CERN-LCGAPP-2012-02
June 1, 2012
Version 1.0

Simplified Calorimeter: Investigations on the lateral profile simulation of hadronic shower shapes

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Abstract

The lateral description of lateral profile of showers induced by hadrons is one of the most important aspects —(together with response, resolution and longitudinal profile) to be considered in the simulation of calorimeters. In this note we present a summary of the studies performed to compare different models and options available in GEANT4 [1] (starting from version 9.5.beta) for the simulation of neutrons. Our studies show that the use of High Precision data-driven libraries for the description of low energy neutron results in wider shower.[1]

1 Introduction

The precise description of the shower lateral profile plays a major role for the development and tuning of cluster reconstruction analysis and jet sub-structure studies performed by LHC experiments. In addition future calorimeters, currently in the R&D phase rely on high granularity to recognize the shower sub-structure and apply particle-flow algorithms to measure the energy of the jets.

A poor description of the lateral shower shape induced by hadrons can cause a degradation of the physics results. While it has been shown [2] that GEANT4 is in general good agreement with experimental data the description of lateral and longitudinal profiles need additional attention [3]. One of the important aspects for the simulation of the longitudinal behavior of showers (i.e. the target diffraction process) has been discussed elsewhere [4, 5]. In this technical note we summarize the results obtained comparing different physics simulation setups for the lateral shower shape.

In the past [6, 7] it has been shown that the use of an intra-nuclear cascade code at intermediate energies (below few GeV) substantially improves the agreement with data for showers lateral dimension. Neutrons production, transport and absorption plays a fundamental role (since neutron tend to travel the longest distances in calorimeters). This aspect is the focus of this report.

[1]The description of this work can be found: https://sft.its.cern.ch/jira/browse/SIM-77

