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PARAMETERISATION OF ELECTROMAGNETIC SHOWERS IN THE ATLAS CALORIMETER

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Abstract

A fast simulation has been built for the electromagnetic calorimeter of the ATLAS detector, on the Large Hadron Collider at CERN, consisting of a parameterisation of the electron shower shape within the calorimeter. The fast simulation is 10 to 100 times faster than the full simulation, depending on the energy of the incoming electron, and the agreement of shower shape and energy deposit between the two simulations is acceptable. Further validation is required to ascertain which physics processes the fast simulation will be capable of simulating with the accuracy necessary for the ATLAS experiment.

Introduction

The Large Hadron Collider (LHC) [1] is the flagship facility at the CERN particle physics laboratory in Geneva. It is a proton - proton collider with centre of mass energy 14 TeV, designed primarily to discover the Higgs boson, required by the spontaneous symmetry breaking mechanism, which is central to the Standard Model of particle physics.

The ATLAS detector [2] sits at interaction point 1 of the LHC, and is one of two large, complex, general purpose detectors which will operate at the LHC. The detector is comprised of an inner tracker, electromagnetic calorimeter, hadronic calorimeter and a muon spectrometer, each situated around the interaction point in a symmetric, barrel geometry.

The ATLAS liquid argon, electromagnetic calorimeter [3] is a lead, liquid argon, sampling calorimeter, positioned around the inner tracker, with coverage of $-3.2 < \eta < 3.2$, where η is pseudorapidity. The lead, liquid argon ‘sandwich’ has an accordion geometry, providing complete azimuthal coverage.

The ATLAS simulation software uses the GEANT4 [4] package to fully reproduce electromagnetic cascades in the electromagnetic calorimeter. This simulation uses an extremely detailed, fine-grained description of the calorimeter geometry, to track and simulate the energy deposits of each individual particle produced in the shower. The time taken to perform this simulation increases linearly with the energy of the incoming particle. For LHC energies, this can mean individual showers requiring 10 - 15 minutes to simulate. In the high luminosity environment of the ATLAS detector under full running conditions, the search for rare physics requires very large numbers of Monte Carlo events, the production of which is hindered by the time taken in the em calorimeter. A parameterisation has been built, in which the four-momenta of the incoming particles is used to determine the shape of the resulting shower, and the energy deposited in the active material accordingly.

Parameterisation Algorithm

To accurately reproduce an electromagnetic cascade, both the longitudinal profile and the radial profiles must be simultaneously parameterised.

The mean longitudinal profile can be described using a gamma function:

$$\langle \frac{1}{E}\frac{dE(t)}{dt} \rangle = f(t) = \frac{(\beta t)^{\alpha-1}\beta e^{-\beta t}}{\Gamma(\alpha)} \tag{1}$$

where t is the shower depth in units of radiation length and E is the shower energy. The longitudinal depth of the shower maximum is $T = (\alpha - 1)/\beta$ and α describes the shape of the shower.

Parameterising according to reference [5], the distributions of $ln(T)$ and $ln(\alpha)$ can be shown to be Gaussian and the longitudinal profile of the shower can be reproduced using the mean of $ln(T)$ and $ln(\alpha)$, while the standard deviation of these describe the fluctuations. These parameters are described in terms of shower energy, scaled by the critical energy for em cascades (E_c), and calorimeter material. Here, the critical energy is the minimum energy required for an electron to induce a shower. In the case of an inhomogeneous sampling calorimeter such as in ATLAS, the parameters are also a function of the sampling frequency (F_s) and the signal ratio of electrons to minimum ionising particles (e/mip) averaged over the whole shower. For each parameterised shower, α_i and T_i are calculated as follows:

$$\begin{pmatrix} ln(T_i) \\ ln(\alpha_i) \end{pmatrix} = \begin{pmatrix} \langle ln(T) \rangle \\ \langle ln(\alpha) \rangle \end{pmatrix} + \begin{pmatrix} \sigma_{lnT} & 0 \\ 0 & \sigma_{ln\alpha} \end{pmatrix} \begin{pmatrix} \sqrt{\frac{1+\rho}{2}} & \sqrt{\frac{1-\rho}{2}} \\ \sqrt{\frac{1-\rho}{2}} & \sqrt{\frac{1+\rho}{2}} \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} \tag{2}$$

where z_1 and z_2 are normally distributed random numbers and ρ is the correlation between lnT and $ln\alpha$.

