Parameterized Shower Simulation in Lelaps: a Comparison with Geant4^{*}

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ABSTRACT

The detector simulation toolkit Lelaps[1] simulates electromagnetic and hadronic showers in calorimetric detector elements of high-energy particle detectors using a parameterization based on the algorithms originally developed by Grindhammer and Peters[2] and Bock et al.[3]. The primary motivations of the present paper are to verify the implementation of the parameterization, to explore regions of energy where the parameterization is valid and to serve as a basis for further improvement of the algorithm. To this end, we compared the Lelaps simulation to a detailed simulation provided by Geant4[4]. A number of different calorimeters, both electromagnetic and hadronic, were implemented in both programs. Longitudinal and radial shower profiles and their fluctuations were obtained from Geant4 over a wide energy range and compared with those obtained from Lelaps. Generally the longitudinal shower profiles are found to be in good agreement in a large part of the energy range, with poorer results at energies below about 300 MeV. Radial profiles agree well in homogeneous detectors, but are somewhat deficient in segmented ones. These deficiencies are discussed.

^{*} Work supported in part by the Department of Energy contract DE-AC03-76SF00515

Introduction

Computer simulations of the passage of particles through matter have applications in many areas, including high-energy physics, medical, and space physics studies. Some studies may require detailed simulations that reproduce as accurately as possible the interactions occurring in nature. Other studies may not require such accuracy. In this case, some interactions that occur in nature may be ignored or combined into parameterizations, which may be based on patterns found in actual data rather than on physical interactions. Generally, less detailed simulations require less computation time, but produce less accurate results than do detailed simulations.

The purpose of this study is to compare a well-tested, detailed simulation of particles passing through material to a less detailed, prototype simulation in order to examine the validity of the prototype simulation and provide a basis for its improvement. The high-energy physics community in particular is concerned with the passage of particles through detector elements designed to detect the energy deposited by particle showers (calorimeters). The context of the simulation performed is that of a beam of particles passing through detectors similar to those used in high-energy physics experiments.

Geant4[4] is a simulation toolkit that allows the detailed simulation of a particle's interaction with matter, tracking each particle down to zero energy. Various electromagnetic, hadronic, ionic, and general physics processes can be considered, making Geant4 capable of handling interactions across a wide energy range. Geant4 is also capable of simulating complicated detector geometries, with volumes composed of different materials and sensitive detector regions. Currently, Geant4 is the standard toolkit used by high-energy physicists to simulate particles traveling through detectors.

In cases when detailed simulations are not necessary and where detector detail is of less importance, a faster program is preferred. One such fast simulation currently being developed is Lelaps[1]. It tracks particles through materials while taking into account multiple scattering and energy loss, but does not create secondary particles. Instead, Lelaps uses a parameterization. For electromagnetic showers, Lelaps uses the algorithm for the parameterization of showers in homogeneous calorimeters of Grindhammer and Peters[2], whom we shall refer to as GP in what follows. Hadronic showers are parameterized using the same GP algorithm for radial profiles, but using the Bock parameterization[3] for longitudinal profiles.

To test the accuracy of the Lelaps simulation, we developed a set of Geant4-based programs to simulate several types of both electromagnetic and hadron calorimeters. Test data were produced using various energies and detector materials, and the resulting shower shape distributions were compared with those created using equivalent examples in Lelaps.

Method

We used five different calorimeter designs for this test. A CsI detector was chosen to model the EM calorimeter in the BaBar detector at SLAC[5]. The other four are candidate designs for calorimeters in various detector concepts for the Linear Collider[6].

Each detector is cylindrical in shape and positioned so that the beam direction is centered on and perpendicular to the circular face of the detector. The detectors are segmented longitudinally into a number of *slices* as shown in figure 1. Each slice is divided into 20 radial *layers* that are 1 cm thick.

The first calorimeter is a special case: it consists of a single material, CsI, and constitutes a simple EM detector consisting of twenty 2.7 cm slices. The radial layers of each slice are treated as sensitive detectors. The designs for the remaining calorimeters call for slices of different widths and materials. A sequence of these slices is repeated throughout the detector. We will refer to the repeated sequence of slices as *units*. The detector geometries are represented in Geant4 as described in Table 1. Only the radial layers of scintillator and silicon slices are treated as sensitive detectors in each calorimeter.

For Lelaps the detector geometry remains the same, but each unit is represented as a single slice of a homogeneous mixture of the materials present in the corresponding slices of the equivalent detector in Geant4. For example, a unit/slice of the large EM detector in Lelaps is 0.6 cm of 66% lead, 13.2% air, 3.3% Tyvek, and 16.5% scintillator by volume. The entire slice is treated as a sensitive detector, as in the CsI calorimeter.

In both Geant4 and Lelaps we ran events in each detector at energies varying from 30 MeV to 300 GeV. For the electromagnetic calorimeters electrons were used, and for the hadron calorimeters both pions and protons were used. We ran 1000 events for each particle at each energy (fewer events for energies higher than 30 GeV to save CPU time for Geant4 simulations) and created histograms to plot the longitudinal and radial profiles of the energy deposited, as well as a measure of the fluctuations in the longitudinal profiles.

