Validation of Geant4 Hadronic Physics Models at Intermediate Energies

Outline

- Motivation
- Models
- Data Used
- Validation Results
- Summary

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Sunanda Banerjee, Fermilab
(on behalf of Geant4 Hadronic Group)

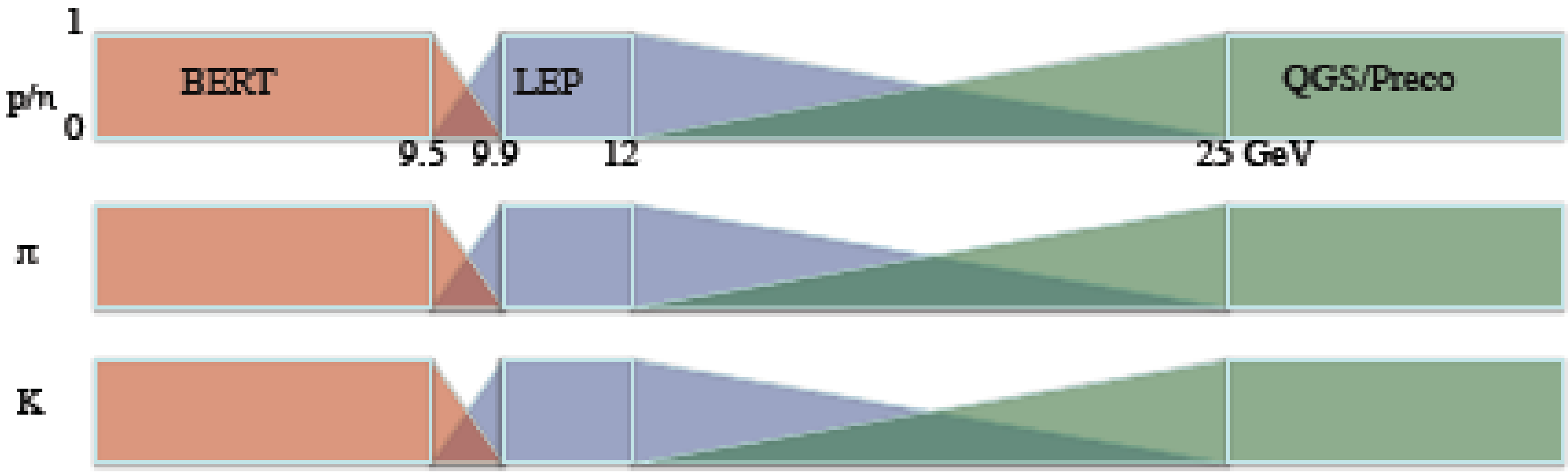
Motivation (I)

- Geant4 provides several models for hadronic processes each having its validity range in term of beam type or incident energy:
  - High energy models are string models (QGS, FTF) or of parametrized type (HEP);
  - Low energy models are cascade (Binary, Bertini, …) or parametrized (LEP).
- It is essential to find out the range of validity of these models by comparing them against available data
- Validation of physics model is an integral part of commissioning the model in Geant4 and has been a part of Geant4 activity from the very early days
- This work has been done within the Geant4 collaboration using published data.

Motivation (II)

- The earlier studies are done with thin and thick target data. Validation with thin target data is crucial to judge the quality of model prediction The thin target validations were done for
  - Stopping particle (anti-protons, π^-)
  - Low energy data (<100 MeV) with inclusive n, p production in n, p, γ beams on nuclear target
  - Medium energy data (100 MeV-20 GeV) with mostly inclusive n (some p, π^+) production in p-A collision upto 3 GeV
  - High energy data (> 20 GeV) with inclusive $\pi^\pm$ production in π^-/p interactions with nuclear targets
- Also some comparisons have been done for complete experimental setups by Geant4 team and also LHC experiments
- However
  - Insufficient validation at beam energies between 5-100 GeV
  - Newer models are available and they need to be verified

Geant4 Models



- At present the best physics list for the LHC experiments is QGSP_BERT_EMV.
- This list utilizes 3 Geant4 models to describe interactions of the hadrons
  - Bertini cascade model at low energies
  - LEP at intermediate energies
  - QGS/Preco at high energies
- These 3 models need to be examined in more detail.

Models Validated

- We have compared data with the predictions of several models using Geant4 version 9.2
- Primary set:
  - LEP: Low energy parametrized model derived from GHEISHA and is intended for incident energies below 25 GeV
  - Bertini Cascade: Bertini intra-nuclear cascade model intended for incident energy below 9 GeV
  - QGS: Quark gluon string model and is intended for incident energy above 12 GeV
- Auxiliary set:
  - Binary Cascade: An intra-nuclear cascade model intended for incident energy below 5 GeV
  - CHIPS: Quark level event generator based on Chiral Invariant phase space model
  - FTF: Fritiof model implementation intended for incident energy above 4 GeV
- The limits are results of validations and compromises
- In recent validation with LHC calorimeters, it was found that existing physics lists ought to be improved in the energy range 5-25 GeV. So some of the models are tested beyond their validity range

Data

Data Set from ITEP: (Yu. D. Bayukov *et.al*., Preprint ITEP-148-1983, Sov. J. Nuclear Physics 42, 116)

- Measurements exist for Lorentz invariant differential cross section as a function of kinetic energy at some fixed angles
- Inclusive proton and neutron production at 4-29 different angles in 8-9 kinetic energy bins in $p/\pi^+/\pi^-$-nucleus collision (12 targets from Be to U) with beam momenta of 1-9 GeV/c
- Statistical errors 1-10% and systematic uncertainties 5-6%

Data from HARP experiment: (M.G. Catanesi *et al*., Eur.Phys.J. C52, 29; Phys.Rev.C77, 055207)

- Double differential distribution of inclusive pion production at large (0.35 – 2.15 rad) and forward (0.03 – 0.21 rad) with proton beam between 3-12.9 GeV/c for a number of nuclear targets from Be to Pb
- Authors quote statistical errors 1-10% and systematic uncertainties ~ 10%

