Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo 2010 (SNA + MC2010)
Hitotsubashi Memorial Hall, Tokyo, Japan, October 17-21, 2010

An Overview of Geant4 Hadronic Physics Improvements

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During the last five years, development of Geant4 hadronic physics models has been driven largely by the anticipated turn-on of the LHC detectors and the subsequent comparison of new data with the simulated detector responses. Work has concentrated on three main areas: hadronic model improvement, validation, and studies of calorimeter response and test beam data. We will discuss developments in high energy string models, intra-nuclear cascade models, precompound and de-excitation models, and elastic scattering, all of which are currently used in the simulation of LHC experiments. The development of an extensive collection of ongoing validations against data will also be discussed. Such validation suites cover the energy range of a few tens of MeV to a few hundreds of GeV, and have guided the development of various models mentioned above. Finally we discuss direct comparisons to test beam data from ATLAS and CMS. These include shower shape parameters, energy deposit in several types of real and simulated calorimeters, and a set of tests developed to evaluate the behavior of various Geant4 physics lists in the crucial transition region between cascade and high energy string models.

KEYWORDS: Geant4, hadronic physics, models, validation

I. Introduction

The anticipated turn-on of the LHC and its detectors has driven a large part of the model development within the Geant4 1) hadronic physics working group for the last five years. As data begin to come in, the validation of these models now represents a major effort. Already for several years, the ATLAS and CMS experiments have provided test-beam data (refs. 2) and 3) , respectively) against which these models have been checked, and other experiments have contributed their data as well 4).

As a result, several areas were identified for improvement, including shower shapes and energy deposition within the calorimeter parts of the detectors. Even though both these features are dominated by electromagnetic processes, changes in the hadronic processes can produce visible effects which allow the models to be checked. These models include quark-gluon strings, intra-nuclear cascades, nuclear de-excitation and elastic and quasi-elastic scattering.

Other areas of hadronic physics, while not having a large impact on the simulation of the LHC detectors, have seen significant improvment as well. These include nucleus-nucleus interactions, alternative cascade models, lepto- and gamma-nuclear models, and high precision neutron models.

The next section deals with some of the major improvements in Geant4 hadronic physics models, and the two sections following that are concerned with thin-target validations and test-beam validations, respectively.

II. Hadronic Model Improvement

Geant4 physics is encoded into classes called "physics lists", which are meant to be a complete specification of the physics employed to simulate a particle's path through an experimental setup. In the Geant4 approach, it is assumed that no one model is sufficient to deal with all the physics over a wide energy range and variety of particle species. In most cases alternative models are also made available that cover similar energy ranges and particle types. It is therefore necessary to splice different models and cross section sets to construct a physics list.

The ATLAS, CMS and LHCb experiments use variants of the QGSP_BERT physics list for their detector simulations. The hadronic part of this physics list contains the Quark-Gluon String (QGS) model for energies above about 20 GeV, the Bertini-style cascade (BERT) for energies below 10 GeV, and the Low Energy Parameterized (LEP) model for the region between 10 and 20 GeV, approximately. Because of their extensive use by experiments, these models have been repeatedly tested and validated. The resulting improvements and bug-fixes represent significant changes to the models.

1. The Transition Region

In constructing a physics list, it is often required that two very different models be joined together to cover a given energy region. In Geant4 this is done by causing the two models to overlap in an energy range where they are both valid, and blending them in that range. The blending is done by randomly choosing one model or the other with a probability that changes linearly with energy over the common interval. The smoothness of the transition from one model to the next depends on the width of the overlap interval and the nature of the two models, and final state distributions in this interval are not guaranteed to vary smoothly with energy. Discontinuities can, and have, appeared in the simulated responses of calorime-