A priori, we expect the parameterization to fail at low energies (< 100 MeV) because of known limitations in the GP algorithm. We also do not expect specifically the radial distributions for hadronic calorimeters to be correct, since the GP algorithm was not designed for hadronic showers, and no further tuning was performed. The best match is expected for the CsI EM calorimeter, since the algorithm we use is specifically applicable to homogeneous calorimeters. We note that Grindhammer and Peters do specify in their paper possible improvements for segmented calorimeters, which have not been implemented in Lelaps.

Results and Analysis

To compare the Geant4 and Lelaps simulations, we created histograms to show both the longitudinal and radial profiles of the energy deposited in each sensitive detector. The graphs are normalized to correct for the energy lost in non-sensitive slices in the Geant4 calorimeters. We also created histograms to show a measure of the longitudinal fluctuations of the data by plotting the mean value of the longitudinal distribution from each event.

EM calorimeters

The overall longitudinal profiles correspond very well for the electromagnetic calorimeters. The best agreement is seen, as expected, in the CsI detector (*e.g. figure 2*). Above 100 MeV the data from Lelaps fall within the error range of the data in Geant4. Below this value the Geant4 data is less sharply peaked in the first few slices than the Lelaps data. This is due to the fact that the GP algorithm is singular below about 100 MeV, and Lelaps just deposits most of the energy in the first slice.

The longitudinal profiles for the luminosity monitor and the large EM calorimeter show that the correspondence between the Geant4 data and the Lelaps data is not as strong as it is for the CsI calorimeter (*e.g. figures 3, 4*). In both detectors, the Lelaps plots are narrower than those of Geant4. This trend is seen in profiles produced at all energies tested, becoming more pronounced as the energy of the beam increases.

The positions of the shower maxima (referred to simply as “peak positions” hereafter) were obtained by fitting Gamma distributions to the data. At different energies they correspond best for the CsI calorimeter (*figure 5*). Peak positions for the large EM calorimeter and the luminosity monitor correspond fairly well (*figures 6, 7*), however, Geant4 generally shows peak positions to be deeper in the detector than Lelaps does. This difference in position increases in both detectors with the beam energy.

Not surprisingly, the mean values for the longitudinal profiles show similar behavior. While a close match for the CsI detector (*figure 8*), for the large EM calorimeter and the luminosity monitor the longitudinal profile mean values do not match as well: the means for Lelaps are lower than those for Geant4 by about 10% (*e.g. figure 9*). This difference seems consistent across the different energies.

The RMS values for the longitudinal profiles are again excellent for the CsI detector, and less accurate for the others (*figure 10, 11*). In these detectors the RMS is significantly higher (almost 20%) for the Geant4 data, reflecting the already observed fact that the Lelaps distributions are narrower.

Figure 12 shows an example of a histogram of the means of individual longitudinal distributions for each event. We use the RMS of these distributions as a measure of how much showers fluctuate from one event to the next. The CsI detector again shows the best agreement, to within about 5% at 1 GeV and above (*figure 13*). Below 1 GeV the RMS of fluctuations in Lelaps show a rising behavior, whereas in Geant4 they do not. While Lelaps leads to lower values than Geant4 in the other EM detectors up to 10 GeV (*e.g. figure 14*), the same rise is seen below 1 GeV, but here Geant4 shows a similar rise. Above 10 GeV Lelaps and Geant4 agree for all EM detectors.

A comparison of the radial profiles for the CsI detector gives excellent results (5% or lower difference) for energies above 300 MeV (*figure 15*). Below this energy the agreement is good for the first few slices, but poorer for later slices, as Lelaps does not deposit any energy in these slices. The data shows similar correspondence for the large EM detector, except in the first radial layer (*figure 16*). In this layer, the Lelaps data is significantly higher (>100%) than the Geant4 data at all energies. This is probably due to the fact that Lelaps simulates a homogenous calorimeter whose sensitive volume extends to the very front, whereas the Geant4 calorimeter has a section of absorber before its first sensitive detector.

Hadron calorimeters

For the hadron detectors, the longitudinal profiles agree reasonably well at energies above 3 GeV, but at lower energies the similarity is poor as Geant4 shows a large loss of energy in the first 5 slices, while the Lelaps graphs are more moderately peaked (*figures 17, 18, 19, 20*).

The agreement in the longitudinal mean (*figure 21*) and RMS (*figure 22*) values is reasonable (generally within 15%) above 3 GeV and poor below this energy. There is little correlation between the estimated peak positions of the longitudinal graphs, except for energies around 10 GeV (*figure 23*). The same occurs for the RMS of the fluctuations graph (*figure 24*). Clearly the shape of the distributions in the Geant4 and Lelaps case are different. Assuming the Bock parameterization is correct (since it is based on real data rather than simulations) and assuming Lelaps represents the Bock parameterization reasonably well, we conclude that further investigation of our Geant4 simulation of hadronic interactions is warranted.