Data set from BNL E-802: (T. Abbott *et al*., Phys. Rev. D45, 3906)

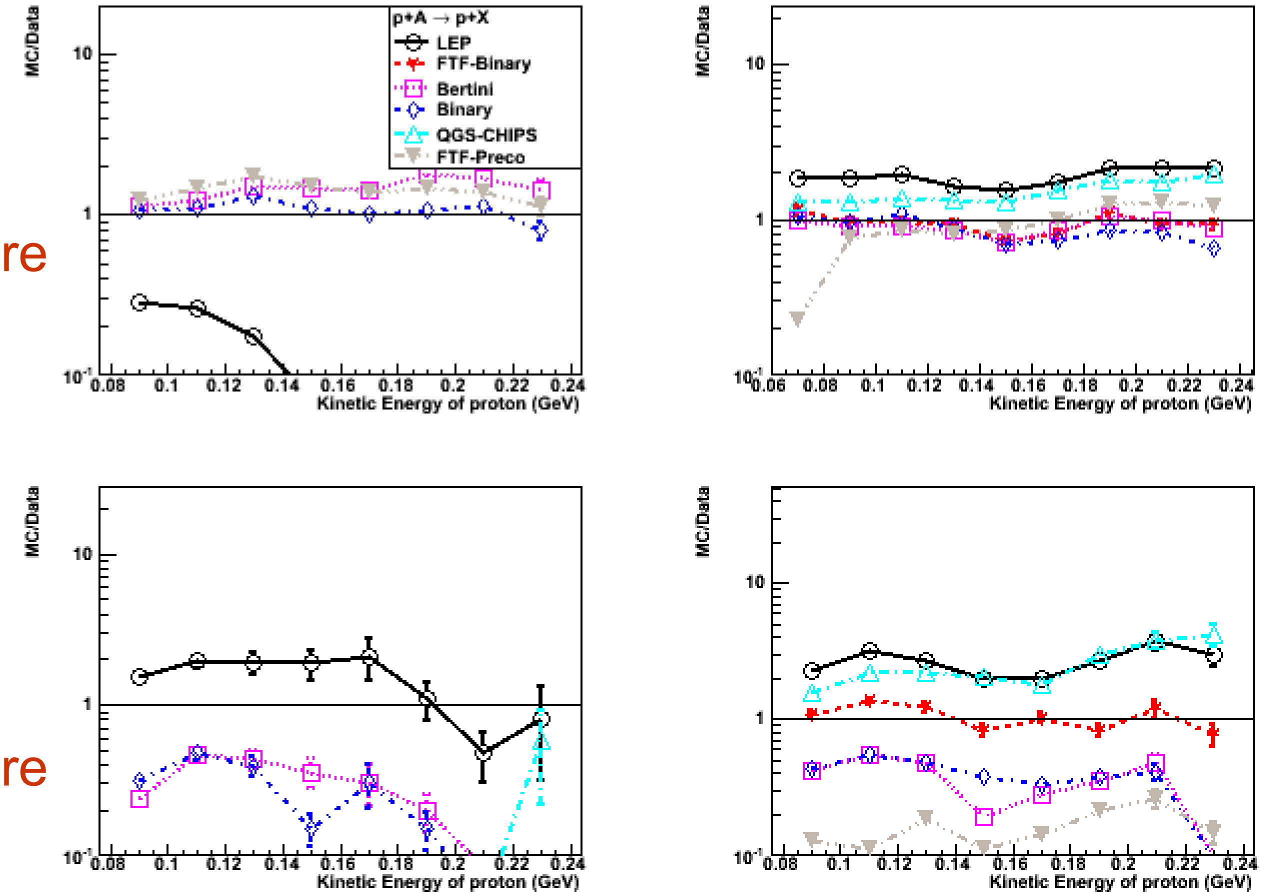
- Inclusive $\pi^\pm$, $K^\pm$ and proton production from p beams at 14.6 GeV/c on a variety of nuclear targets (Be … Au)
- Quantities measured are Lorentz invariant differential cross sections as a function of transverse mass (m_T) in bins of rapidity (y)
- Data quality: statistical error 5-30%; systematic uncertainty 10-15%

