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## Improvements in the Geant4 Hadronic Physics

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# Improvements in the Geant4 Hadronic Physics

Geant4 Hadronic Working Group

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**Abstract.** 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 for high energy string models, intranuclear cascade models, precompound and de-excitation models, and elastic scattering which are currently used in the simulation of LHC experiments. These development are tested against a large collection of thin target data and dedicated test beam experiments using calorimeter prototypes. Salient improvements in physics and computing performance of these models will be discussed.

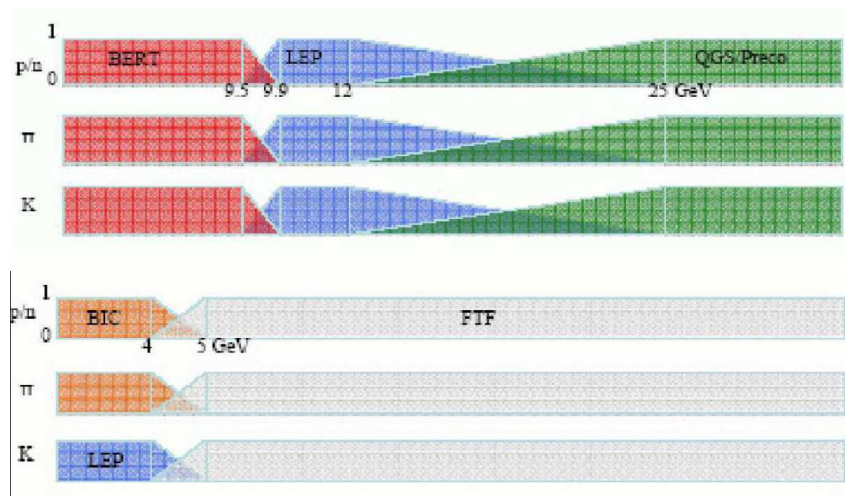
## 1. Introduction

The GEANT4 toolkit [1] has been developed for the Monte Carlo simulation of high energy and nuclear physics experiments. The turn on of the LHC detectors has motivated the improvements of hadronic physics models [2] within GEANT4. In the recent past, test beam data have spotlighted flaws and driven these improvements. Important feedback has come from the test beam activities of the ATLAS, CMS and CALICE collaborations as well as dedicated experiments like HARP. In the near future data from the full detectors will provide stronger tests of the models.

Developments has concentrated on several models for inelastic interactions. These include precompound models at very low energy to intra-nuclear cascade models at intermediate energies and quark-gluon string models at high energies. Also the parametrization of the elastic and inelastic cross sections are revised and improved. Improvement of these models has resulted in better agreement with the test beam data.

None of the models within GEANT4 could explain all physics processes over a large energy domain. It is customary to register several physics processes in a Physics List[3]. Electromagnetic processes are usually valid over the entire energy domain - but each discrete process is described separately, *e.g.*, pair production, Compton scattering etc. On the other hand, hadronic processes are valid over a finite energy domain. Two models may have validity over an overlapping energy region. These two models are used in the overlapping period using a smooth transition mechanism. Figure 1 provides an illustration for the two physics lists: QGSP\_BERT and FTF\_BIC.

Three hadronic models are used in the physics list QGSP\_BERT for charged pions, kaons and protons/neutrons: the Bertini Cascade model (BERT) at low energies, the low energy parametrization model (LEP) at intermediate energies and the quark gluon string model (QGS) with the Pre-compound model (Preco) at the back-end for high energies. The transition between



**Figure 1.** Illustration for the physics lists QGSP\_BERT and FTF\_BIC

Bertini Cascade and LEP models is made at 9.5–9.9 GeV and between LEP and QGS-Preco models at 12–25 GeV. For all other hadrons, the parametrized model is used.

The physics list FTF\_BIC on the other hand uses two hadronic models for each of the particle species, charged pions, kaons, neutrons/protons. Binary cascade model is used at low energies for charged pions and nucleons while low energy parametrized model (LEP) is used as the low energy model for kaons. The high energy part for all these three types of particles is handled by the Fritiof fragmentation (FTF) model. The transition region is between 4 and 5 GeV. Again other hadrons are treated by the parametrized model as done in QGSP\_BERT.

