Geant4 Hadron Shower Simulation: Status and Plans

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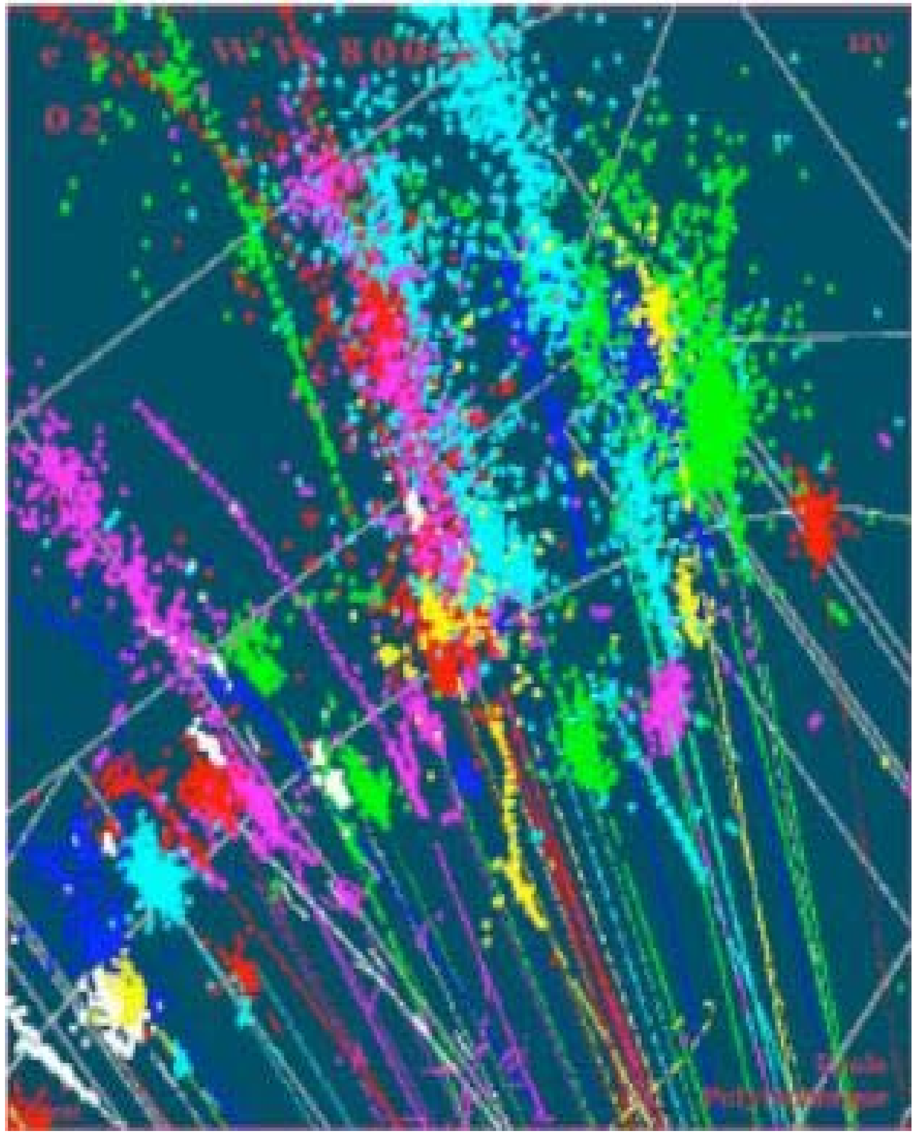
ALCPG Meeting
4 January 2007

Outline

- Hadronic shower simulation and particle flow algorithms
- Comparison with data
  - shower shapes at test beams
  - thin target tests
- Inter-comparison with other codes
- Strengths and weaknesses of Geant4 hadronic code
- Development/improvement plans

Hadronic Showers and Particle Flow

- Operation in jet-dense environment requires knowledge of:
  - lateral shower shape (how much do showers overlap)
  - longitudinal shower shape (how well can showers be separated)
- High-granularity calorimeters allow tracks to be associated with clusters
  - particle-flow calorimetry depends on good energy and baryon conservation