Inclusive p in p-C collisions

1.4 GeV/c   7.5 GeV/c

Forward Hemisphere $\theta = 59.1^o$

Backward Hemisphere $\theta = 119^o$



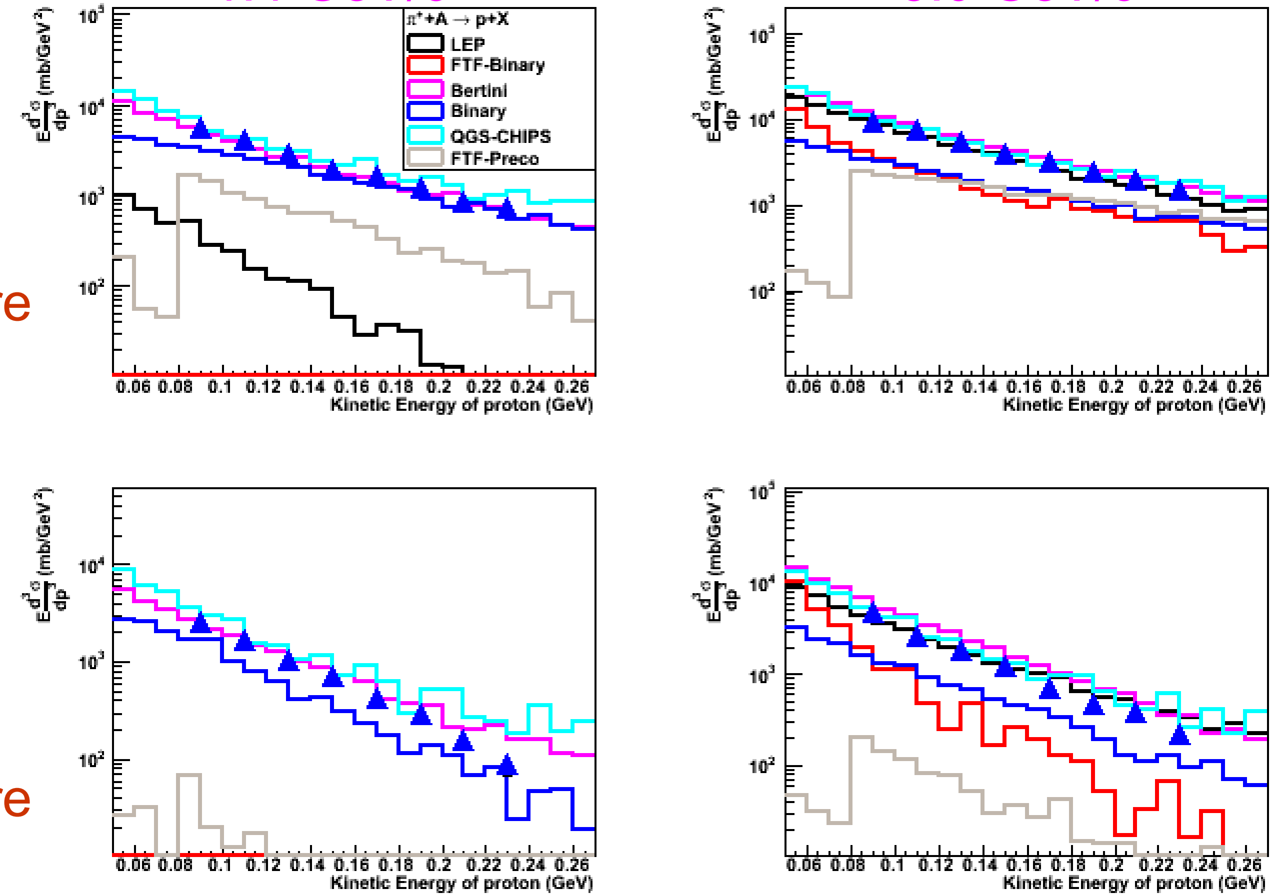
- **Bertini** reasonable in the forward hemisphere
- **LEP** over estimates at high energy and underestimates at low energy in the backward hemisphere
- **QGS/CHIPS** has large difference at low energies
- **FTF/Binary (FTF/Preco)** over(under) estimates in backward hemisphere
- **Binary** good at low energy in forward hemisphere

Inclusive p in π⁺-U collisions

1.4 GeV/c | 5.0 GeV/c

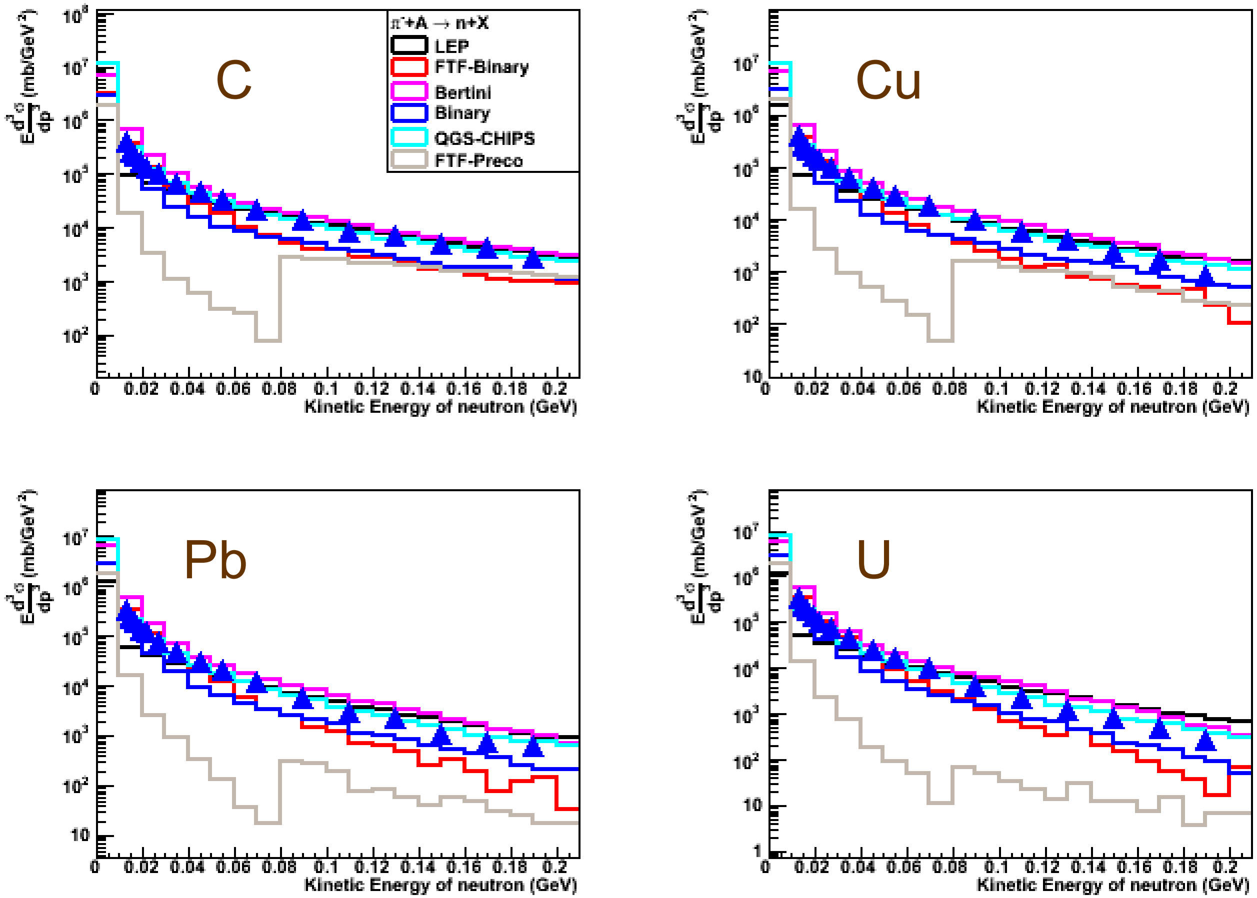
Forward Hemisphere — θ = 59.1°

Backward Hemisphere — θ = 119°



- **Bertini** OK in forward hemisphere; overestimates in the backward
- **LEP** is OK at high energy
- **QGS/CHIPS** provides reasonable prediction
- **Binary** predictions are below the data
- **FTF/Binary (FTF/Preco)** cannot provide a good prediction