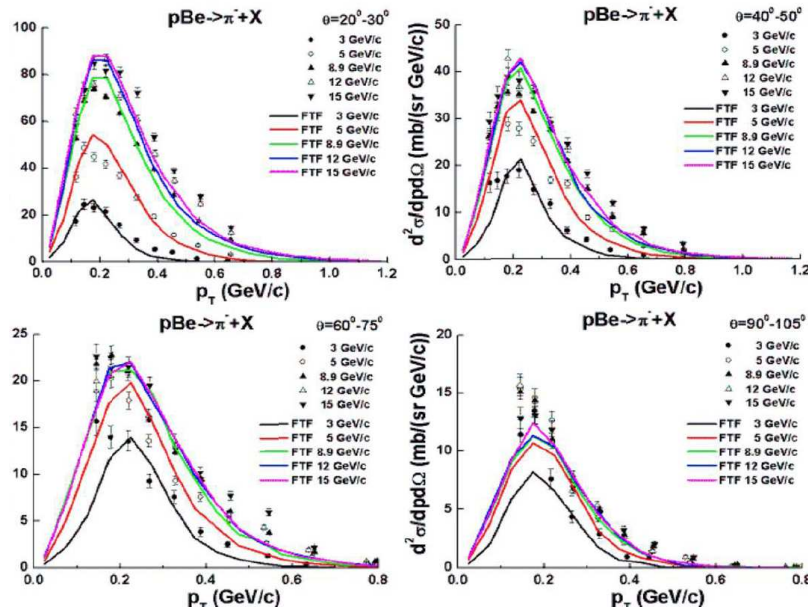
## 2. Hadronic Models

String models are used for hadronic interactions at high energies. Quark-gluon string (QGS) model has been used extensively in GEANT4 physics lists. This model provides good performance at high energies (energies above 20 GeV). It has been found that the model predictions are not valid for beam energies below 10–15 GeV/c. This model is stable over the past few years and is used by all the LHC experiments.

The Fritiof fragmentation (FTF) model is much improved during the past 2–3 years. Single diffraction process is added within this model. A cascade model motivated by Reggeon theory is included in this model. With these changes, the model now performs well down to 5–10 GeV. So it is now possible to join FTF model directly to the Bertini cascade model in the energy range 5–10 GeV. Thus the intervening parametrized model LEP is no longer needed in the definition of the physics list. This has resulted in a significant reduction in the discontinuity of energy response function at the model boundaries.

Figure 2 shows measurements of invariant cross section by the HARP-CDP collaboration [4] for inclusive  $\pi^-$  production at four different angles in proton beryllium interactions as a function of  $p_T$  at five different beam energies. The data are compared with predictions from FTF model as implemented within GEANT4. As can be seen from the figure the model provides a good description of the data at small angles. The agreement worsens in the backward hemisphere particularly at higher energies.

The Bertini style cascade code is used in the QGSP\_BERT physics list (and a few others) to handle inelastic collisions of charged pions, kaons and nucleons from 0 to 10 GeV. It provides good performance at energies below 5–6 GeV. It may be responsible for part of the discontinuity



**Figure 2.** Invariant cross section for inclusive  $\pi^-$  production at four different angles in proton beryllium interactions as a function of  $p_T$  for five different energies. The data are compared with predictions from FTF model as implemented within GEANT4.

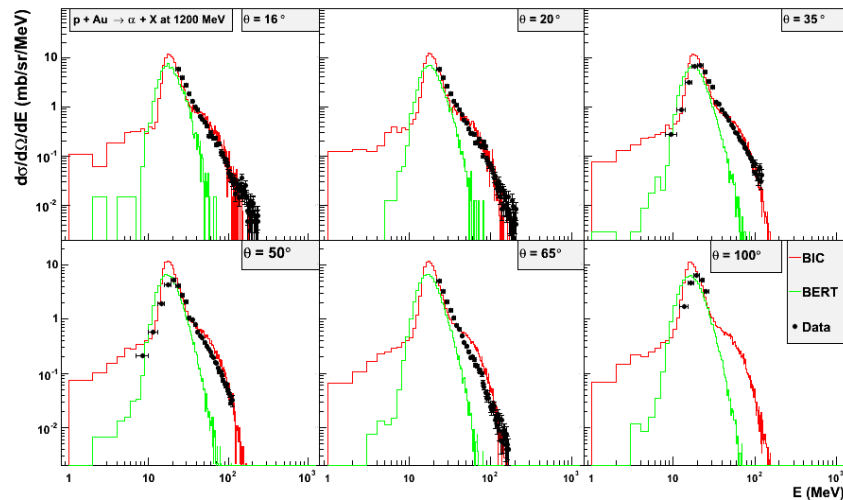
observed in the description of calorimeter response at  $\sim 10$  GeV as reported by ATLAS, CMS and HARP collaborations. Recent improvements include enforcement of energy-momentum conservation at most of the places. The old and inaccurate description of pion-nucleon and nucleon-nucleon angular distributions are now replaced with new ones. With these changes, the agreement with thin target data has improved. In addition to these physics improvements, effort has been made to improve the computing performance. There is a significant reduction in object creation and deletion (by a factor of  $\sim 10$ ) and also a significant improvement in the CPU speed.

