Testing suite for validation of Geant4 hadronic generators

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Abstract. The testing suite for validation of Geant4 hadronic generators with the data for thin target experiments has been updated. We automated and extended the suite providing a production mode of operation. The new data sets for incident proton beam momentum up to 12.9 GeV/c have been included. The results of comparisons with the inclusive neutron and pion production data for different Geant4 hadronic generators are shown.

1. Introduction
The sampling of inelastic interactions of hadrons with atomic nuclei is one of the general tasks for Geant4 simulation of LHC experiments. The precision of simulation may be a limiting factor for precision of final results. The Geant4 toolkit [1] includes a variety of hadronic generators for different projectile energy and particle type [2-4]. The cascade energy range, in which binary interaction between hadrons and nucleons dominates, is an important part of hadronic physics for LHC and other HEP experiments. The testing suite [5] has been developed for the deployment of the Binary [6] and Bertini [7] cascades. It was designed for validation of hadronic models versus data of thin target experiments. Recently the testing suite has been significantly updated:
- new data sets added;
- energy range extended;
- a software for running in a production mode developed;
- a complete migration from PAW to ROOT has been performed.
Below we describe new software and discuss new results of validation of Geant4 hadronic models.

2. Testing suite
The testing suite consists of several components (figure 1):
- experimental data;
- converters of data into internal formats;
- c++ software to run tests;
- macro files per data set;
- results of simulation per data set and per Geant4 reference tag;
- macro files for analysis of simulation and comparison with the data;
- scripts to run tests in the production mode.

Data sets are made per single beam energy and target material. As a result of a test run, a number of comparison plots are produced for each data set. The total number of data sets is about 100 and the total number of single plots is about 1000. The store of the software and results is located at a dedicated afs volume at CERN and is accessible via web.
The following inclusive reactions are used for validation tests:
\[ p + A \rightarrow n + X, \]
\[ d + A \rightarrow n + X, \]
\[ \alpha + A \rightarrow n + X, \]
\[ ^{12}\text{C} + A \rightarrow n + X, \]
\[ p + A \rightarrow \pi^{\pm} + X, \]
where A is a target nucleus, X – is a final hadronic system. The double differential and differential inclusive pion and neutron production cross sections are under study. The systematic uncertainties of the data are taken into account. The binning of histograms for the simulation is selected to be the same as for the data. Because of that, several formats for data and output results are used depending on the type of the experiment and on the beam energy. Correspondingly different converters and ROOT scripts are prepared. The suite has a possibility to include data for inclusive production of protons and gammas and also for data with other primary beams, for example, pion or neutron. For that only extra converters and scripts are needed. If a new data format is different from existing once, the main software does not need to be modified. The addition of any new Geant4 model requires a minimal modification of the current software. The following Geant4 models are exercised by the testing suite so far:
- the Low Energy Parameterized model (LHEP) [2];
- the Binary cascade (BIC) [6];
- the Bertini cascade (BERT) [3, 7];
- the PreCompound model (PRECO) [3, 6];
- the Quark-Gluon String model with the PreCompound model backend (QGSP) [3, 8];
- the Quark-Gluon String model with the CHIPS generator backend(QGSC) [3, 9];
- the Fritiof fragmentation model with the PreCompound model backend (FTFP) [4, 8];
- and some others.
3. Results

The example of results for the 22 MeV proton beam bombarding a thin iron (Fe) target [10] are shown in figure 2. In the first five plots the double differential cross sections for the inclusive neutron production for different polar angles of secondary neutrons (30, 60, 90, 120, 150 degrees) are shown as a function of neutron energy. The right-bottom plot demonstrates cross section differential in energy. The data shows mainly evaporation of neutrons with small contribution of the quasi-elastic channel. The Binary cascade predictions are practically identical with the PreCompound model results, because at low energies the Binary cascade [6] uses internally the PreCompound model. Both are in a good agreement with the data. For this data set the Bertini cascade predictions are more precise for the evaporation part of spectra and less précised for the quasi-elastic part. This comparison is important not only for simulation of low-energy beam interactions but also for high energy applications, because hadronic shower shape depend on energy and angular spectra of neutrons produced by shower particles of any energy.

Figure 2. Inclusive neutron production by 22 MeV proton beam in a thin iron target: points – data [10], histograms – Geant4 9.0 simulation with the Binary cascade (BIC), the Bertini cascade (BERT) and the PreCompound model (PRECO).

The same trend is demonstrated for the 256 MeV protons beam interaction with a thin lead (Pb) target [11] (figure 3). The PreCompound model cannot be applied for this energy, because its validity range limited by the pion production threshold. The Bertini cascade predictions are more precise for the evaporation part of a spectrum at any neutron angle, while the Binary cascade provides more precise predictions for the quasi-elastic part. The precise simulation of the quasi-elastic reaction is an important requirement for simulation of the longitudinal shape of the high energy hadronic showers. For ILC calorimetry [12] the detailed predictions for secondary spectra is even more strong requirement to simulation software, because in all calorimeters proposed for ILC a detailed information about secondary particles will be used for reconstruction of hadronic jets.
Figure 3. Inclusive neutron production by 256 MeV proton beam in a thin lead target: points – data [11], histograms – Geant4 9.0 simulation with the Binary cascade (BIC) and the Bertini cascade (BERT).

Figure 4. Inclusive forward $\pi^+$ production by 12.9 GeV/c proton beam in aluminium target: points – data [14], histograms – Geant4 9.0ref01 simulation with fragmentation models FTFP, QGSP and QGSC.
The data for the inclusive spectra of pion production was recently published by the HARP collaboration [13]. The results [14] of the forward production of $\pi^-$ (figure 4) are already used to decrease systematic uncertainty of the measurement of the neutrino oscillation by the K2K experiment [15]. For the recent Geant4 reference tag 9.0-ref-01 the results of all three string models QGSP, QGSC and FTFP are in a good agreement with the data. It is worse noting, that no special tuning of Geant4 models to the HARP data have been performed. Only bug fix for the QGSC model was done on top of the 9.0 release of Geant4.

The results [16] for the large angle pion production by 5 GeV/c proton beam in a thin tantalum (Ta) target (figure 5) are important for the design of a proton driver and a target station of a future neutrino factory. These results demonstrate that the parameterized GHEISHA-type model LHEP overestimates forward pion production and well describes backward pion production. Geant4 cascade models qualitatively follow the data. The Binary cascade predictions are better than the Bertini cascade predictions practically at all angles.

4. Conclusions

The new software developed for the Geant4 hadronic testing suite cardinally improves the control on the performance of Geant4 hadronic models. A complete migration from PAW based analysis to ROOT scripting has been performed and the production mode of the testing suite is provided. With the CERN LXBATCH system the run of the complete testing suite can be performed in few days. The results of verification are accessible via web that provides an immediate feedback to Geant4 developers. The current software allows easy extension of the testing suite. Personal usage of testing suite software by a developer is also possible.
Acknowledgments
Authors wishing to acknowledge S. Giani and J. Panman for stimulation of this work, J. Apostolakis and G. Folger for the support of the activity and valuable comments.

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