Inclusive n in π⁻-A collisions

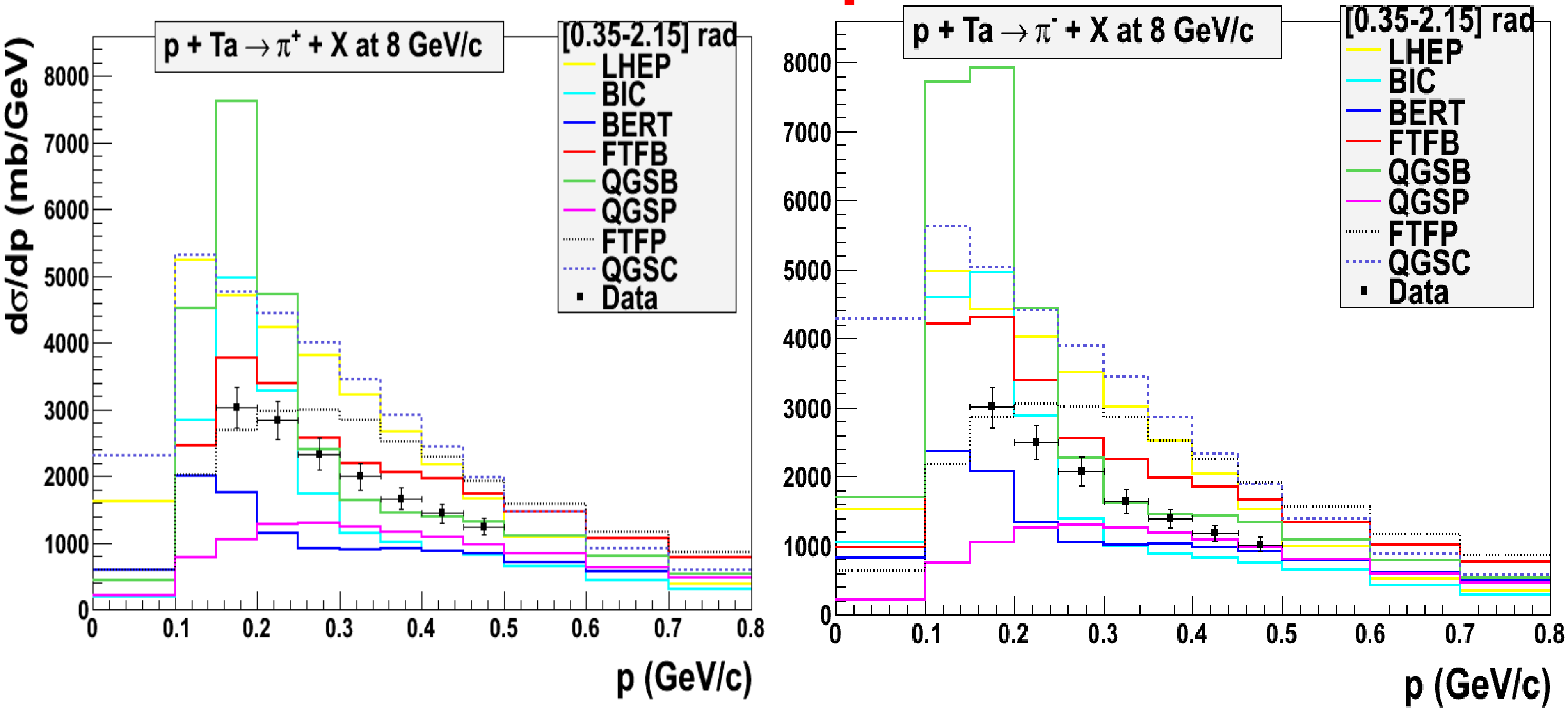


θ = 119°

5.0 GeV/c

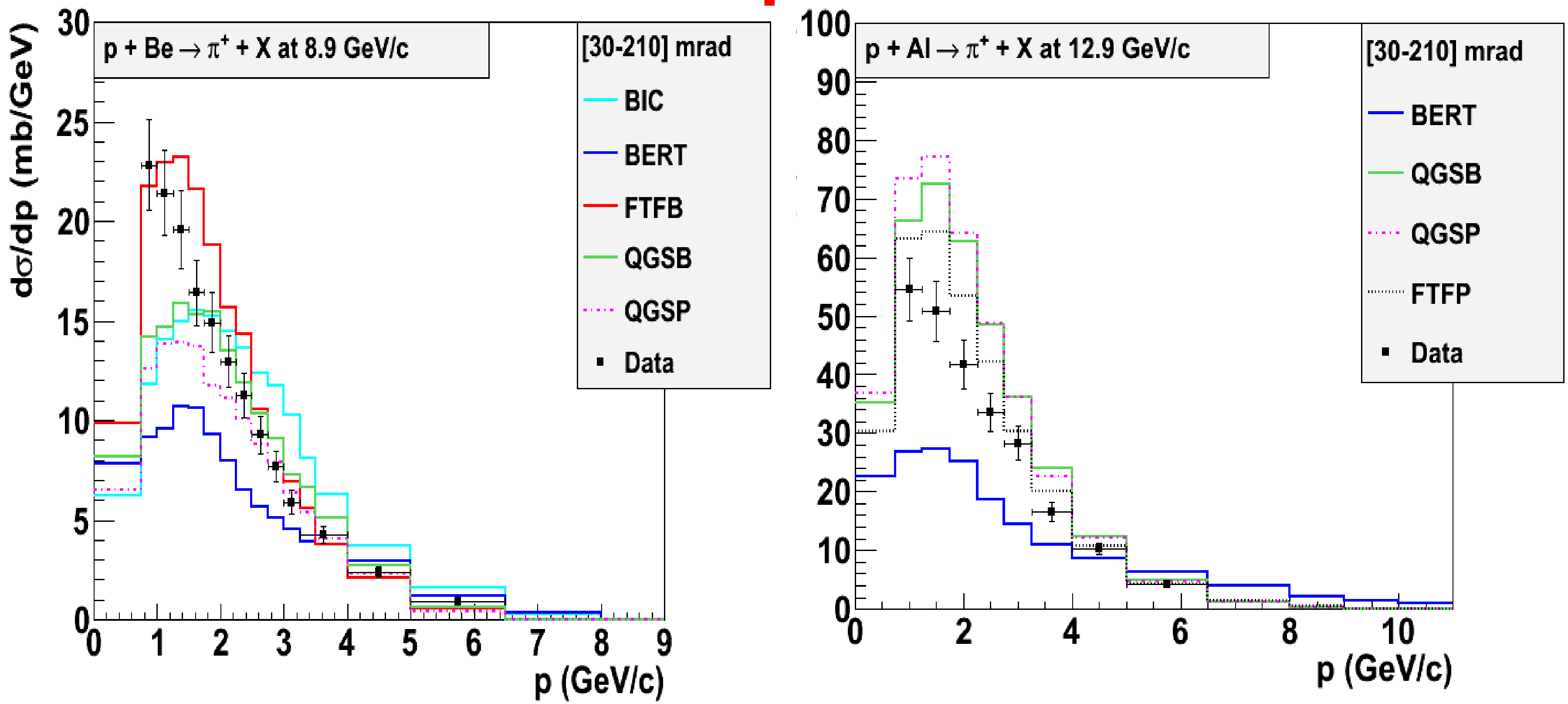
- **Bertini** gives reasonable predictions
- **LEP** predicts larger cross sections for heavier targets
- **QGS/CHIPS** provides reasonable agreement
- **Binary** predicts smaller cross section
