Validation of Geant4 hadronic physics models at intermediate energies



2010 J. Phys.: Conf. Ser. 219 032002

(http://iopscience.iop.org/1742-6596/219/3/032002)

# Validation of Geant4 Hadronic Physics Models at Intermediate Energies

**Sunanda Banerjee**
**(on behalf of Geant4 Hadronic Group)**
Fermilab, P. O. Box 500, Batavia, Illinois 60510, USA
E-mail: sunanda@fnal.gov

**Abstract.** GEANT4 provides a number of physics models at intermediate energies (corresponding to incident momenta in the range 1-20 GeV/c). Recently, these models have been validated with existing data from a number of experiments: (a) inclusive proton and neutron production with a variety of beams ($\pi^-$, $\pi^+$, p) at different energies between 1 and 9 GeV/c on a number of nuclear targets (from beryllium to uranium); (2) inclusive pion/kaon/proton production from 14.6 GeV/c proton beams on nuclear targets (from beryllium to gold); (3) inclusive pion production from pion beams between 3-13 GeV/c on a number of nuclear targets (from beryllium to lead). The results of simulation/data comparison for different GEANT4 models are discussed in the context of validating the models and determining their usage in physics lists for high energy application. Due to the increasing number of validations becoming available, and the requirement that they be done at regular intervals corresponding to the GEANT4 release schedule, automated methods of validation are being developed.

## 1. Introduction

GEANT4 [1] provides several models for hadronic processes each having its validity range in term of beam type or incident energy. For example, there are theory driven string models or parametrized model which are valid at high energies (for beam momenta above few ten's of GeV/c). At low energies there are cascade models or parametrized models to complement the high energy models. It is essential to find out the range of validity of these models by examining them against available data.

Validation of physics models is an integral part of commissioning the model within GEANT4 toolkit and has been performed from the very early days. This work is done either within the GEANT4 collaboration using published data or by users with a complete description of their detector setup. The earlier studies were done with thin and thick target data. Comparisons with thin target data is crucial because it directly compares the models against data without the effect of other processes like particle propagation or electromagnetic physics effects.

The earlier thin target results are done with (a) stopping particles ($\bar{p}$, $\pi^-$), (b) inclusive production of neutrons and protons in low energy (below 100 MeV/c) nuclear interactions with neutron, proton or photon beams, (c) medium energy data (100 MeV/c to 3 GeV/c) on mostly neutron (some proton and $\pi^+$) production in proton-nucleus collision, (d) high energy ($>$ 100 GeV/c) data for inclusive $\pi^\pm$ production in $\pi^-/p$ interactions with nuclear target. These results are documented in reference [2] and presented in several earlier conferences [3].

Simulation of detector setups uses a collection of models and each model is defined for a given type of interaction within a specified range of energy. This collection is termed a "physics list". LHC (Large Hadron Collider) experiments routinely compared the results from the test beam studies with GEANT4 predictions to validate the physics lists within the framework of LCG (LHC Computing Grid) simulation validation [4]. Based on these validation results, the LHC experiments have chosen QGSP_BERT as the default physics list. For the description of hadronic physics, this list uses three GEANT4 models (see Figure 1). It uses Bertini cascade model at low energies, low energy parameterization model at intermediate energies and quark gluon string model with pre-compound at the back-end for high energies. There is a transition between Bertini and LEP models at 9.5-9.9 GeV and between LEP and QGS/Preco at 12-25 GeV.

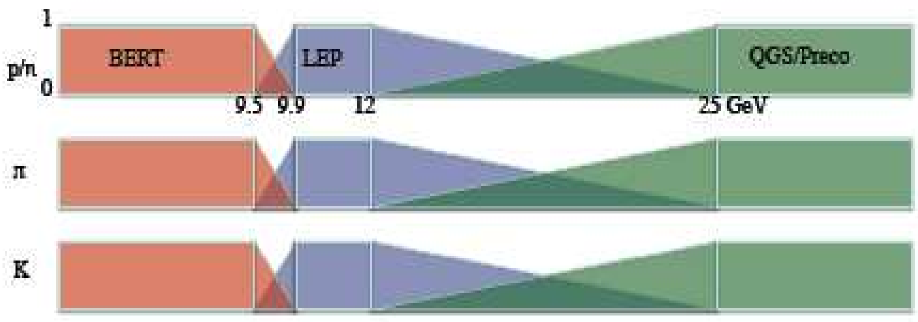


**Figure 1.** Illustration of QGSP_BERT physics list as used for nucleons, pions and kaons [5].

However, very little validation results exist at beam energies between 3.2 and 100 GeV/c. Also GEANT4 has improved or incorporated several new models recently. The current work is devoted to test the new models and to validate all existing models with thin target data at intermediate energies. Special emphasis is given to the three models used by the LHC experiments.