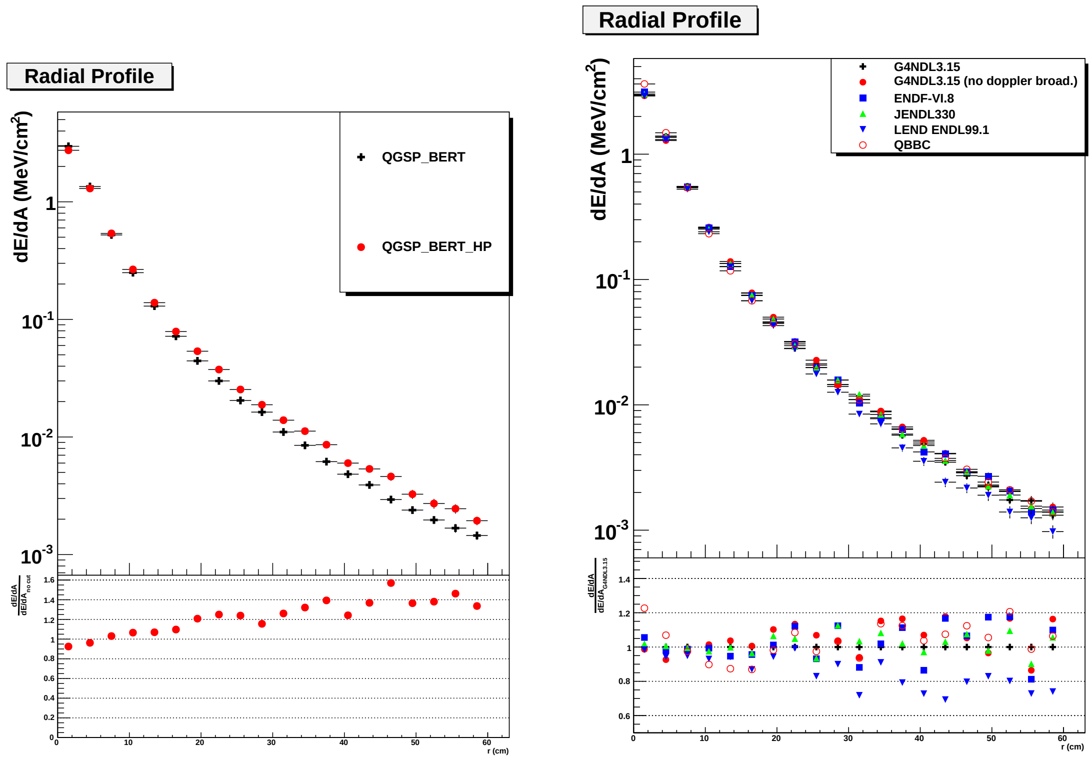

Figure 1: Left: shower profile comparison between QGSP_BERT and QGSP_BERT_HP for the Pb/LAr calorimeter. The profiles are obtained for π^- at 4 GeV. Right: comparisons for different low-energy neutron models.

1.1 Simulation

To study the lateral development of the simulated hadron showers the *Simplified-Calorimeter* validation and testing suite has been used. The application allows for detailed studies of calorimetric observables via the analysis of *shower moments* [8].

Semi-realistic calorimeters have been used: a lead / liquid argon sampling calorimeter is the main setup used in the following. We are mainly interested in the production and transport of neutrons and the use of heavy materials has been chosen to enhance the role of neutrons (in such materials neutrons are mainly produced during the phases of nuclear cascade and evaporation of the wounded nucleus).

However in very light materials (scintillators) they also play an important role for the formation of the experimental signal (energy is "released" by neutrons via the process of elastic scattering on the hydrogen nuclei of the organic scintillators). For this reason we have cross-checked our results also on a iron / scintillator sampling calorimeter. The conclusions are consistent between the two setups.

It should be noted that the SimplifiedCalorimeter application does not include the description of the detector read-out or other experimental effects (with the important exception of the Birks' attenuation). Finally the granularity chosen to study the lateral profile is much higher with respect to present LHC calorimeters. With these two approximations the far tails of lateral profile distributions can be studied, condition that is probably not possible in the real LHC calorimeters.

2 Results

Several aspects of the simulation of neutrons will be studied. An initial comparison is performed between two GEANT4 physics list with different treatment of low energy neutrons: QGSP_BERT and QGSP_BERT_HP . The latter has a special treatment of neutrons with energies below 20 MeV. With the HP model ata-driven tables, based on international databases, are used for cross-sections and for capture, inelastic, elastic and fission processes.

In the following the simulation is performed with negatively charged pion beams of 4 GeV kinetic energy. The energy point has been chosen to avoid the transition region in the QGSP_BERT family physicss list and because this is around the global maximum of the lateral shower moment distribution [8]. It is thus a favorable energy point to enhance the role of the lateral profile tail.

2.1 High Precision neutron libraries

Left plots of Figure 1 show the effect of the high precision description of low energy neutrons. The shower profile is compared between the two physics lists: QGSP_BERT_HP , that includes the precise description of low-energy neutrons, shows wider showers with respect to QGSP_BERT . In particular showers can be larger up to 40% at large radial distances. However it should be noted that the energy density at radii larger than 30 cm is reduced of two order of magnitudes, with respect the energy density at the center of the shower. In real data the experimental noise and multi particle pile-up can decrease the sensitivity in this region.

Since GEANT4 version 9.5.beta a new data-library format is used that allows to use almost transparently different international libraries for the description of neutrons. A comparison between them is shown in right plots of Figure 1. The G4NDL3.15 is the default database library used in GEANT4 . Comparison is performed against ENDF-VI.8, JENDL 3.30 and ENDL 99.1 libraries.

Two special setups are also included: a version of QGSP_BERT_HP without the (on-the-fly) calculations for doppler broadening and the experimental QBBC physics list. The latter uses a simplified version of the HP models (other peculiarities of this physics list are not interesting for our discussion).