- **FTF/Preco** predicts smaller cross section (better for **FTF/Binary**)

Inclusive $\pi^{\pm}$ in p-Ta collisions



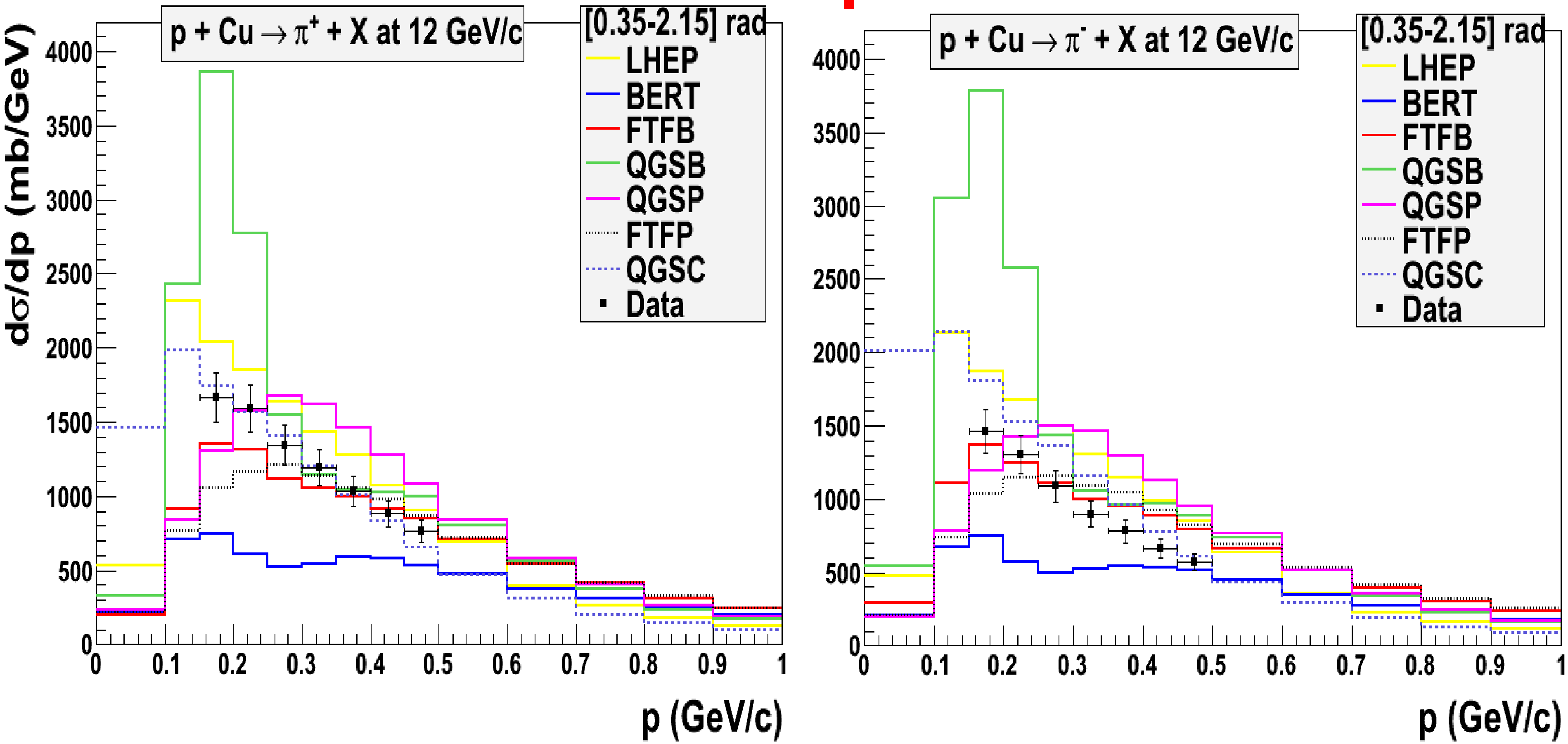
- **QGS/Binary** is closest to data above 250 MeV/c
- **LEP** predicts larger cross sections at all momenta
- **QGS/CHIPS** and **FTF/Binary** predicts larger cross section
- **QGS/Preco** and **Bertini** predict smaller cross sections