## 2. Data

This work includes three sources of data. The first set of data comes from an ITEP experiment [6] which has carried out an extensive set of measurements on inclusive neutron and proton production in hadron-nucleus collision at energies between 1 and 9 GeV/c. The experiment measured Lorentz invariant double differential cross section as a function of kinetic energy of the final state particle at fixed angles in the laboratory frame. There have been three types of data. In the nuclear scan, measurements exist at 4 different emitted angles in 8-9 kinetic energy bins with 7.5 GeV/c proton beam on 12 nuclear targets ranging from beryllium to uranium. In the angular scan, two beam particles (7.5 GeV/c protons or 5.0 GeV/c $\pi^-$) are used with 4 nuclear targets (carbon, copper, lead and uranium) and inclusive production is measured at 29 different angles in 8-9 bins of kinetic energies. In the energy scan, the same set of targets are used while data exist at 4 different angles with proton, $\pi^+$ and $\pi^-$ beams at 11/7/3 momenta. The typical statistical uncertainty in these data sets is 1-10% while the systematic uncertainty is 5-6%.

The second set of data comes from the HARP experiment [7]. This experiment measures double differential distributions of inclusive pion production in proton-nucleus collision. There are two sets of measurements one at large angle (0.35-2.15 radians) with five beam momenta between 3-12 GeV/c on seven nuclear targets (beryllium to lead) and the other in the very forward direction (0.03-0.21 radians) with six beam momenta between 3-12.9 GeV/c on nine different targets. The statistical uncertainty in these data sets is 1-10% while the systematic uncertainty is about 10%.

The third set of data come from the BNL E802 experiment [8] where measurements are made with proton beam at 14.6 GeV/c. Published data exist on inclusive production of charged pions, kaons and proton for a variety of nuclear targets ranging from beryllium to gold. The measured quantities are Lorentz invariant cross sections as a function of transverse mass in bins of rapidity. Statistical uncertainties are between 5% and 30% while systematic uncertainties are 10-15%.

## 3. Models

Comparisons are made with predictions of the following models inside Geant4 using the release 9.2.p01 of March, 2009. Details of these models are documented in the physics reference manual [9]. The primary set of models comprises of

LEP: low energy parametrized model derived from Gheisha [10] and intended for incident energies below 25 GeV;

Bertini Cascade: Bertini intra-nuclear cascade model intended for momenta below 9 GeV;

QGS: quark-gluon string model intended for energies above 12 GeV.

In addition, the following three models are also considered:

Binary Cascade: data driven intra-nuclear cascade model intended for energies below 5 GeV;

CHIPS: quark level event generator based on chiral invariant phase space model;

FTF: Fritiof model implemented inside Geant4 and intended for energies above 4 GeV.

In recent validation work done by the LHC experiments, it has been found that the standard physics lists have limitations in describing data between 5 and 25 GeV/c. To explore the possibility of finding suitable model candidates in this energy domain, some of the models are tested beyond their prescribed validity range.

## 4. Results

ITEP data are compared with predictions of the six models: LEP, FTF/Binary, FTF/Preco, Binary and Bertini cascades and QGS/CHIPS. The FTF/Binary, FTF/Preco and QGS/CHIPS models are FTF and QGS models where the nuclear de-excitation is taken care of by Binary, Precompound and CHIPS model. As examples only three sets of comparisons are shown. Other comparisons also lead to similar conclusions.

Figure 2 compares model predictions to inclusive proton production at 59.1° and 119.0° in p-Carbon interactions at 1.4 and 7.5 GeV/c as a function of proton kinetic energy. As can be seen from the figure, Bertini cascade model gives a reasonable description of the data in the forward hemisphere while it under-estimates in the backward hemisphere at low energies. LEP over-estimates at high energy and under-estimates at low energy in the forward hemisphere. QGS/CHIPS has large difference at low energies. FTF/Binary (FTF/Preco) over(under)-estimates in the backward hemisphere. Binary cascade model is good only in the forward hemisphere.