The precompound and de-excitation model in GEANT4 is used in QGSP\_BERT and many other physics lists. It is responsible for de-exciting the nucleus after high energy interaction of the string models. It is valid at energies below  $\sim 200$  MeV. Improvements during the last two years include calculation of improved density of state; use of modern data to estimate emission probabilities; hybrid use of Weiskoff-Ewing and GEM models (improving nuclear fragment spectra from decay).

Figure 3 shows measurements [6] of invariant cross section of inclusive  $\alpha$  production at six different angles in proton gold interactions at 1.2 GeV as a function of kinetic energy of the emitted particle. The data are compared with the predictions of two different cascade models within GEANT4. The binary cascade model which uses the precompound model provides excellent agreement with the data. Bertini cascade model does not explain the data at energies above 30 MeV.

### 3. Hadronic Cross Sections

Several parametrizations exist for describing hadronic cross section as a function of energy. The parametrizations due to Barashenkov, Axen-Wellis and GHEISHA are widely used in GEANT4 physics list. They provide good performance in the energy range of 1-90 GeV. However, the Barashenkov parametrization does not show the rise in cross section at high energies. These



**Figure 3.** Invariant cross section for inclusive  $\alpha$  production at six different angles in proton gold interactions at 1.2 GeV as a function of kinetic energy of the emitted  $\alpha$ . The data are compared with the predictions of the Bertini and the Binary cascade models as implemented within GEANT4.

cross sections do not show the details of resonances at low energies. Cross sections for kaons and anti-nucleons are also not treated well.

In recent time, several alternative cross sections have been developed. Two notable developments are

- parametrizations of elastic as well as inelastic cross sections for more particle types done within the CHIPS model;
- parametrizations based on Glauber-Gribov theory to include the high energy rise.

Figure 4 shows measurements of inelastic cross section for n-C interaction as a function of neutron energy. The measurements are compared with the recent parametrizations based on Glauber-Gribov theory. As can be seen from the figure, the new parametrization gives a good description of the data.

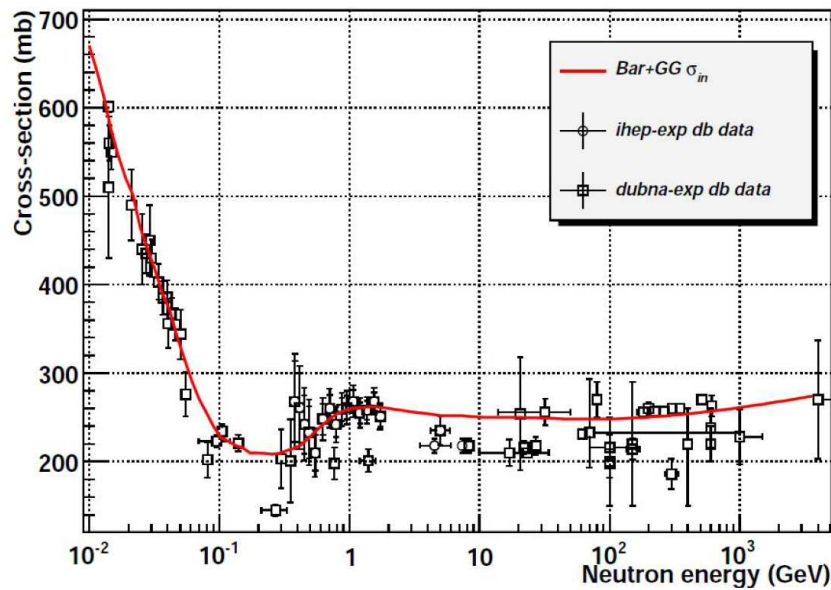
#### 4. Hadronic Physics Validation

During the past two years much effort has been devoted to improve validation of GEANT4 hadronic models. The hadronic working group of GEANT4 participates regularly in the validation efforts comparing GEANT4 to other Monte Carlo codes. For example they participate in

