is more complex due to its different geometry.

The positions and widths of η bins can be decided by examining an energy vs η profile, e.g. figure 4 for EMEC. Small bins should be introduced in regions with jumps in the energy, but bins can be made wider in regions with a roughly uniform energy response. Bins should not be made too fine to avoid very low statistics and the associated errors.

At simulation time a low energy particle is replaced by a frozen shower stored in the library. The shower to substitute is decided by a complex algorithm which ensures that the shower is from an initial particle with similar properties to the one which is to be replaced. Showers are not removed from the library, so can be used repeatedly in a single simulation or in many more runs.

2.2 New Method of Generating Frozen Shower Libraries

The current method creates quite realistic libraries, but there are some areas where they can be improved. An alternative method of generation uses 20-50 GeV particles started from an interaction point and propagated through to the calorimeter by GEANT4, just as in a full simulation. The four-momenta and positions of the particles in the showers are stored to build the frozen shower library.

This method creates libraries which are still binned in η, but energy storage is continuous rather than fixed.

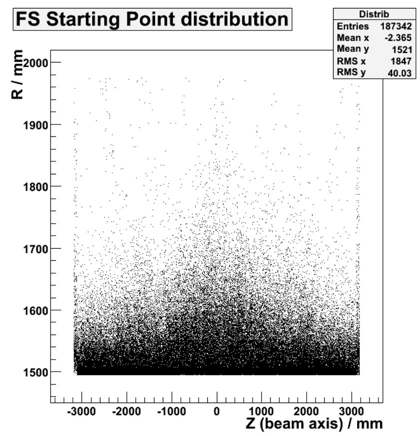

Figure 5: A plot of the frozen shower starting positions in the calorimeter for the new EMB electron library.

Figure 5 is a plot of the distribution of frozen shower starting points in the calorimeter for libraries created with this new method. Starting points can be distributed throughout the calorimeter rather than at fixed values of η as with the current method. Additionally, more showers are stored in the locations which will be called more often. Information for the two library types is given in the appendix. It can be seen that the current generation method creates libraries with the same number of showers in every bin, while for the new method each bin contains a number of showers which is proportional to the number of times that bin will be required.

3 Results

3.1 Validation of Libraries

Library validation requires running full and fast simulations with the same settings and comparing the produced files. Python scripts were used to run both types of simulations- for fast simulations the ROOT files of the frozen shower libraries were included and utilised at simulation time. Initially both simulations were run with the settings which were used to create the frozen shower library. This provides an output check that everything is working as it should, then other regions can be tested to see how accurate the library is.

3.1.1 Current Libraries

An existing electron library for EMB was validated using the settings it was created with (ATLAS release 16.6.7.6, Geometry version ATLAS-GEO-18-01-00 and Conditions tag OFLCOND-SDR-BS7T-05-06) with electrons generated with energies between 20 and 50 GeV. The produced output files from the full and fast simulations are compared in figure 6.

The Erec/Egen histograms from the two simulations have similar mean values and the same shape. This suggests that the energy responses are roughly the same for the two methods of

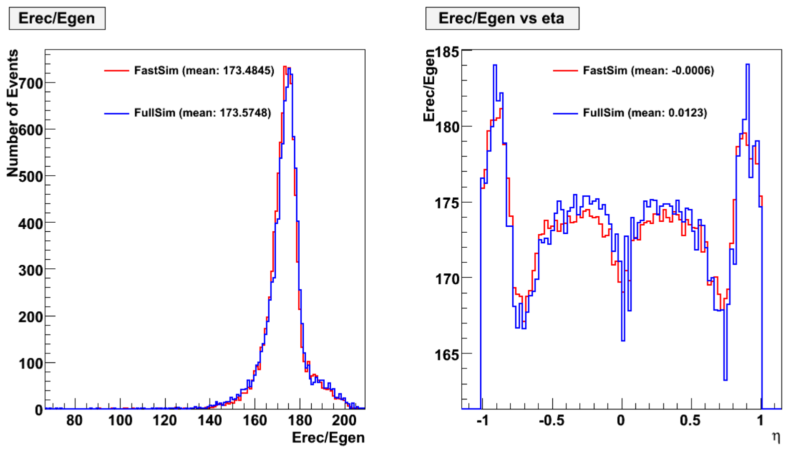

Figure 6: An Erec/Egen histogram and a profile of Erec/Egen vs η to compare fast simulation with current libraries to the full simulation.

simulation. Generally the current library appears to give realistic results, but there are some local differences of about 1-2% at η=0 and η=$\pm$0.8. At η=0 there is a small crack region in EMB, so Erec/Egen is less at this point. The calorimeter is symmetric about η=0 and at η=$\pm$0.8 the geometry changes leading to a discrepancy between the two simulations.