Figure 3 compares model predictions to inclusive proton production at 59.1° and 119.0° in $\pi^+$-Uranium interactions at 1.4 and 5.0 GeV/c as a function of proton kinetic energy. As can be seen from the figure, Bertini cascade model gives reasonable description of the data in the forward hemisphere but over-estimates in the backward hemisphere. LEP is reasonable at the high energy point. QGS/CHIPS also provides reasonable predictions. Predictions from Binary cascade model are below the data. FTF/Binary (FTF/Preco) cannot provide good predictions.

Figure 4 compares model predictions to inclusive neutron production at 119.0° with different nuclear targets in $\pi^-$ induced interactions at 5.0 GeV/c as a function of neutron kinetic energy.

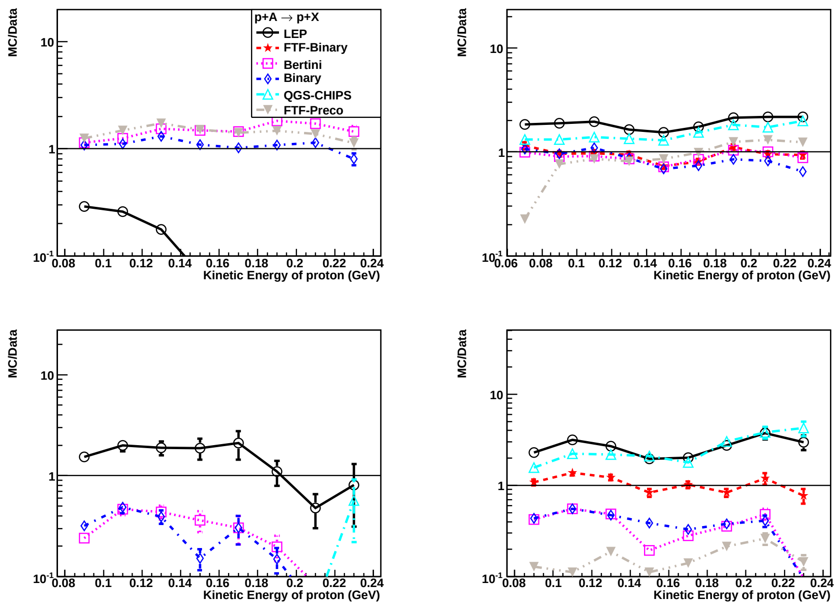


**Figure 2.** Ratio of Lorentz invariant cross sections between model prediction and data for inclusive proton production at 59.1° (top row) and 119.0° (bottom row) in p-Carbon interactions at 1.4 GeV/c (left column) and 7.5 GeV/c (right column) as a function of proton kinetic energy. Predictions of the six GEANT4 models are shown.

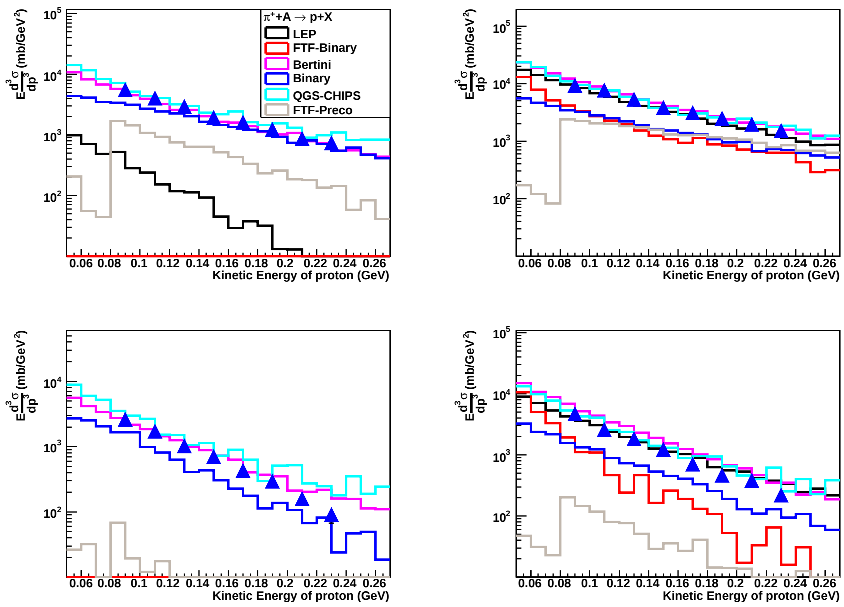


**Figure 3.** Lorentz invariant cross section for inclusive proton production at 59.1° (top row) and 119.0° (bottom row) in $\pi^+$-Uranium interactions at 1.4 GeV/c (left column) and 5.0 GeV/c (right column) as a function of proton kinetic energy being compared with predictions of the six GEANT4 hadronic models.