Inclusive π^+ in p-Be/Al collisions



- QGS/Binary over predicts particularly for higher momenta
- FTF/Preco(Binary) provides the best description among all the models
- QGS/Preco predicts larger cross section for Al and gives good description for Be above 2 GeV/c
- Bertini predicts smaller cross sections

Inclusive $\pi^{\pm}$ in p-Cu collisions



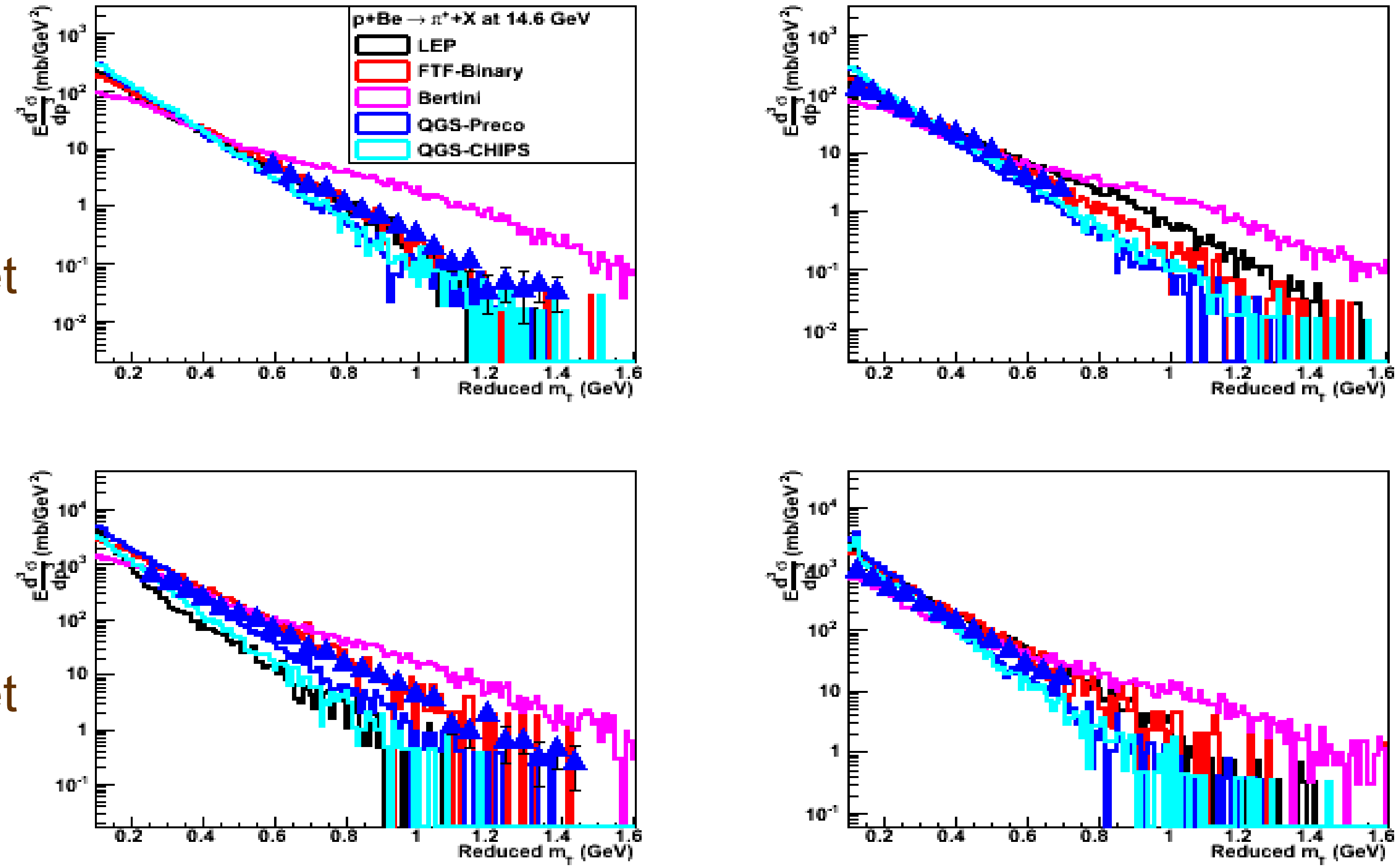
- QGS/Binary is close to the data above 250 MeV/c
- QGS/Preco predicts larger cross sections at higher momenta
- QGS/CHIPS describes the data quite well
- Bertini predicts smaller cross sections
- FTF/Binary provides good description of the data