The radial profiles in Lelaps show poor correspondence with those in Geant4 for all positions and energies (*figure 25*). In general Lelaps gives all of the energy to only a few layers while the Geant4 distribution is more spread out. This is clearly an area where Lelaps needs further tuning.

These conclusions hold for both the large and small detectors and for both pions and protons.

Conclusions

Analysis of the histograms created by Geant4 and Lelaps shows that the data produced by Lelaps corresponds well with that of Geant4 under certain conditions, but that improvements need to be made for others. In general, Lelaps has proven to be most accurate for studying electromagnetic interactions, for homogeneous detectors, and for energies above 100 MeV. In addition, the longitudinal profiles, including those for hadronic interactions, are more accurate than the radial profiles.

This study has shown that, as predicted, the parameterization used for the radial profiles in hadronic interactions does not sufficiently simulate the events that occur in a hadron calorimeter. In addition, the method of depositing all energy in the first slice at initial energies of 100 MeV and below does not give an accurate representation of low energy showers.

Finally, the partitioning of calorimeters in Geant4 causes some discrepancies to surface when comparing with the homogeneous design of Lelaps calorimeters. Because the particles encounter non-sensitive materials before reaching the sensitive detectors in Geant4, the particle showers appear to begin in earlier slices of the detector than in Lelaps. This causes the radial graphs of Geant4 to be more spread out than those of Lelaps for the first slices.

While Lelaps does not in every case produce results consistent with those observed in a more detailed simulation, data showing the more important aspects of shower simulation can be quickly and accurately produced using Lelaps. Although timing studies were not a major motivation in the present work, we note that the Lelaps simulation of

e.g. the 10 GeV electrons in the CsI calorimeter (*figure 3*) was more than 30 times faster than the Geant4 simulation and the simulation in the large EM calorimeter (*figure 4*) was more than 90 times faster. Of course, both simulations could be changed in various ways to improve speed.

The results of this study may be used to improve the implementation and tuning of the shower parameterization in Lelaps, especially in regards to the radial profiles and low-energy distributions.

References

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Detector	Slice	Slice Width (cm)	Material	Repeated Units
CsI	1	2.7	CsI	20
Large EM	1	0.4	Lead	40
	2	0.04	Air	
	3	0.01	Tyvek	
	4	0.1	Scintillator	
	5	0.01	Tyvek	
	6	0.04	Air	
Luminosity Monitor	1	0.2	Tungsten	50
	2	0.03	Silicon	
	3	0.1	G10	
	4	0.17	Air	
Large Hadron	1	0.8	Lead	120
	2	0.04	Air	
	3	0.01	Tyvek	
	4	0.2	Scintillator	
	5	0.01	Tyvek	
	6	0.04	Air	
Small Hadron	1	2.0	Iron	34
	2	1.0	Scintillator	

Table 1. Detector designs as represented in Geant4. Each series of materials constitutes one *unit* to be repeated the given number of times. See references 5 and 6.

Figure 1. Basic layout of the calorimeter.

Figure 2. Longitudinal profile for the CsI calorimeter (10 GeV).

Figure 3. Longitudinal profile for the large EM calorimeter (10 GeV).

Figure 4. Longitudinal profile for the luminosity monitor (10 GeV).

Figure 5. Longitudinal peak positions for the CsI calorimeter.

Figure 6. Longitudinal peak positions for the large EM calorimeter.

Figure 7. Longitudinal peak positions for the luminosity monitor.

Figure 8. Longitudinal mean values for the CsI calorimeter.

Figure 9. Longitudinal mean values for the large EM calorimeter.

Figure 10. Longitudinal RMS values for the CsI calorimeter.

Figure 11. Longitudinal RMS values for the large EM calorimeter.

Figure 12. Distribution of the means of individual longitudinal distributions for each event.

Figure 13. RMS values of the longitudinal fluctuations graphs for the CsI calorimeter.

Figure 14. RMS values of the longitudinal fluctuations graphs for the large EM calorimeter.

Figure 15. Radial profiles for the CsI calorimeter.

Figure 16. Radial profiles for the large EM calorimeter.

Figure 17. Longitudinal profile for the large hadron calorimeter (10 GeV, π^-).

Figure 18. Longitudinal profile for the large hadron calorimeter (10 GeV, proton).

Figure 19. Longitudinal profile for the small hadron calorimeter (10 GeV, π^-).

Figure 20. Longitudinal profile for the small hadron calorimeter (10 GeV, proton).

Figure 21. Longitudinal mean values for the large hadron calorimeter (pi-).

Figure 22. Longitudinal RMS values for the large hadron calorimeter (pi-).

Figure 23. Longitudinal peak positions for the small hadron calorimeter (pi-).

Figure 24. RMS values of the longitudinal fluctuations graphs for the large hadron calorimeter (pi-).

Figure 25. Radial profiles for the large hadron calorimeter (pi-).