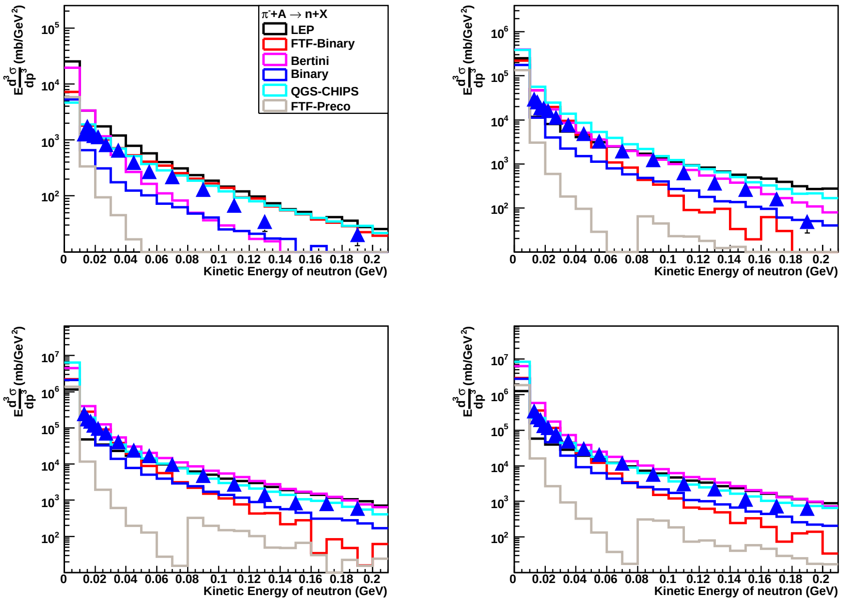


**Figure 4.** Lorentz invariant cross section for inclusive neutron production at 119.0° in $\pi^-$-nucleus collisions at 5.0 GeV/c as a function of neutron kinetic energy for carbon (top left), copper (top right), lead (bottom left), uranium (bottom right) targets being compared with predictions of the six Geant4 hadronic models.

As can be seen from the figure, Bertini cascade model prediction agrees well with the data. LEP predicts larger cross section for heavier targets. QGS/CHIPS provides reasonable description of the data. Binary cascade model (also FTF/Binary) predicts smaller cross section while FTF/Preco predictions are well below the data.

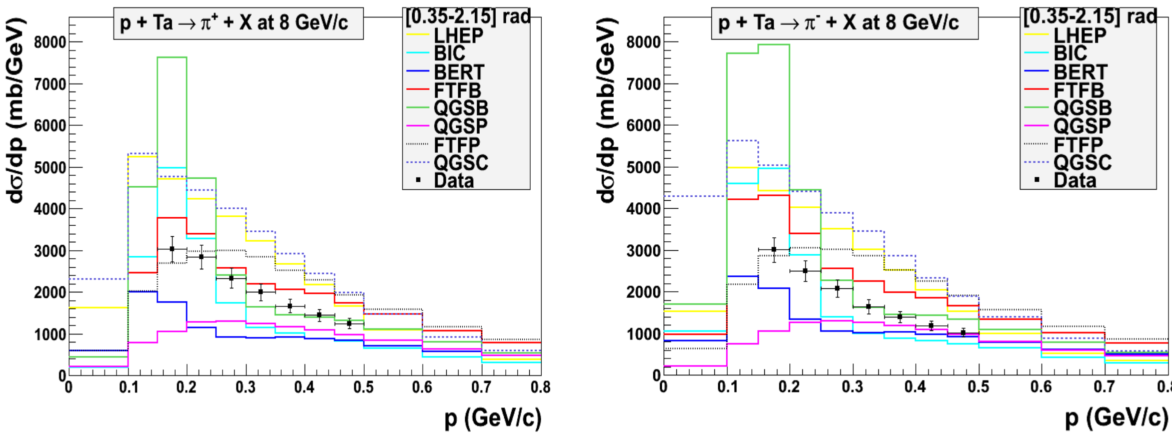


**Figure 5.** Inclusive momentum spectra of $\pi^+$ (left) and $\pi^-$ (right) from proton-tantalum interactions at 8 GeV/c with the final state particles detected at large angle (0.35-2.15 radian).