With the exclusion of ENDL99.1 and QBBC there is no big differences between the neutron libraries. ENDL 99.1 seems to produce smaller energy deposits at very

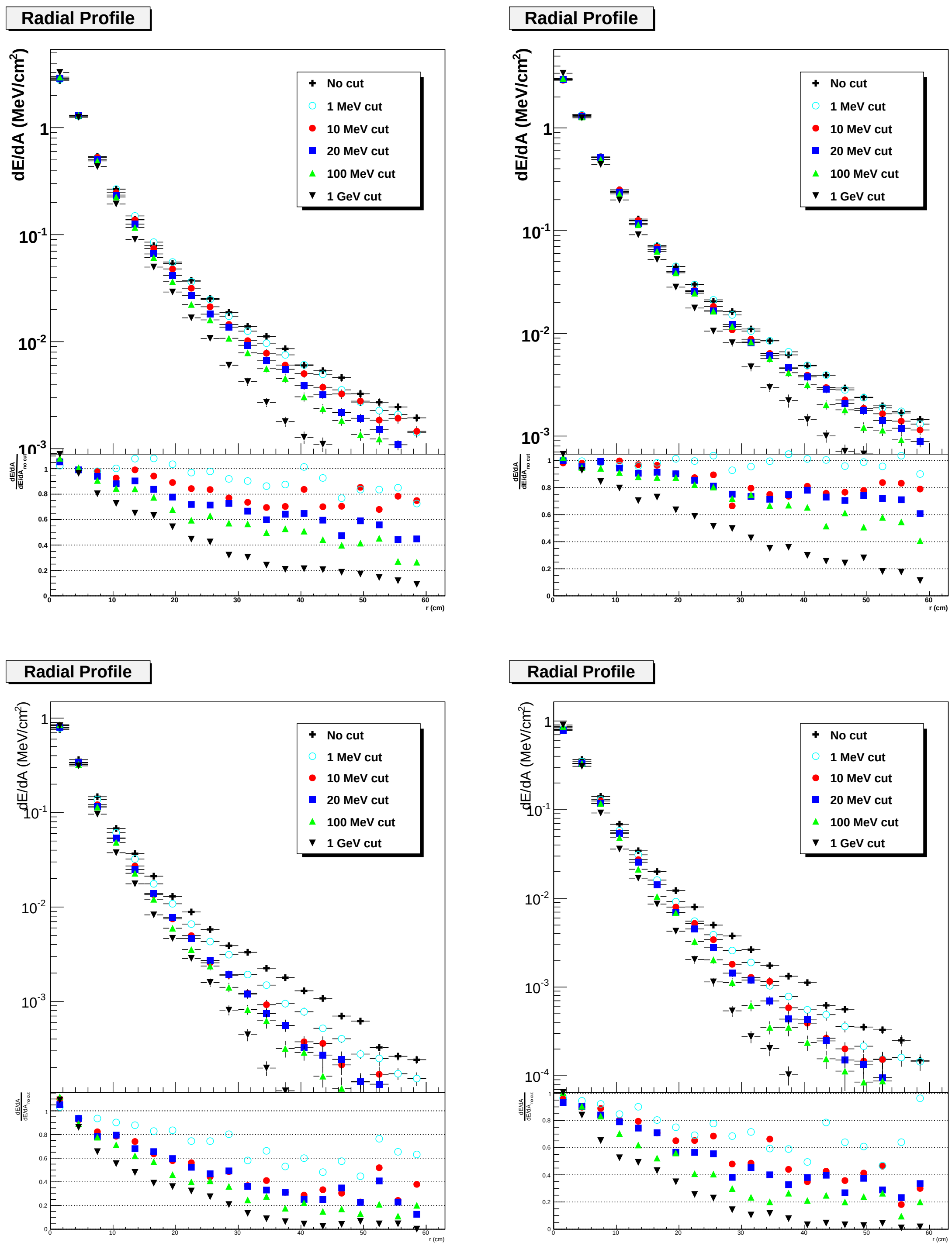

Figure 2: Top row: shower profile for lead / liquid argon calorimeter. Bottom row: shower profiles for iron / scintillator case. Left column shows results obtained with QGSP_BERT_HP physics list, while the right column shows the results obtained with QGSP_BERT physics list. The curves show the simulation obtained for π^-, 4 GeV pions removing from the particle stacks neutrons below a specified kinetic energy.

large radii, while QBBC predicts larger energy deposits at small radii and smaller deposits at intermediate radii. Both behaviors are not favorite by experimental data.