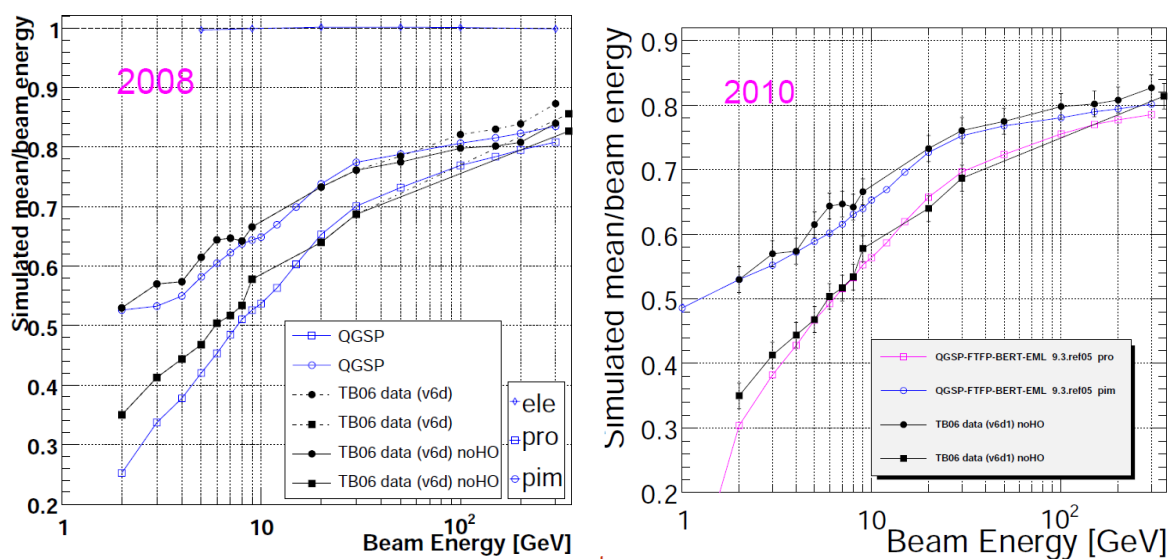
**IAEA** which uses wide range of spallation data in the energy range between 0 and 3 GeV;

**SATIF** which compares results on shielding applications.

A large number of validation suites have been developed to test GEANT4 hadronic physics over all energy ranges. In order to carry out validation of a large number of models over the entire energy spectra, an automated validation framework is under development. This framework includes (1) executing the tests, (2) merging the statistics (if required) and comparison of the results with references, (3) storing the results for future reference or for publishing to the user community, (4) publishing the results. The requirement and the design documents for the framework are written and are available [7, 8].



**Figure 4.** Inelastic cross section for n-C interaction as a function of neutron energy compared with the recent parametrizations based on Glauber-Gribov theory.



**Figure 5.** Response of the CMS calorimeter to  $\pi^-$  and proton beam as a function of beam energy being compared with predictions of GEANT4 during 2008 (left) and 2010 (right).

CMS and ATLAS made extensive tests using their calorimeter data with test beams. They monitored the improvements of GEANT4 hadronic models over years. Figure 5 shows plots of mean energy response of the CMS calorimeter [9] to beams of  $\pi^-$  and proton as a function of the beam energy. The measurements are compared to predictions of GEANT4 physics lists during 2008 and 2010. As can be seen from the figure, the agreement between data and Monte Carlo has improved over years from  $\sim 10\%$  level to  $\sim 2\text{--}3\%$  level.

## 5. Summary

GEANT4 provides a large number of models for hadronic physics each valid over a certain energy domain for a number of incident particles. These models are put together in a physics list to satisfy a given application domain. The models are continuously improved over the years adding new features and new models are added to the list.

The models are validated against data obtained from thin target experiments as well as from thick targets and calorimeters. A validation framework is being developed to keep track of results from all the comparisons.

LHC experiments have successfully deployed GEANT4 physics list to model the performance of the detectors. Hadronic models can be successfully used also for space and medical applications.

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