Figure 5 shows a comparison of the HARP data on inclusive pion production in tantalum target as a function of the pion momentum. QGS/Binary model predictions are closest to the data. FTF/Binary predicts larger cross sections while QGS/Preco and Bertini predict smaller cross sections.

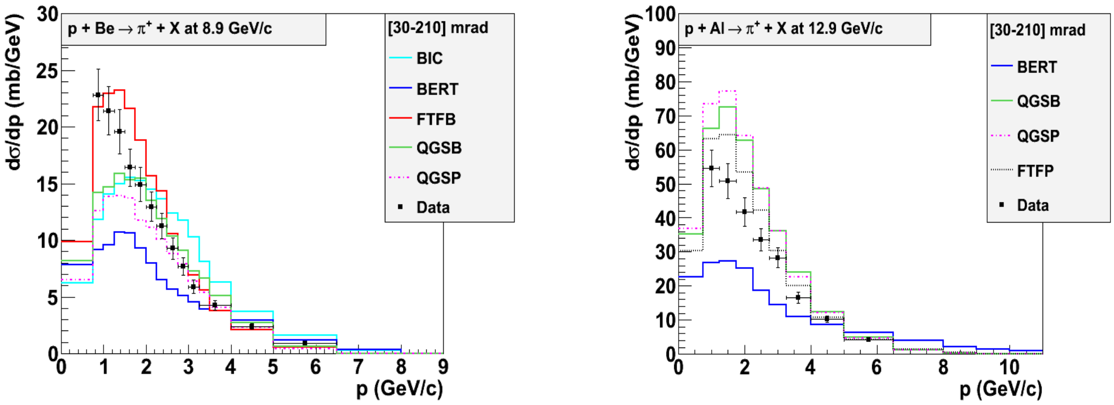


**Figure 6.** Inclusive momentum spectra of $\pi^+$ from proton-beryllium (left) and proton-aluminum (right) interactions at 8.9 GeV/c with $\pi^+$ detected in the very forward region (0.03-0.21 radian).

Figure 6 shows a comparison of the HARP data on inclusive $\pi^+$ production in beryllium and aluminum targets as a function of the pion momentum. QGS/Binary model under-predicts at smaller momenta for beryllium target while FTF/Preco(Binary) are closest to the beryllium data. QGS/Preco predicts larger cross section for aluminum and gives good description for beryllium above 2 GeV/c. Bertini predicts smaller cross sections.

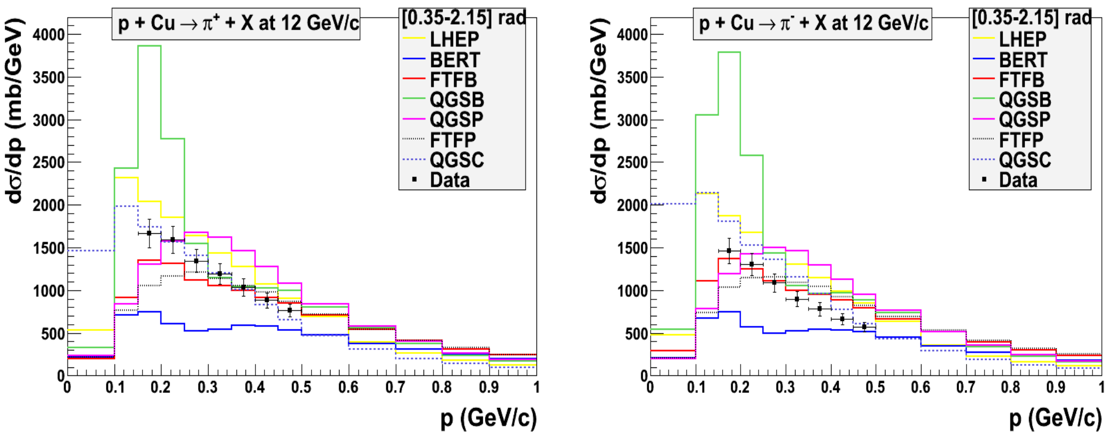


**Figure 7.** Inclusive momentum spectra of $\pi^+$ (left) and $\pi^-$ (right) from proton-copper interactions at 12 GeV/c with the final state particles detected at large angle (0.35-2.15 radian).