An important result is that the doppler broadening does not play an important role for this observable. Considering that the calculations of the broadening takes a very large fraction of the CPU time, this results suggests that the approximation of fixed temperature can be used to substantially increase CPU performances of QGSP_BERT_HP without a degradation of physics performances (in this setup QGSP_BERT_HP is up to 5 times slower than QGSP_BERT but it is only ∼40% slower without doppler broadening).

2.2 Low energy neutrons

We have shown that low energy neutrons play an important role in the description of radial profile. We have performed different simulations in which the neutrons are removed from the stack of particles to be simulated when their kinetic energy falls below a given threshold. With these simulations we can understand the relative importance of progressively colder and colder neutrons.

Results are shown in Figure 2. The top plots show the results obtained for the lead / liquid argon sandwich calorimeter, while the bottom plots have been obtained with the iron / scintillator case. Left column shows the QGSP_BERT_HP physics list while the right column refers to QGSP_BERT .

It can be seen that QGSP_BERT_HP is more sensitive to very low energy (below 1 MeV) neutrons with respect to QGSP_BERT . This can expected since QGSP_BERT has only rough approximations below 20 MeV and the approximations are too large to have reliable results. Another important consideration can be made comparing the differences between the two materials: the scintillator based calorimeter is more sensitive to low energy neutrons. For this calorimeter type the energy of cold neutrons is transferred, via elastic scattering, to protons that can still release important signals in the scintillators. Removing low energy neutrons from the shower reduces the registered signal.

Comparing the different energy thresholds it is possible to see that important differences can be already seen with few MeV cut. Low and very-low energy neutrons play an important role for the lateral description of showers and should not be cut if a precise simulation is needed.

2.3 Time structure of neutron propagation

Low energy neutrons may take long times to propagate in the calorimeter, this has to be taken into account since the read-out systems have usually a relatively short read-out window. In the case of scintillators, read with photomultipliers the sensitivity is typically of the order of 50 ns. It can get significantly longer in calorimeters where the signal is collected from ionization in liquid argon.