$p + A \rightarrow \pi^+ + X$ at 14.6 GeV/c

y = 1.1 | y = 2.3

Be Target

Au Target

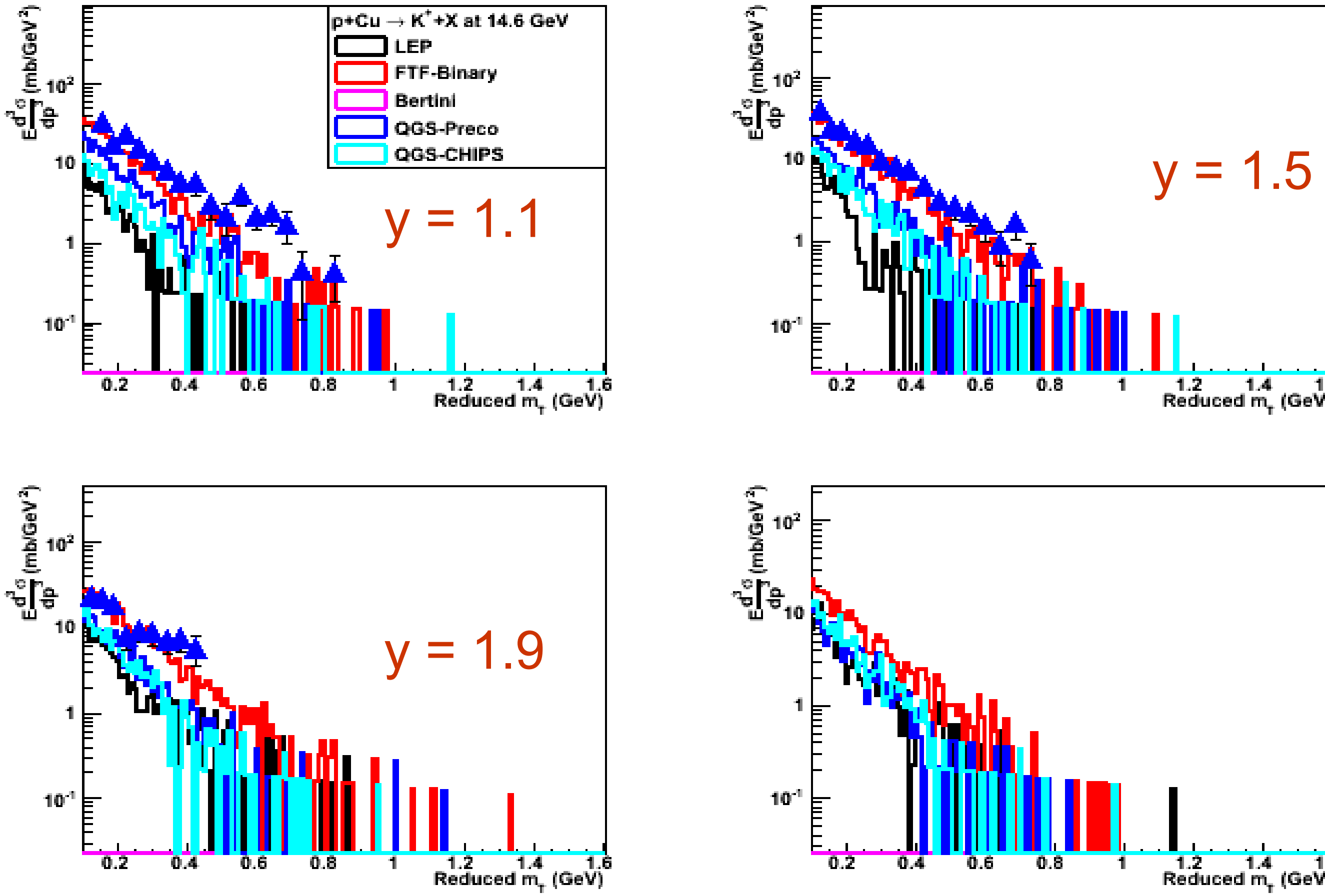


- **Bertini** fails to reproduce data
- **LEP** predicts larger cross sections at large y and m_T
- **QGS/Preco** and **QGS/CHIPS** predict smaller cross sections at large m_T
- **FTF/Preco (FTF/Binary)** good for all y and m_T values