3.1.2 New Libraries

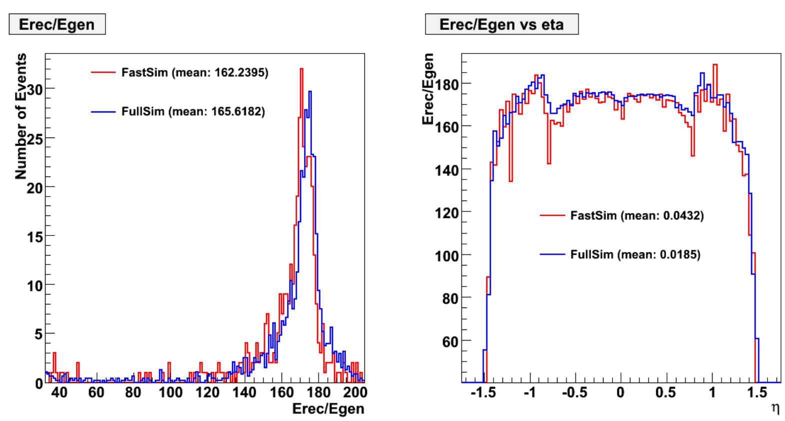

Figure 7: An Erec/Egen histogram and a profile of Erec/Egen vs η to compare fast simulation with new libraries to the full simulation.

Frozen shower libraries were generated for electrons, photons and neutrons in EMB using the new continuous energy storage model. The validation process was then identical to that for the pre-existing library, but all three new EMB libraries were included in the fast simulation.

Figure 7 shows the results of the validation of these new libraries, with 2000 electrons generated with energies between 20 and 50 GeV and in the range -1.5 $\leq \eta \leq$ 1.5. The agreement between the two simulations is not quite as good as it was for the current library, but it must be noted that these are the results of the very first validation, with very few statistics, while the current libraries have undergone tuning of up to 2% in problem regions.

The Erec/Egen profile in figure 7 shows a discrepancy in Erec/Egen between the two simulations at $\eta= \pm 0.8$. This difference is again due to the change in calorimeter geometry at this point, and is completely expected in the first validation. Improvements can be made by varying the η binning around 0.8.

3.1.3 Examining η=0

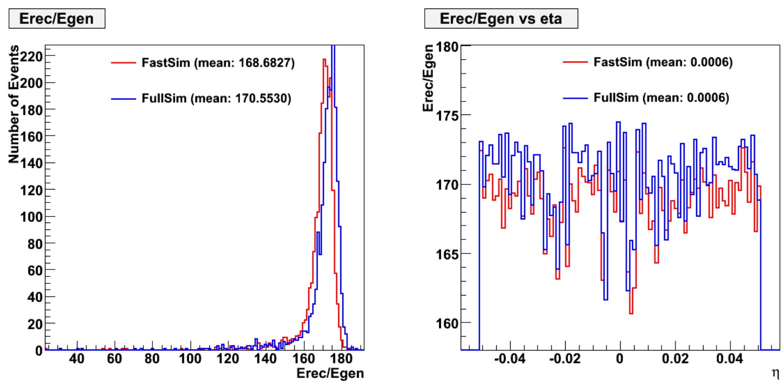

Figure 8: Erec/Egen histogram and Erec/Egen vs η profile for the $\eta \simeq 0$ region.

Current frozen shower libraries are somewhat unrealistic at η=0 due to a small crack region (see figure 2). To test the new libraries at this point another validation was performed with the same conditions as before, but considering 2000 electrons in the range -0.05 $\leq \eta \leq$ 0.05 rather than the whole EMB range.

The results of this validation are shown in figure 8. It is clear that this new library does not fix the problems in this region as the results of fast simulation are still somewhat different to the full simulation. However the Erec/Egen histograms have the same shape, so tuning of the library by altering the η bins around η=0 should correct these problems and increase the energy response across the whole region, thus improving the agreement in the Erec/Egen vs η profile.