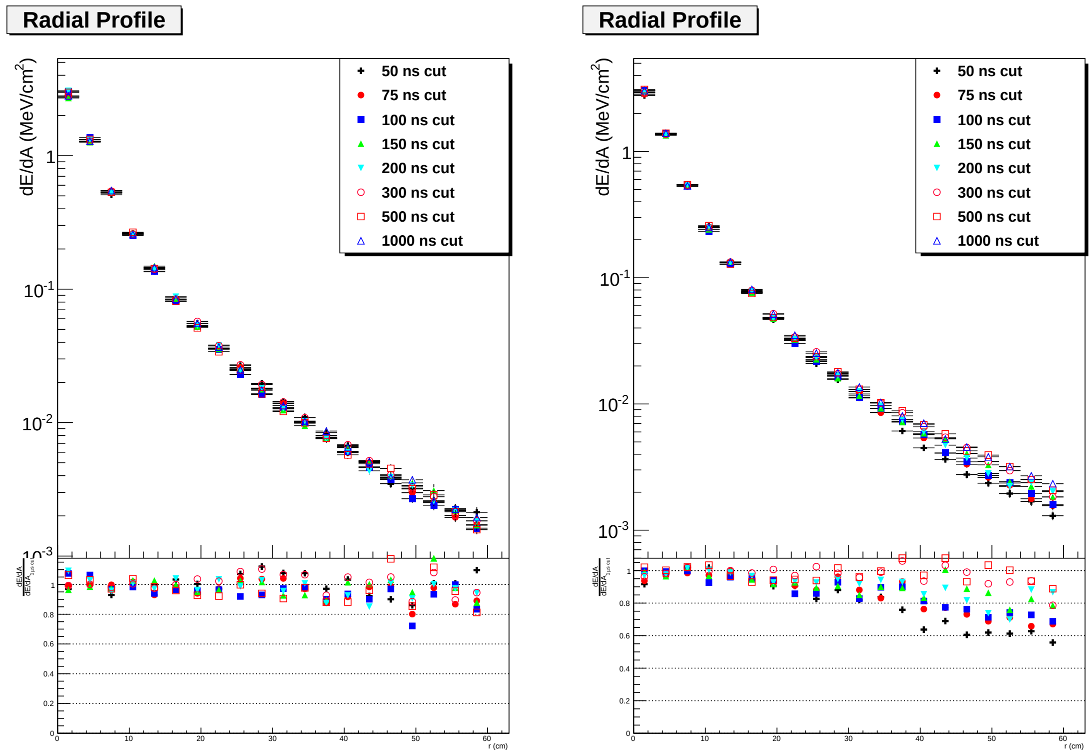

Figure 3: Shower profiles for lead / liquid argon simplified calorimeter. Left column shows results obtained with QGSP_BERT_HP physics list, while the right column shows the results obtained with QGSP_BERT physics list. The curves show the simulation obtained for π^-, 4 GeV pions removing from the particle stack neutrons after the specified simulated time is elapsed.

Very slow neutron will contribute little to the energy deposits at large radii and thus the effect of slow neutrons will become less and less important for longer time scales.

To study the effect of neutron time tracking we have simulated the setup removing neutrons after they have been tracked for a given amount of time. Figure 3 shows the results obtained on the lead / liquid argon sandwich calorimeter for time cuts from 50 ns to 1 μs. For QGSP_BERT_HP (left plot) the differences between the curves is very small. The role of late neutrons is marginal. For the QGSP_BERT physics list, there are more important differences, in particular the response at large radii decreases substantially with shorter time cuts. Recent reports from CALICE collaboration show an agreement with QGSP_BERT_HP for what the time structure of hadronic showers is concerned, while agreement of time structure with QGSP_BERT is strongly disfavored. This is an important indication that the high precision model is needed if the correct time structure is required and that QGSP_BERT results are