Geant 4

$p + A \rightarrow K^+ + X$ at 14.6 GeV/c

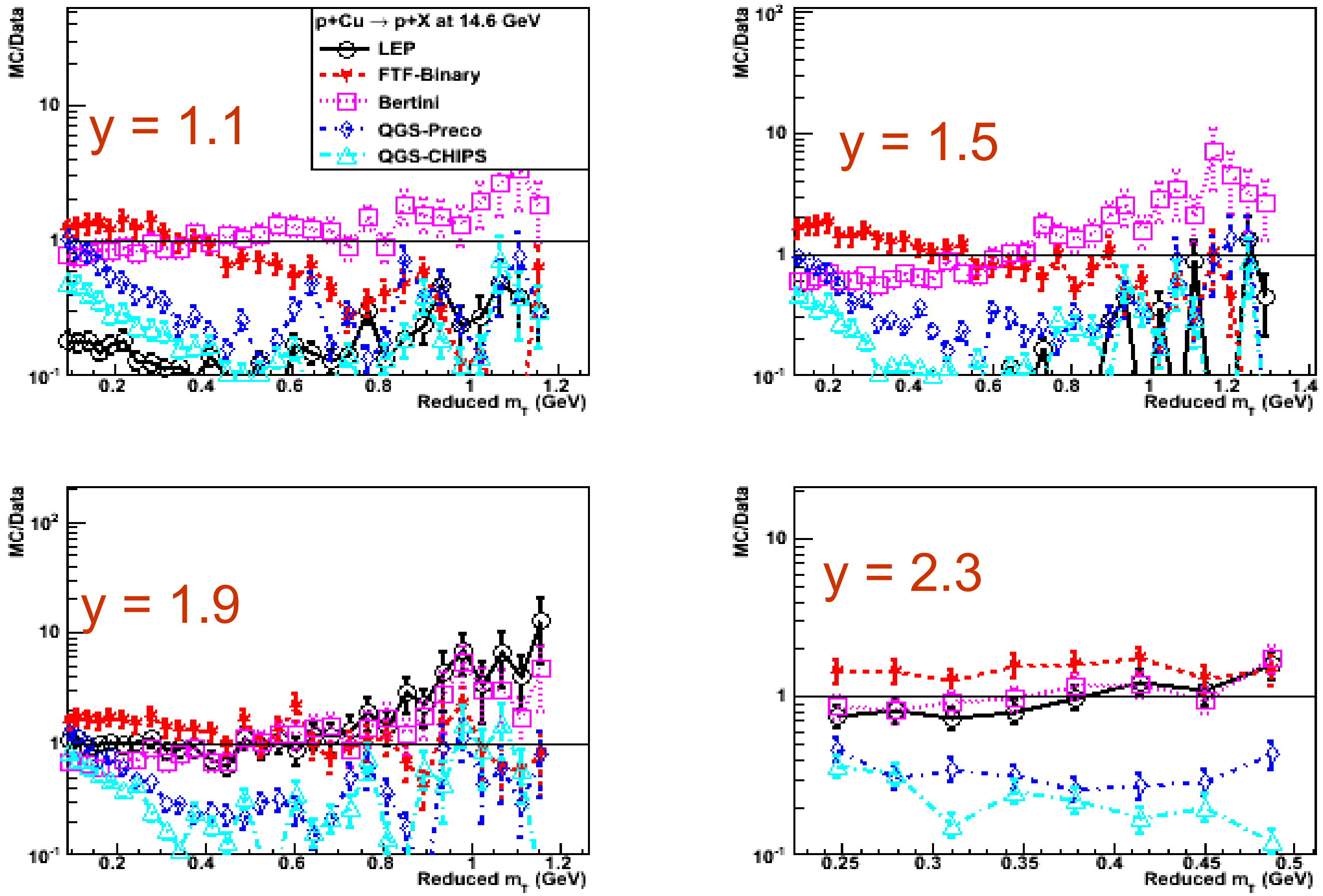
Cu Target



- **FTFP** good for moderate y and under-predicts at small y values
- **LEP**, **QGSP** and **QGSC** models predict smaller cross sections over the entire space of y and m_T

p + A → p + X at 14.6 GeV/c

Cu Target



- **FTF** is good for at large **y** values and under-predicts at small **y**, large **m_T**
- **LEP** predicts smaller cross sections for small **y** and larger cross sections for large **y** and **m_T**
- **QGSP** and **QGSC** predict smaller cross section at small **m_T**
- **Bertini** gives a fair description of the data

Summary

- Systematic studies are being made by comparing results from several thin target experiments with predictions from different models of hadronic interactions
- The models showed their strengths and weaknesses in these comparisons. These could guide us to have the right choice of models for HEP application.
- For example, Bertini cascade model gives good overall description of data below 9 GeV. However for low-A nuclei, it under-estimates production of proton/neutron in the backward hemisphere.
- The modified version of FTF model gives good over all description of data above 5 GeV. It has some deficiency in predicting inclusive proton and neutron production for heavier targets at energies below 5 GeV.

Conclusion & Outlook

- We now have a good validation of hadronic models in the energy region between 5 and 15 GeV.
- Currently the validation efforts are done by several test codes sitting in the Geant4 CVS repository and running them in a semi-automatic way. Effort is under way to automate this process and to have a uniform approach in providing the results to the users. Also include validation efforts at lower and higher energies in this process.

BACKUP SLIDES

Models for Hadronic Interactions

- Data driven models: When sufficient data are available with sufficient coverage, data driven approach can be an optimal way
  - neutron transport, photon evaporation, absorption at rest, inclusive cross section, ….
- Parameterized models: Extrapolation of cross sections and parameterizations of multiplicities and final state kinematics
  - adaptation of GHEISHA and now a newer version with some improvements is on the way
- Theory based models: Includes a set of different theoretical models describing hadronic interactions depending on the addressed energy range
  - diffractive string excitation, dual parton model or quark gluon string model at medium to high energies
  - intra-nuclear cascade models at medium to low energies
  - nuclear evaporation, fission models,`… at very low energies

Data (I)

Data Set from ITEP: (Yu. D. Bayukov *et.al*., Preprint ITEP-148-1983, Sov. J. Nuclear Physics 42, 116)

- Measurements exist for Lorentz invariant differential cross section as a function of kinetic energy at some fixed angles
- Nuclear Scan: Inclusive proton production at 4 different angles in 8-9 kinetic energy bins in proton-nucleus collision (12 targets from Be to U) with 7.5 GeV/c proton beam
- Angular Scan: Inclusive proton production at 29 different angles in 8-9 kinetic energy bins in p-nucleus or π^--nucleus interactions (4 targets from C to U) with 7.5 (5.0) GeV/c p (π^-) beam
- Energy Scan: Inclusive proton/neutron production at 4 different angles in 8-9 kinetic energy bins in p/π^+/π^--nucleus collisions (4 targets from C to U) with 11/7/3 beam momenta between 1 and 9 GeV/c
- Statistical errors 1-10% and systematic uncertainties 5-6%

Data (II)

- Data from large angle HARP experiment:
  - 0.35 – 2.15 radians
  - Proton beam: 3, 5, 8, 8.9, 12 GeV/c
  - Targets: Be, Al, C, Cu, Sn, Ta, Pb
  - Pion momentum: 0.1 – 0.7 GeV/c
- Data from forward angle HARP experiment
  - 0.03 – 0.21 radians
  - Proton beam: 3, 5, 8, 8.9, 12, 12.9 GeV/c
  - Targets: Be, C, N, O, Al, Cu, Sn, Ta. Pb
  - Pion momentum: 0.5 – 8.0 GeV/c
- Statistical accuracy of data for plots below 1- 6%
- Systematic uncertainty 8 -12 %

Data (III)

Data set from BNL E-802: (T. Abbott *et al*., Phys. Rev. D45, 3906)

- **Inclusive $\pi^{\pm}$, $K^{\pm}$ and proton production from p beams at 14.6 GeV/c on a variety of nuclear targets (Be … Au)**
- **Quantities measured are Lorentz invariant differential cross sections as a function of transverse mass (m_T) in bins of rapidity (y)**
- **Data quality: statistical error 5-30%; systematic uncertainty 10-15%**
- **Targets studied Be, Al, Cu, Au for all the final states available**