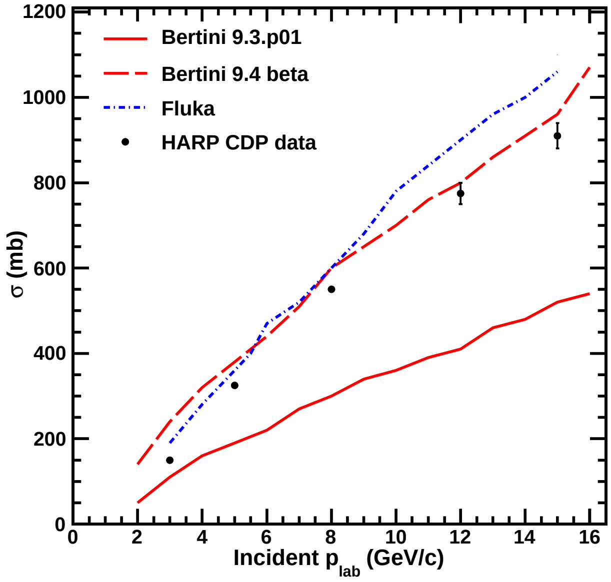

Fig. 1 Integrated cross section for p Ta → π^+ X predicted by the Bertini cascade (part of the QGSP_BERT physics list) from Geant4 versions 9.3.p01 and 9.4 beta, and Fluka, compared to data from HARP-CDP. The cross section data and simulations were integrated over the pion angular range 20^o to 50^o.

ters and test-beam experiments. One such discontinuity in the 10 GeV/c region, was demonstrated by the HARP-CDP collaboration[5)].

The reason for this discontinuity has been known for some time to be due to deficiencies in the models covering the transition region. In the QGSP_BERT physics list, nucleons and pions are handled by the Bertini-style cascade from 0 to 9.5 GeV incident particle energy. From 9.5 to 9.9 GeV, the Bertini model is blended with the LEP model, and from 9.9 GeV to 12 GeV the LEP model is used exclusively.

Before recent improvements in the Bertini code, the physics list significantly under-estimated the cross sections in the angular range 20^o to 50^o measured by HARP-CDP. The LEP model over-estimated them, and continues to do so, and the narrowness of the transition between the two models amplified the discontinuity.

These improvements, mentioned below, have apparently solved this problem for energies below 10 GeV. Fig. 1 shows the effect of the change in going from Geant4 release 9.3.p01 to 9.4 beta. Also shown is the prediction of the Fluka[6)] code, taken from the report by the HARP-CDP group[5)].

Here, the Bertini model does a good job of reproducing the data up to 15 GeV. The LEP model, which is not shown in the plot, handles the upper energy end of this transition region. It is a highly parameterized model which does a generally good job reproducing shower shapes, but not specific final state distributions. For most HEP applications, it is intended that this model will be replaced by either extending the applicability of the Bertini model to higher energies, or extending the QGS or alternate string models to lower energies, or both. Improvements in these models make it likley that the remaining part of the discontinuity (above 10 GeV/c) will then be removed.

2. Bertini-style Cascade

A comprehensive review of the Geant4 Bertini-style cascade code[7)] has been underway for more than two years. Its partial cross sections, angular distributions, Lorentz transformations and energy conservation properties are all under consideration. Significant improvements in the partial cross sections were achieved by a direct comparison to p-p and pi-p data, which showed errors in the original INUCL code from which the Geant4 Bertini model was derived. Improvements in the two-body final state angular distributions were made when it was realized that there were errors both in the original INUCL code, and in the transcription of that code from Fortran to C++.

More recently, the Bertini model, which in many cases relied upon non-relativistic energy and momentum manipulations, has been converted entirely to covariant operations. This has resulted in the elimination of nearly all energy non-conservation in the model.

Improvements in CPU performance, both in speed and memory handling, are also sought. Already a 10-fold reduction in the amount of object creation and deletion has been achieved and significant increases in speed are anticipated.

3. Quark-Gluon String Model

The Quark-Gluon String (QGS) model[8)] handles the highest energy interactions in Geant4 hadronics by simulating hadron-nucleon interactions as exchanged quarks, which form strings, which in turn stretch and hadronize to produce multi-particle hadron final states. Early test beam validations showed that physics lists using the QGS and precompound models produced very short showers. This was due in part to the fact that QGS does only deep inelastic scattering, while the inelastic cross section used by the model also includes quasi-elastic scattering. Hence, there were too many hadronic secondaries and too few high energy particles which had scattered quasi-elastically. By applying an empirical scaling of the cross section based on data, and developing a quasi-elastic channel to be used in competition with QGS, the number of hadronic secondaries was reduced and the number of quasi-elastically scattered hadrons was increased. These improvements are compared with ATLAS tile calorimeter data in the following section.