3.2 Longitudinal Shower Shapes

It is possible to study the longitudinal shower shape by looking at the energy deposited in different sampling regions of the calorimeter. For particle identification purposes, it is important for frozen shower simulations to have a good agreement with full simulations for shower shape as well as energy response. Figure 9 shows distributions of the energy deposited in the first four sampling regions of the calorimeter. The data sets show agreement for the first three regions (s0, s1 and s2) suggesting that the shower shapes are similar, but in the fourth region (s3) more energy is deposited by the full simulation than by the fast simulation. This is to be expected, as frozen showers are generally more compact and very few showers are energetic enough to reach so far into the calorimeter. The showers that do penetrate that far into the calorimeter deposit very little energy (only a few 10s of MeV rather than a few GeV in the second and third sampling regions) so the fractional energy in s3 is very small and this discrepancy does not matter too much.

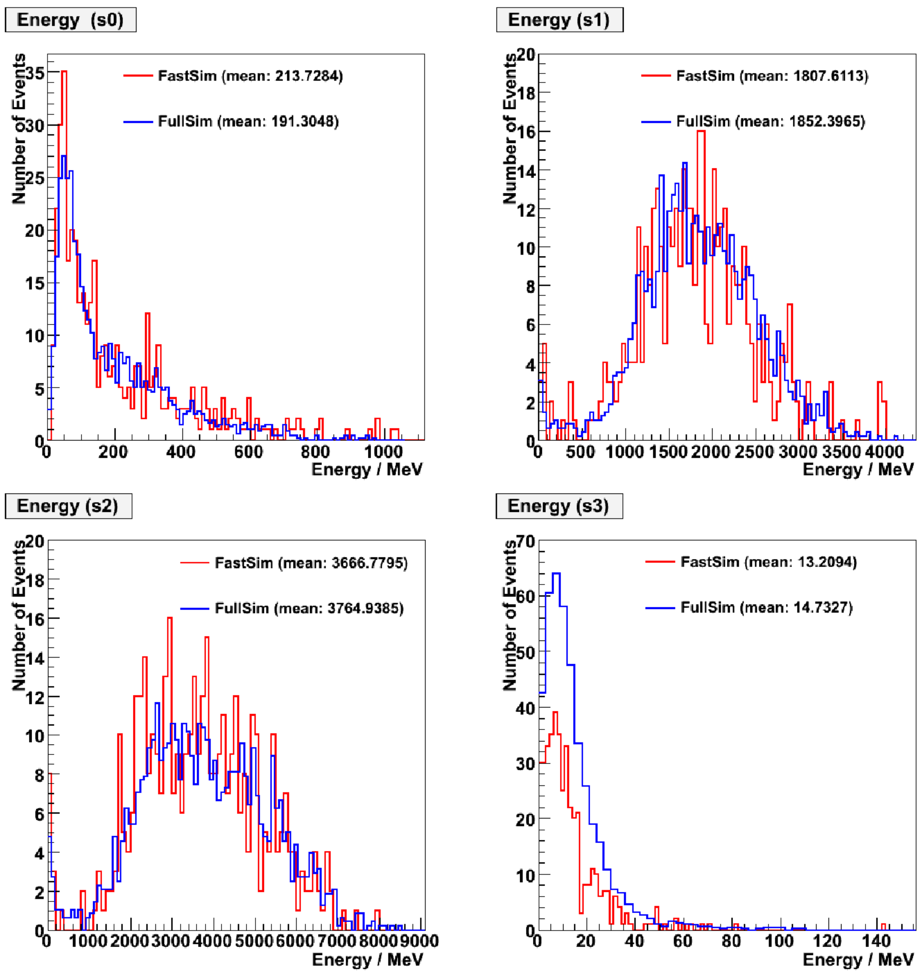

Figure 9: Histograms comparing the energy deposited in the first four sampling regions of the EMB calorimeter for full and fast simulations.

3.3 CPU Improvement

Figure 10 shows that the CPU time for fast simulations is roughly 15% of that for full simulations with GEANT4. It is also clear from the profile to the right of this figure that the CPU time is almost independent of energy for fast simulations, while for full simulations the CPU time for 50 GeV particles is more than double that for 20 GeV particles. This makes frozen showers an especially attractive option for high energy particle simulations which can be incredibly slow to compute with full simulations.