Figure 7 shows a comparison of the HARP data on inclusive pion production in copper target as a function of the pion momentum. QGS/Binary model predictions are close to the data above 250 MeV/c. FTF/Binary predicts the best description among all the models. QGS/Preco predicts larger cross sections at higher momenta while Bertini predict smaller cross sections.

The BNL data are compared with five different models: LEP, Bertini cascade, QGS/Preco, QGS/CHIPS and FTF/Binary. Again only a small subset of some representative comparisons are shown here.

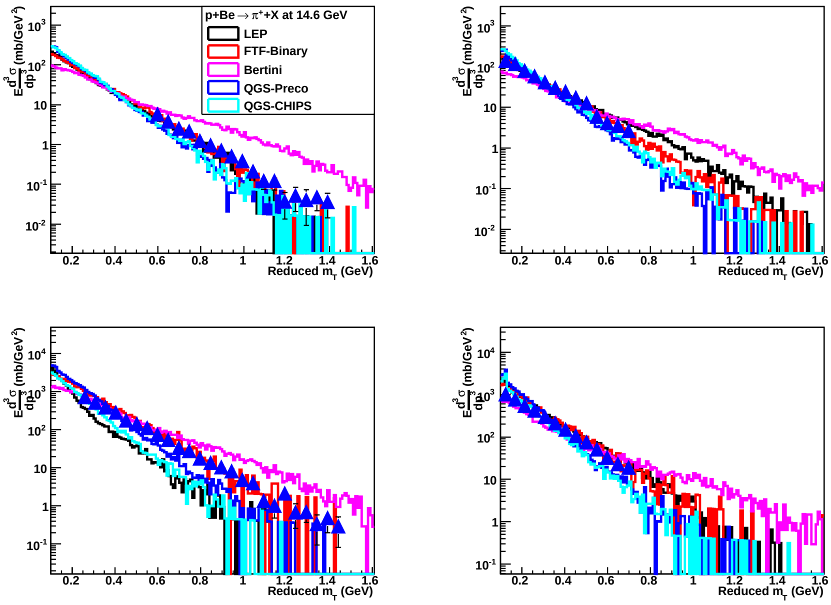


**Figure 8.** Lorentz invariant cross section for inclusive $\pi^+$ production in $p$-nucleus collisions at 14.6 GeV/c for beryllium (top row) and gold (bottom row) targets as a function of reduced transverse mass at rapidity values of 1.1 (left column) and 2.3 (right column) being compared with predictions of the five GEANT4 models.

Figure 8 compares model predictions to inclusive $\pi^+$ production at rapidity values of 1.1 and 2.3 in interactions of protons with beryllium and gold targets at 14.6 GeV/c as a function of reduced transverse mass ($m_T$). Bertini clearly predicts a wrong shape in all these plots. It is to be noted that this energy is way above the validity range of the model. LEP predicts larger cross sections at large $y$ and $m_T$. QGS/Preco and QGS/CHIPS predict smaller cross sections at large $m_T$. FTF/Binary model predictions are good for all rapidity ($y$) and transverse mass values.

Figure 9 compares model predictions to inclusive proton production at four rapidity values from 1.1 to 2.3 in $p$-copper interactions at 14.6 GeV/c as a function of reduced transverse mass. Bertini gives a fair prediction of the data. LEP predicts smaller cross section for low $y$ and larger cross sections at large $y$ and $m_T$. QGS/Preco and QGS/CHIPS predict smaller cross sections at small $m_T$ values. FTF/Binary is good at small $y$ values while it over-predicts at large $y$.

## 5. Summary

Systematic studies are being made by comparing results from several thin target experiments with predictions from different models of hadronic interactions inside the GEANT4 toolkit. The models showed their strengths and weaknesses when confronted with the data. These comparisons could guide us to design a good physics list for high energy physics application.