4. Precompound and De-excitation Models

In physics lists whose names begin with QGSP, the Geant4 precompound model is used to bring the nucleus from the highly excited state created by the initial high energy interaction (QGS), to the equilibrium state where several other de-excitation channels compete to bring the nucleus to the ground, low-lying excited, or disintegrated states. Further discussion of this model can be found in the proceedings of this conference[9)].

5. Other Models

In addition to the models discussed above, Geant4 offers alternative models which cover similar energy ranges and incident particle types. Physics lists using these models have been developed both as a way to solve existing validation problems, and to provide physics coverage in completely different areas of application.

The Fritiof fragmentation (FTF) model10) has recently undergone many improvements which extend its validity down to about 5 GeV. Using this model to replace the QGS and LEP models, will provide a smooth energy response in the 9-10 GeV region, when used in conjunction with the Bertini-style cascade.

It is also possible to replace the Bertini-style cascade with the Geant4 Binary cascade (BIC)11), which is a time-dependent model of the intra-nuclear cascade. BIC has the ability to do re-scattering of hadrons from either of the high energy models (GQS or FTF). It is thus a more physical way to join the cascade and string models, than the current random sampling.

Yet another alternative cascade model is INCL/ABLA. This combination of precise cascade and nuclear de-excitation is designed for the 0-3 GeV energy range and is useful for studying spallation reactions, among other things. More details for the model can be found in12).

The Chiral Invariant Phase Space (CHIPS) model13) is a general interaction model which can be used for stopped particle reactions, lepto-nuclear and gamma-nuclear reactions, and nuclear de-excitation. Recently a capability for quark-gluon string interactions was developed for the CHIPS model, but this feature is not yet ready for general use.

Nucleus-nucleus collisions are also supported in Geant4. In addition to an extension of the Binary cascade which handles collisions up to 5 GeV/A for light nuclei, the Geant4 Quasi-molecular Dynamics model (QMD) is now available. A presentation of this model has been made at this conference14). A more general reference to QMD can be found in Ref15).

Finally there are the Low Energy Parameterized (LEP) (mentioned above) and High Energy Parameterized (HEP) models. These were the first Geant4 hadronic models and were derived from the GEISHA16) code. They are highly parameterized, can be used for all long-lived hadrons, and do well in describing shower shapes, but they perform poorly in energy and momentum conservation. Hence in most Geant4 physics lists, they are used only when no other model is appropriate.

III. Validation

1. Thin Target Validation

In the development and testing of a hadronic model, it is desirable to validate the model in isolation from external effects. For most of the data coming from high energy physics, this is nearly impossible, and one must turn to data from experiments using single-energy, high-purity beams incident on thin targets. In this way, corrections for absorption and rescattering and the like can be minimized, and the incident beam energy and particle type can be controlled. The bulk of the hadronic validation work done in Geant4 deals with