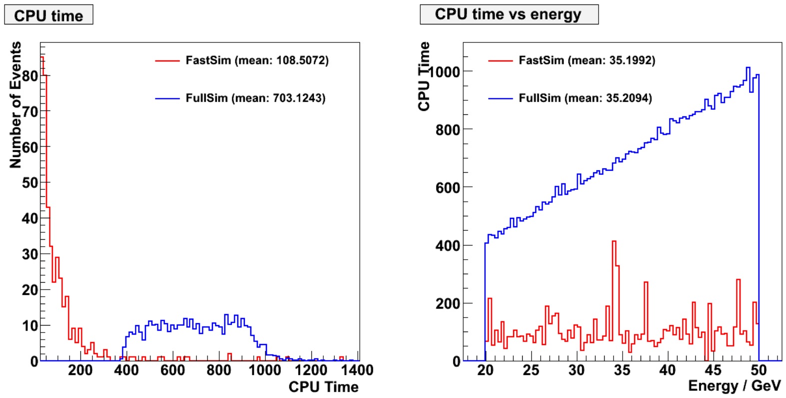

Figure 10: A CPU time histogram and a profile of CPU time vs energy for full and fast simulations.

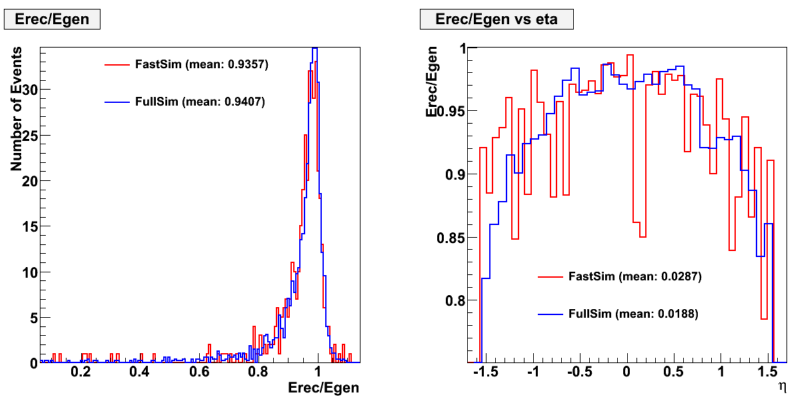

Figure 11: An Erec/Egen histogram and a profile of Erec/Egen vs η plotted from the ntuple.root files from both full and fast simulation after reconstruction.

3.4 After Reconstruction

To study description of the electron identification variables used in the analyses, the samples generated with the full and frozen shower simulation were digitized and reconstructed. Standard job transformation scripts, 'Digi_trf.py' and 'Reco_trf.py' were used for digitiation and reconstruction respectively. The resulting AOD files were then converted to ntuple.root for plotting.

Figure 11 has a histogram of the Erec/Egen ratio and a profile of Erec/Egen against η. After reconstruction the mean of the Erec/Egen histogram should be close to 1, which it is for both full and fast simulations in this figure. Frozen showers seem to give a reasonable description of the reconstructed energy, but more statistics are required to fully validate the region close to η=0.

Figure 12 shows the default plots after the reconstruction stage. The top-centre and top-right plots compare the transverse shower shape of full and fast simulations. There seems be be good agreement between the two samples, suggesting that the frozen shower shapes are realistic and usable. Fast simulations also appear to give a decent description of the shower width- described in the bottom-left and bottom-right plots of figure 12. In general the two data sets seem close in all the plots.