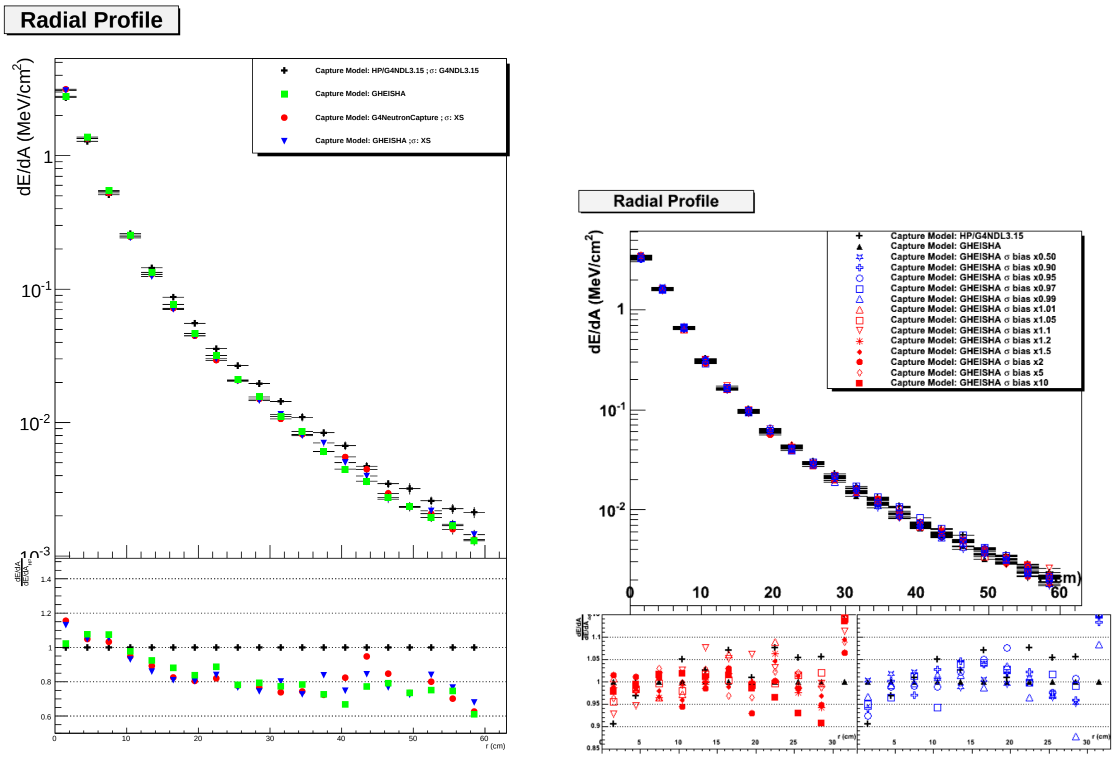

Figure 4: Shower profiles for lead / liquid argon simplified calorimeter. Left: results obtained with different models for the capture of neutrons. Right: Effect of biasing the capture cross section, in blue the capture cross-section is reduced by a factor up to 2, red points show the effect of increasing the capture cross section by a factor up to 10.

not fully reliable on this aspect.

2.4 Precise description of materials

Capture cross-sections at low-energy show strong resonances that are isotope dependent. We have thus included special simulations in which the precise material description is implemented. ATLAS chemical analysis performed on the materials used to construct the calorimeters have been used to describe the relative abundance of elements in the simulation. The Geant4 NIST database is used to describe the relative isotope abundance for each given material.

The simulations performed with the precise description of materials or with a simpler (average atomic number, no impurities considered in materials) give the same results for lateral shower shapes. The aspect of precise material description does not play a role for this calorimetric quantity.

2.5 Capture models

Neutrons produced during the evolution of a hadronic shower are removed from the shower evolution if they leave the experimental setup or they get absorbed by nuclei. Geant4 provides different models for the description of neutron capture. The model used by default in all physics lists is derived from GHEISHA. Physics lists with the HP extension instead use precise data-driven cross-sections. Recently a new intermediate model (*G4NeutronCapture*) has been developed, it uses a set of cross-section that, starting from HP ones reduces the number of data-points and removes the isotope dependence (this set of cross section is called *XS*). This latter new development is used in QBBC physics list.

To study the role of capture model special simulations have been run replacing GHEISHA model and cross-section with the one from QBBC. The results are shown in the left plot of Figure 4. No important differences are observed between the default model and replacing either only the cross-section or both cross-section and models with QBBC ones. The shower remain more compact with respect QGSP_BERT_HP . As observed in Figure 1 QBBC models seems to predict higher energy in the core of the shower with respect to GHEISHA ones.

To further test the importance of capture of neutrons we have performed simulations biasing the cross-section (see right plot of Figure 4), even with larger bias factors no particular effect has been observed for lateral shower shapes.

3 Conclusions

We have studied several aspects of the simulation of low energy neutrons and their role in describing the lateral evolution of hadron-induced showers in calorimeters. Two different setups have been used: one with heavy materials (lead and liquid argon) and one with light ones (iron and scintillator).

Comparisons between different models and different options have been done with Geant4 version 9.5.beta and 9.5 (released at the end of 2011).

The main option available in Geant4 to improve the description of low-energy neutrons is the use of the High Precision (HP) extension. It has the effect to increase the lateral dimension of showers, especially at large radii. Other options and tuning have been also studied. We can give few recommendations for the simulation of calorimeters used in HEP experiments:

- HP models increases the size of the lateral dimensions of showers. This conclusions holds also switching off the doppler broadening simulation. This can significantly speed-up the precise simulation of low energy neutrons.

- QGSP_BERT and QGSP_BERT_HP predict different time structure of showers. Preliminary experimental results tends to favor the use of HP models. In any case these studies show that implementing the correct time-sensitivity in the read-out simulation can play an important role.

- Average material descriptions can be safely used in simulations without having an impact on hadron shower lateral dimension.

The use of HP seems the only option to improve the simulation of neutrons. However its use in HEP is limited due to the large CPU requirements. However additional studies could be performed to provide the most important process in a modular way to be added on top of reference physics lists and find a reasonable compromise between CPU usage, memory consumption and physics performances.

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