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The New ATLAS Fast Calorimeter Simulation

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Producing the large samples of simulated events required by many physics and performance studies with the ATLAS detector using the full GEANT4 detector simulation is highly CPU intensive. Fast simulation tools are a useful way of reducing the CPU requirements when detailed detector simulations are not needed. During Run 1 of the Large Hadron Collider (LHC), a fast calorimeter simulation (FastCaloSim) was successfully used in ATLAS. FastCaloSim provides a simulation of the particle energy response at the calorimeter read-out cell level, taking into account the detailed particle shower shapes and the correlations between the energy depositions in the various calorimeter layers. It is interfaced to the standard ATLAS digitisation and reconstruction software, and it can be tuned to data more easily than Geant4. Now an improved version of FastCaloSim is in development, incorporating the experience with the version used during Run 1. The new FastCaloSim aims to overcome some limitations of the first version by improving the description of substructure variables for boosted jets, and giving a better performance in the forward calorimeters, which is important for forward jets in vector boson fusion topologies. A first partial prototype is available and is being tested and validated now. ATLAS plans to use this new FastCaloSim parametrisation to simulate several billion events in the upcoming LHC runs.

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1. Introduction

To run successful data analyses for the ATLAS experiment [1] at the LHC [2], simulated Monte Carlo event samples are required to accurately represent both the physical processes of interest and their interactions with the detector. The full simulation of the ATLAS detector is handled with the Geant4 package [3] which models a detailed description of particles as they interact with the materials in the full detector geometry. However the disadvantage of this level of detail is the CPU time requirement of several minutes per event, in particular about 90% of this time is spent simulating the development of particle showers in the calorimeters [4]. As the luminosity of the LHC increases, this simulation time requirement becomes increasingly challenging to produce events with sufficiently large statistics. The ATLAS Fast Calorimeter Simulation (FastCaloSim) was developed to provide a parametrised simulation of the particle energy response and distribution in the calorimeter, reducing the simulation time by an order of magnitude. This article outlines how an improved version of FastCaloSim is being developed, describing its major principles of operation. Section 2 will give an overview of the structure of the ATLAS calorimeter, with a summary of legacy FastCaloSim and the improvements included in the upgrade in Sections 3 and 4 respectively. The current state of the package along with steps to validate it are presented in Section 5, followed by a summary in Section 6.

2. The ATLAS Calorimeter

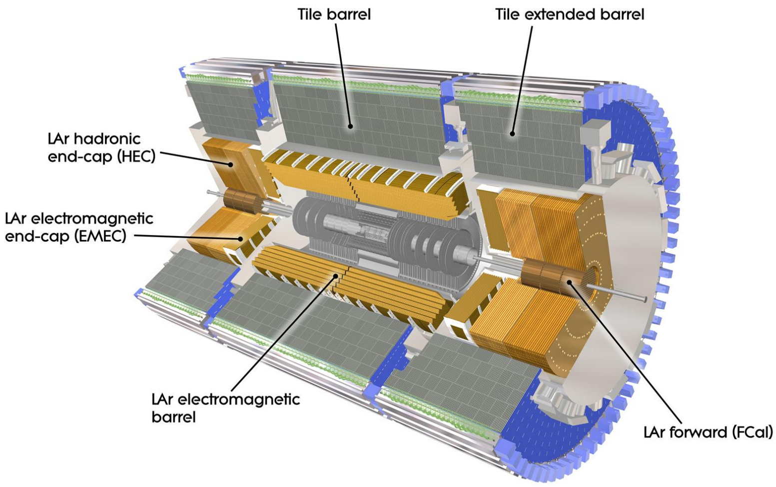

Figure 1: A schematic of the ATLAS calorimeter system [1].

The calorimeter system of the ATLAS detector is shown and labelled with its principal layers in Figure 1. The electromagnetic calorimeter is divided into a barrel section (EMB, $|\eta| \leq 1.475$) and an end-cap section (EMEC, $1.375 \leq |\eta| \leq 3.2$). It is a liquid-argon (LAr) detector with zig-zagging accordion shaped electrodes and lead absorber plates. The hadronic tile barrel (TileCal) is composed of two small extended barrel cylinders ($0.8 \leq |\eta| \leq 1.7$) and a larger barrel ($|\eta| \leq 0.8$).

TileCal is a sampling calorimeter comprising of alternating layers of steel absorber and scintillating tiles as the sampling medium. The hadronic end-cap (HEC, $1.5 \leq |\eta| \leq 3.2$) overlaps with TileCal, but uses LAr as the active medium and copper plate absorbers. Finally the forward calorimeter (FCal, $|\eta| \leq 4.9$) uses, on each end-cap, an innermost module with copper absorber optimised for electromagnetic interactions, and then two other modules with tungsten absorber for hadronic showers, the FCal also uses LAr as the active medium [1].

3. Legacy ATLAS Fast Calorimeter Simulation

Legacy FastCaloSim was developed to speed up the time spent simulating each event, while still reproducing the key features of reconstructed particle properties. This is managed by simplifying the calorimeter geometry by modelling the cells as cuboids, then replacing the development of particle showers with a parametrised calorimeter response based on the full Geant4 simulation of $\sim 30 \times 10^6$ single particle events. To further simplify the model, only photons and electrons are used for the parametrisation and simulation of electromagnetic showers, and charged pions are used in lieu of all hadrons [5].