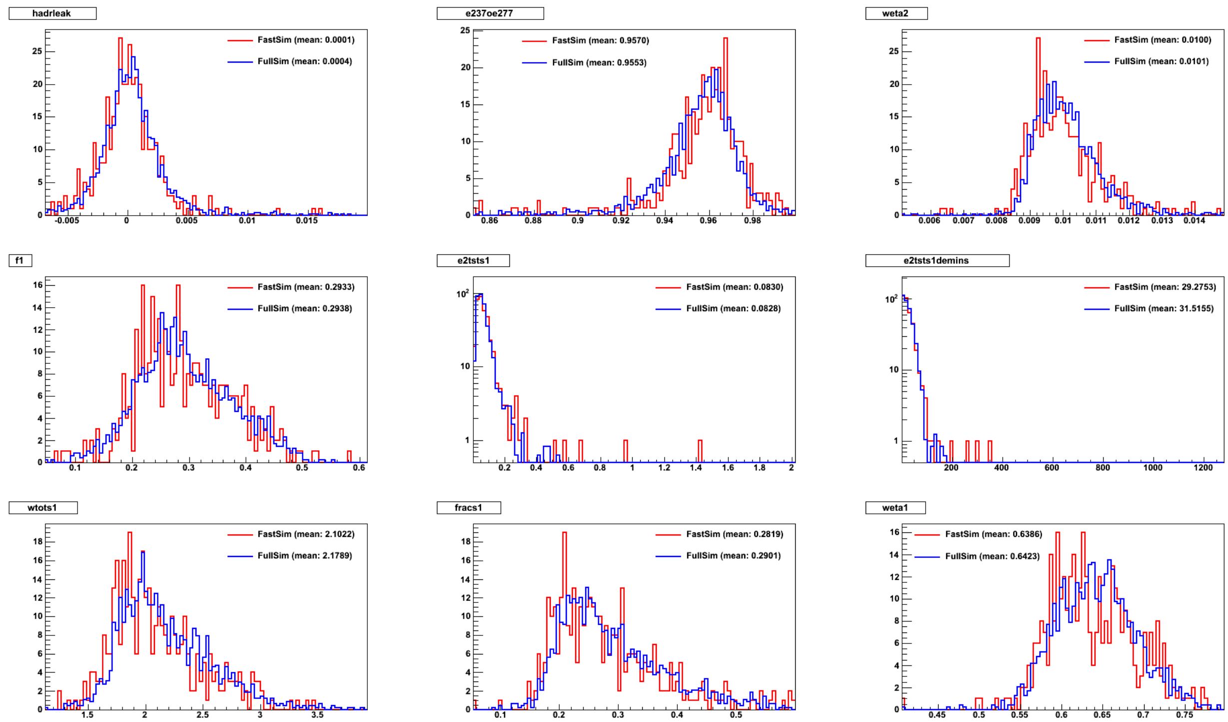

Figure 12: Nine default plots from the script used to plot the ntuple.root files after reconstruction. Full and fast simulations are compared.

4 Conclusions

A new frozen shower library has been produced for EMB using 'continuous energy storage' rather than energy binning which is currently used. This method creates frozen shower starting points throughout the calorimeter, so should improve the accuracy of fast simulations. An initial validation of this new library type has been performed using generated electrons and libraries for electrons, photons and neutrons in EMB. These new libraries have been found to give similar results to the libraries used in ATLAS production, but this was achieved with no tuning and the library in production has had corrections of up to a few percent with tuning in some regions.

The next step is to repeat the validation simulations with higher statistic samples and then proceed to vary η binning to tune the libraries, especially around η=0.8 and η=0 where there are geometry changes and crack regions respectively. The ultimate goal is to produce libraries which can be used without tuning of η binning.

5 Acknowledgements

I would like to thank George Sedov for his technical help and the use of his many scripts and Sasha Glazov for his advice and feedback on my work. The DESY Summer Student Programme has been extremely useful and enjoyable. It has been fun to meet people from around the world with similar interests, learn about different cultures and of course to live and work in Germany for 8 weeks.

References

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[3] The ATLAS Collaboration. The ATLAS Simulation Infrastructure. *European Physical Journal C*, 70:823–874, December 2010.

[4] E Barberio and J Boudreau et al. Fast shower simulation in the atlas calorimeter. *Journal of Physics: Conference Series*, 119(3):032008, 2008.

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6 Appendix

Number of etabins: 8 | Number of ebins 10

etas\ebins	1.0	2.0	5.0	10.0	20.0	50.0	100.0	200.0	500.0	1000.0
0.1	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
0.3	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
0.5	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
0.795	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
0.8	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
0.81	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
1.1	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
1.3	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

Figure 13: The layout of a current frozen shower library for electrons- showers are binned in energy and η and each bin contains the same number of showers.

Number of etabins: 9
Number of showers: 85867

etas\ebins	<1	<2	<5	<10	<20	<50	<100	<200	<500	<1000
# 0.0	515	150	371	555	682	862	505	424	424	328
# 0.1	1126	303	769	1180	1468	1686	1091	883	949	726
# 0.3	1100	312	759	1230	1492	1681	1113	866	886	685
# 0.5	1435	544	1369	2174	2577	2834	1662	1274	1265	929
# 0.795	17	14	27	35	54	53	33	21	15	20
# 0.8	41	21	60	78	94	93	57	35	40	25
# 0.81	1401	580	1875	3010	3462	3497	1838	1307	1135	720
# 1.1	888	484	1467	2291	2663	2571	1295	800	679	365
# 1.3	611	437	1387	2161	2409	2193	1020	655	419	230

Figure 14: The layout of the new frozen shower library for electrons- showers are still binned in η, but a continuous energy storage is used. Each bin contains a number of showers which is proportional to the number of times the bin will be required.