The radial dependence was parameterised for each longitudinal interval of X_0 in length, in units of the Moliere radius [6], by:

$$\langle \frac{1}{dE(t)} \frac{dE(t,r)}{dr} \rangle = f(r) = p \frac{2rR_C^2}{(r^2 + R_C^2)^2} + (1-p) \frac{2rR_T^2}{(r^2 + R_T^2)^2} \tag{3}$$

where R_C and R_T are the medians of the core and tail components respectively and p is the relative weight of the core component.

Fluctuations in the radial profile are taken care of by tuning the number of spots deposited in the calorimeter per shower according to:

$$\frac{\sigma}{E} = \frac{c}{\sqrt{E}} \tag{4}$$

where c is the sampling fraction of the calorimeter and σ is the rms of the distribution of energy deposited for a given initial energy.

Obtaining Parameters

The functional forms of the longitudinal parameters of a sampling calorimeter are [5]

$$\begin{aligned} \langle lnT \rangle &= ln(l_1 + l_2 F_s^{-1} + lny) \\ \langle ln\alpha \rangle &= ln(l_3 + l_4 F_s^{-1} + l_5 lny) \\ \sigma_{lnT} &= (l_6 + l_7 lny)^{-1} \\ \sigma_{ln\alpha} &= (l_8 + l_9 lny)^{-1} \end{aligned} \tag{5}$$

where $y = E/E_c$ is the energy scaled by the critical energy of the calorimeter material.

Following ref [5] the parameters l_1 to l_9 can be calculated from the physical properties of the calorimeter, but the complexity of the ATLAS geometry makes this approach inadequate, so the parameters were determined by fitting to data obtained using full GEANT4 simulation. In this case T and α are computed using the first and second moments of the longitudinal distribution, Z_1, Z_2, where;

$$Z_n = \int_0^\infty z^n f(t) dt \tag{6}$$

and

$$\begin{aligned} T_i &= \frac{2Z_1^2 - Z_2}{Z_1} \\ \alpha_i &= \frac{Z_1^2}{Z_2 - Z_1^2} \end{aligned} \tag{7}$$

The fits for the mean and rms of T and α are presented in figure 1.

As with the longitudinal profile, the functional form of the parameterisation was taken from reference [5], but the constants were determined by fitting data from the full GEANT4 simulation. The equations describing

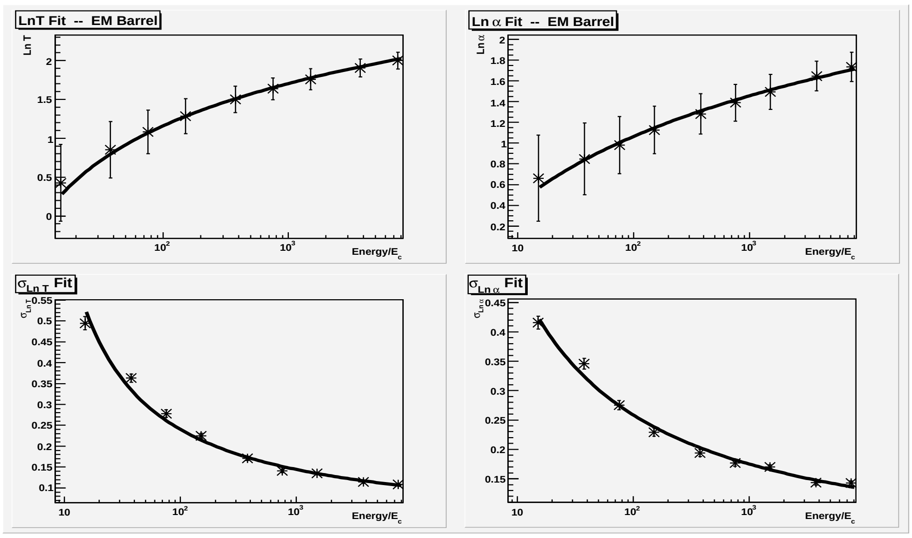

Figure 1: Results of fit for the barrel of the calorimeter.