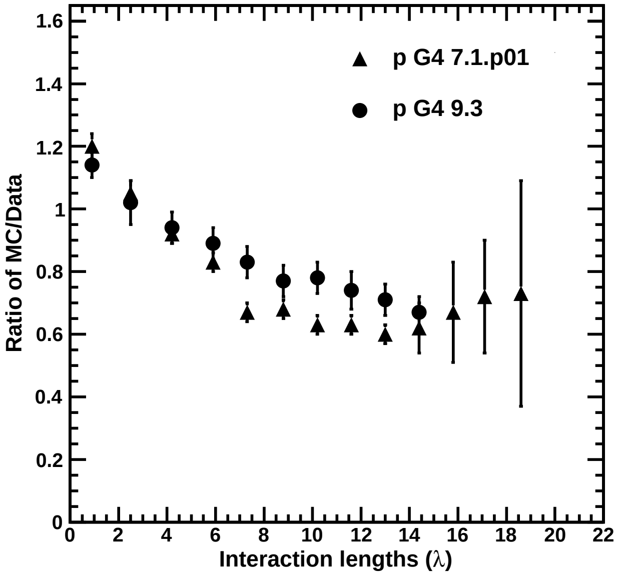

Fig. 2 Longitudinal shower profile resulting from 180 GeV protons incident at 90 degrees on the ATLAS TileCal wedge. The ratio of simulated to measured energy deposit is plotted vs. depth in the detector. The QGSP_BERT physics list was used in the simulation.

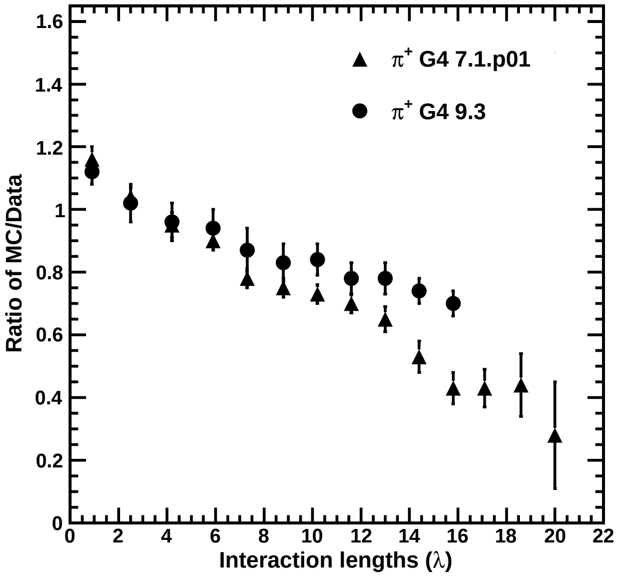

Fig. 3 Longitudinal shower profile resulting from 180 GeV pions incident at 90 degrees on the ATLAS TileCal wedge. The ratio of simulated to measured energy deposit is plotted vs. depth in the detector. The QGSP_BERT physics list was used in the simulation.

this kind of data, and a large database of single-model validation results has been assembled. The results of this validation program are the subject of another paper[17)] and will not be covered here.

2. Test Beam and Simple Calorimeter Studies

Test beam data supplied by ATLAS and CMS have been instrumental in identifying shortcomings in the hadronic models, and indicating how they might be improved. One of the more sensitive tests of Geant4 physics processes in general, and the hadronic processes in particular, is the comparison of shower shapes induced in calorimeter segments. Figs. 2 and 3 illustrate the longitudinal shower shape resulting from 180 GeV proton and pion beams incident on a wedge of the ATLAS tile calorimeter[18, 19)]. Shown is the ratio of simulated to measured energy deposit as a function of depth, in interaction lengths, in the detector.

Model improvements between Geant4 releases 7.1.p01 (October 2005) and 9.3 (December 2009), are evident in these plots; the newer models produce significantly longer showers, in better agreement with data. The lateral spread of the simulated showers (not shown here) has also increased, again in better agreement with data. Most of this improvement is due to the better treatment of quasi-elastic scattering used in the QGS model, and better two-body partial cross sections in the Bertini-style cascade.

We are aware of the need for further improvements in both shower length and shower width. Related physics models are now being refined, and new physics lists are being developed and tested in order to address these issues.

IV. Summary

During the last five years, developments in many of the models used in Geant4 physics lists have resulted in substantial improvements in agreement with data from test beams and thin-target experiments. These include a better reproduction of the shower shape in the ATLAS tile calorimeter test beam setup, and improved energy response and resolution in validation against CMS test beam data. A smoother transition between different models in the energy and angular range tested by HARP-CDP is also seen.

In the near future, new validation data from the LHC experiments will become available, providing strict tests of the hadronic models. Such tests will help to refine the physics lists and potentially provide the guidance necessary to choose from the several options available.

Acknowledgments

This work was supported in part by the U.S Department of Energy, CERN, and the European Space Agency.

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