The single particle events are generated in a fine grid of energy and pseudorapidity, then when simulating a particle in the calorimeter the closest matching parametrisation is loaded into memory and the response is randomly sampled from that. Shower development is split into longitudinal energy deposition per calorimeter layer and lateral shape of the energy density around the shower axis. Legacy FastCaloSim uses a longitudinal parametrisation that reproduces fluctuations and correlations in shower development, but only average lateral shower properties and uncorrelated energy fluctuations. This renders the fast simulation unable to describe hadronic shower sub-clusters, preventing use in analyses involving jet substructure. It is the objective of the FastCaloSim upgrade to allow it to describe sub-clusters while also incorporating developments of updated geometry and physics lists from Run 1 data.

4. ATLAS Fast Calorimeter Simulation Upgrade

For the FastCaloSim upgrade, the general concept of the original package is followed but is implemented using machine learning techniques. Pion, photon, and electron single particle events are run in Geant4 using the latest ATLAS geometry and used to create the parametrisations. For the longitudinal energy parametrisation, a Principal Component Analysis (PCA) is used to convert the correlated fractions of the total energy deposited per layer into an uncorrelated set of principal components. A neural network is then used to approximate the cumulative histograms to reduce the amount of data required to be stored for the parametrisations. When the simulation step is performed, uncorrelated random numbers are generated and used to determine the fraction of total energy to be deposited per layer using the PCA weights as the parametrisation inputs.

For the lateral shower shape, the parametrisation describes the average shower shape for a given particle type in each calorimeter layer, determined for each bin of the leading principal component as generated by the PCA. This is binned in coordinates of radius from and angle around the radially symmetric shower centre. This is normalised and used as a probability distribution from which random numbers are used to determine the position of energy deposits for each layer. The

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lower the number of energy deposits per layer, the more localised and irregular the shape, which leads to a clustered structure when reconstruction is performed. This gives rise to the shower substructure that was missing from legacy FastCaloSim.

In addition to the revised shower parametrisation, the exact geometry of the forward calorimeter is added in place of the simplified model, and corrections are implemented in the cell assignment of energy deposits in the LAr calorimeters by using a 'wiggle function' to take the accordion shape of the electrodes into consideration.

5. Progress and Validation

There is currently a functional prototype of the new FastCaloSim that can be used for single particles and is under validation. Plots are produced comparing properties of the simulated particle showers to assess the upgrade's performance against the legacy package and with Geant4.

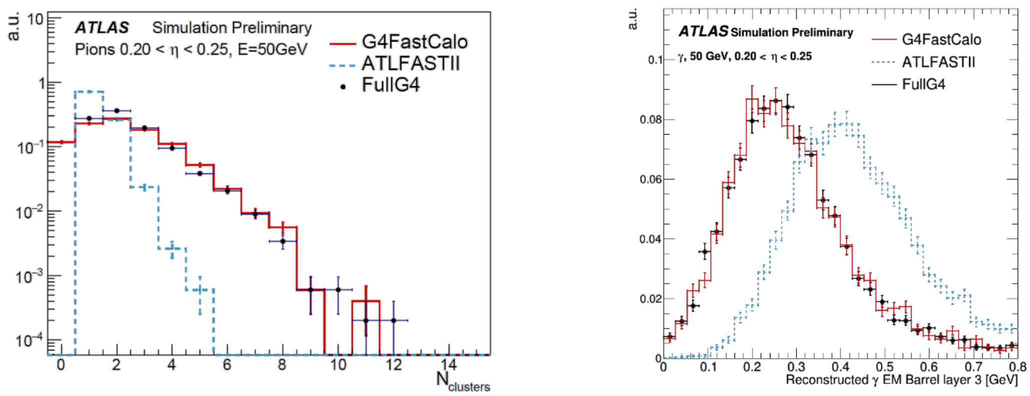

Figure 2: The left plot shows the number of sub-clusters produced per event while the right plot shows the reconstructed energy of photons in the third layer of the EMB. G4FastCalo denotes results from the upgrade, the legacy package is labelled as ATLFASTII, while Geant4 is shown as FullG4.

The two plots shown in Figure 2 show the performance of the FastCaloSim upgrade in comparison with the legacy package and with full Geant4 simulation. It can be seen that the number of clusters from the upgrade prototype is in better agreement with Geant4 due to the lateral shape simulating with greater fluctuations. There is also an improvement in determining the energy deposited by photons in the electromagnetic barrel due to an enhanced parametrisation of longitudinal energy deposition. The package is not complete however and can only simulate single particles in a range of $0.20 < \eta < 0.25$, so further development is important.

6. Summary

FastCaloSim was developed as a parametrised calorimeter response in order to generate Monte Carlo events at a much higher rate than Geant4. The upgrade to FastCaloSim under development is implementing methods to improve the simulation of particle shower substructure and a working prototype has been produced. Efforts to improve this prototype after validation against Geant4 and legacy FastCaloSim are underway.

References

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