the parameters R_C, R_T and p are:

$$\begin{aligned} R_C(y,\tau) &= r_1 + r_2 lny + r_3\tau \\ R_T(y,\tau) &= r_4(e^{r_5(\tau-r_6)} + e^{(r_7-r_8 lny)(\tau-r_6)} \\ p(y,\tau) &= r_9 e^{\frac{r_{10}-\tau}{r_{11}+r_{12}lny} + e^{\frac{r_{10}-\tau}{r_{11}+r_{12}lny}}} \end{aligned} \tag{8}$$

Parameterisation Strategy

The particle is tracked using the full GEANT4 simulation from the point of origin until it reaches the first active layer of the calorimeter, where the fast simulation takes over; the advantage of this is that the parameterisation is not affected by the presence of upstream material. The particle is then tested for identification, only electrons are parameterised, and for containment, the shower must be 99% contained within the calorimeter. There is also an energy range, outside of which, the parameterisation is not a good representation of the shower. Particles which fail these tests are returned to the full simulation; for those which pass the parameterisation steps through the calorimeter, depositing energy in the active material, according to the above equations. If a particle has been returned to full simulation, each new particle created during the shower will be tested again until it passes the tests, at which time the fast simulation takes over.

Results

Comparisons of 1000 electron showers at 10 GeV in the ATLAS em calorimeter barrel, simulated by fast simulation and full simulation, are presented in figure 2. The plots show good agreement by the fast simulation for the longitudinal profile, and also for the integrated radial profile. It should be noted however, that the data shown are from GEANT4 hits, which have a very fine resolution, whereas when smeared by the spatial resolution of the detector, it is expected that the disagreement will wash out. A validation process is currently under way, which involves the simulation of actual physics processes using fast simulation as well as full simulation. This will provide information on where the parameterisation can be used effectively to increase statistics, without degrading performance.

The speedup factor of the simulation of the showers ranges from 10 for an average 1 GeV electron shower, to 500 for a 100 GeV shower. While the time required for full simulation increases linearly with energy, the same ratio is logarithmic for the fast simulation. The speedup factor as a function of energy is shown in figure 3.

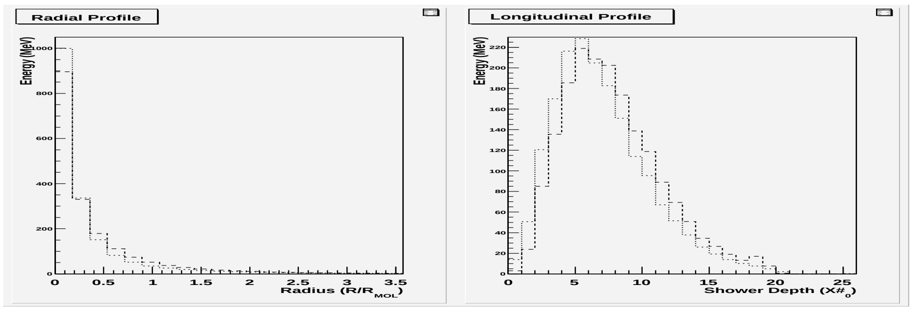

Figure 2: Comparisons of profiles for 1000 10 GeV electron showers in the ATLAS EM barrel. Full simulation is the dashed line and fast simulation is the dotted line.

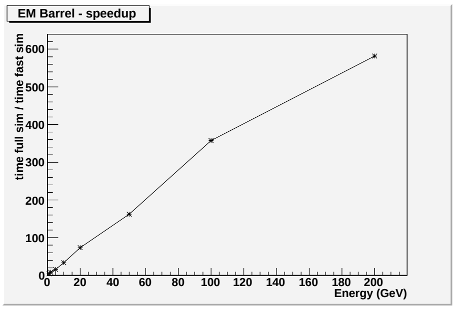

Figure 3: Speedup factor of the fast simulation for the barrel of the ATLAS em calorimeter.

Conclusion
A parameterisation was built for the ATLAS em calorimeter, which allows electron showers to be simulated with a factor of 10 to 100 speedup, depending on energy. Comparisons show an acceptable agreement with the standard simulation; further testing is underway to ascertain how far this agreement extends and how it may be used to compliment the ATLAS physics programme.

References

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