Two models seem to provide satisfactory results - the Bertini cascade model for the lower energies and the FTF/Binary model for the higher ends of the energy explored. However, both these models have certain limitations. Bertini cascade model under estimates proton and

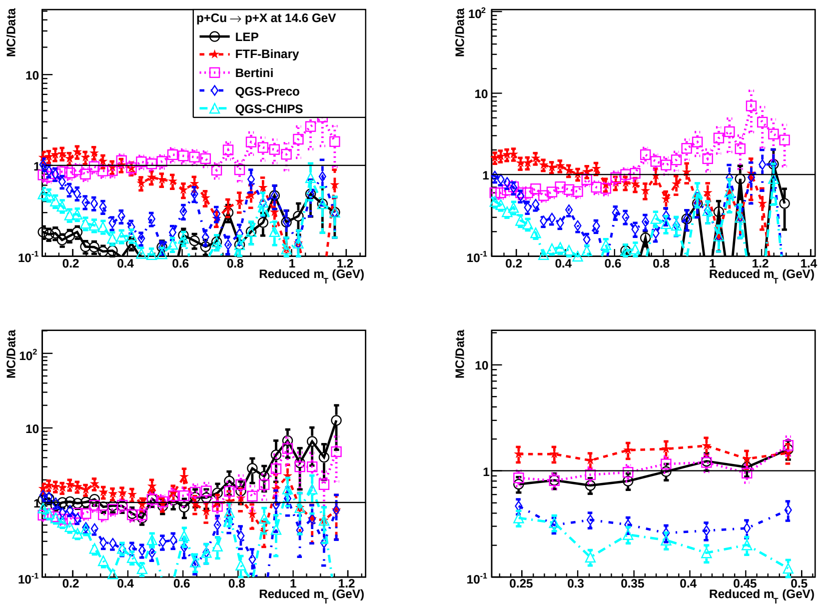


**Figure 9.** Monte Carlo to data ratio of Lorentz invariant cross section for inclusive proton production in $p$-Copper interactions at 14.6 GeV/c as a function of reduced transverse mass at rapidity values of 1.1 (top left), 1.5 (top right), 1.9 (bottom left) and 2.3 (bottom right). Comparisons are shown for the five GEANT4 models.

neutron production in the backward hemisphere for light nuclei. It also produces too many very low energy protons. FTF model, on the other hand, has some deficiency of predicting nucleon production. The results of the comparison are also used in improving the model predictions.

We now have a good validation of hadronic models in the energy regions between 5 and 15 GeV/c. Currently the validation efforts are done by several test codes inside the GEANT4 code repository. They are executed in a semi-automated way. Effort is under way to automate this process and to have a uniform approach in providing the results to the users. This effort will include also low and high energy validation of hadronic models.

## References

[1] GEANT4: S. Agostinelli *et al* , Nuclear Instruments and Methods **A506** (2003) 250; J. Allison *et al* , IEEE Transactions on Nuclear Science **53** (2006) 278.
[2] *http://geant4.fnal.gov/hadronic_validation/validation.htm*
[3] V. N. Ivanchenko *et al* , CHEP03 Conf Proc. CHEP-2003-MOMT009; V. N. Ivanchenko and A. Ivantchenko, J. Phys. Conf. Series **119** (2008) 032026; G. Folger *et al* , IEEE NSS Conf. Proc. IEEE-2008-NSS-N37-4.
[4] *http://lcgapp.cern.ch/project.simu/validation/*
[5] A. Ribon *et al* , IEEE NSS Conf. Proc. IEEE-2008-NSS-N02-89.
[6] Yu. D. Bayukov *et al* , Soviet Journal of Nuclear Physics **42** (1983) 116.
[7] M. G. Catanessi *et al* , European Physics Journal **C52** (2007) 29; European Physics Journal **C53** (2008) 177; European Physics Journal **C54** (2008) 37.
[8] T. Abbot *et al* , Physical Review **D45** (1992) 3906.
[9] D. H. Wright *et al* , AIP Conf. Proc. 867 (2006) 479; D. H. Wright *et al* , AIP Conf. Proc. 896 (2007) 11; G. Floger *et al* , CHEP03 Conf Proc. CHEP-2003-MOMT007; G. Folger *et al* , Eur. Phys. J. **A21** (2004) 407; A. Heikkinen *et al* , CHEP03 Conf. Proc. CHEP-2003-MOMT008.
[10] H. Fesefeldt, RWTH Aachen Preprint, PITHA 85/02 (1985).