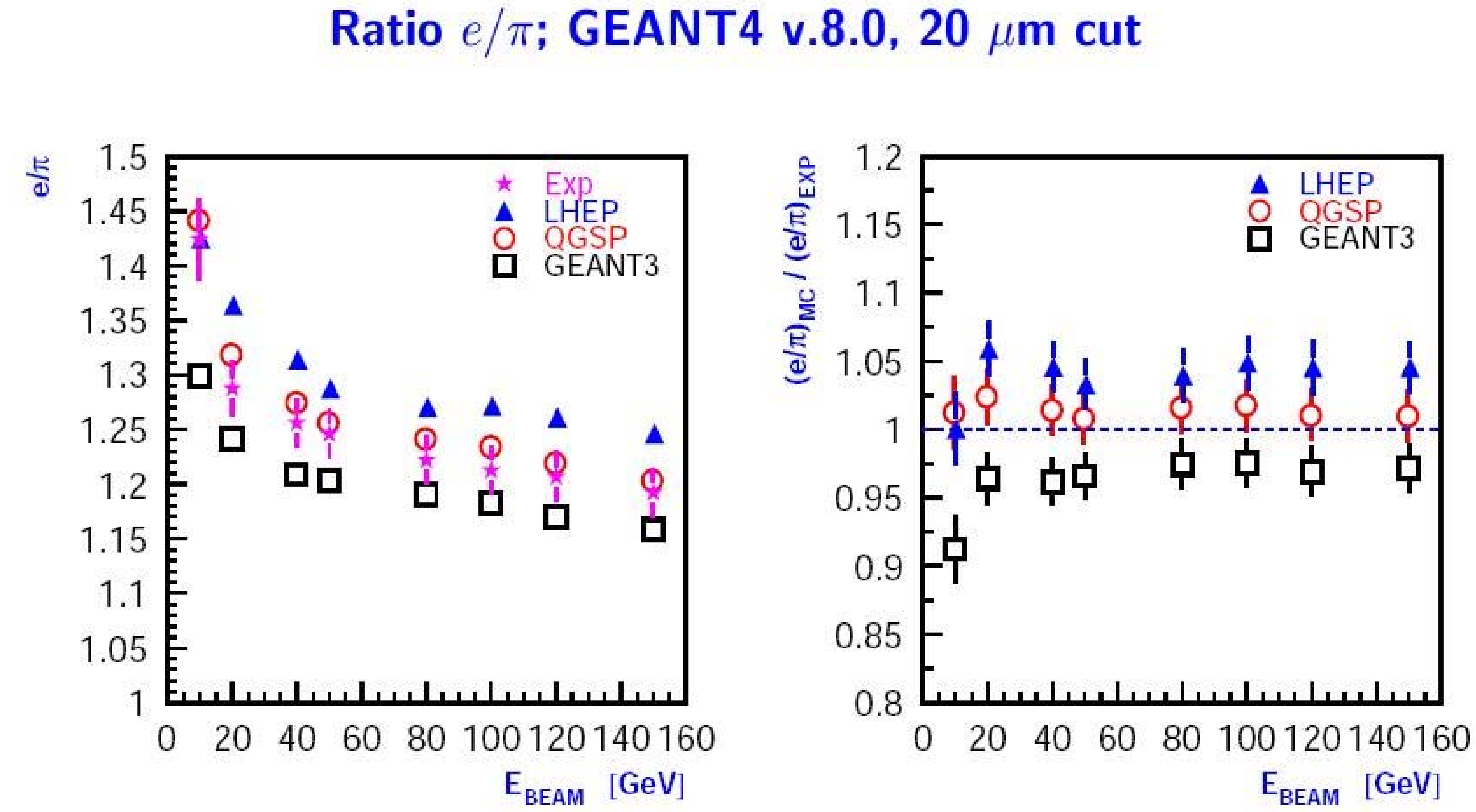
Hadronic Showers and Particle Flow

- Shower shapes:
  - hadronic interactions play a significant role:
    - diffraction, pomeron trajectory parameters
    - ~100 MeV protons, π^0 fraction, neutrons below 10 MeV
- Energy/momentum conservation
  - the fastest Geant4 codes treat this on average, but not event-by-event
  - detailed codes which obey conservation are used for most, but not all particles
- Baryon conservation
  - a problem for fast models and some low energy ones

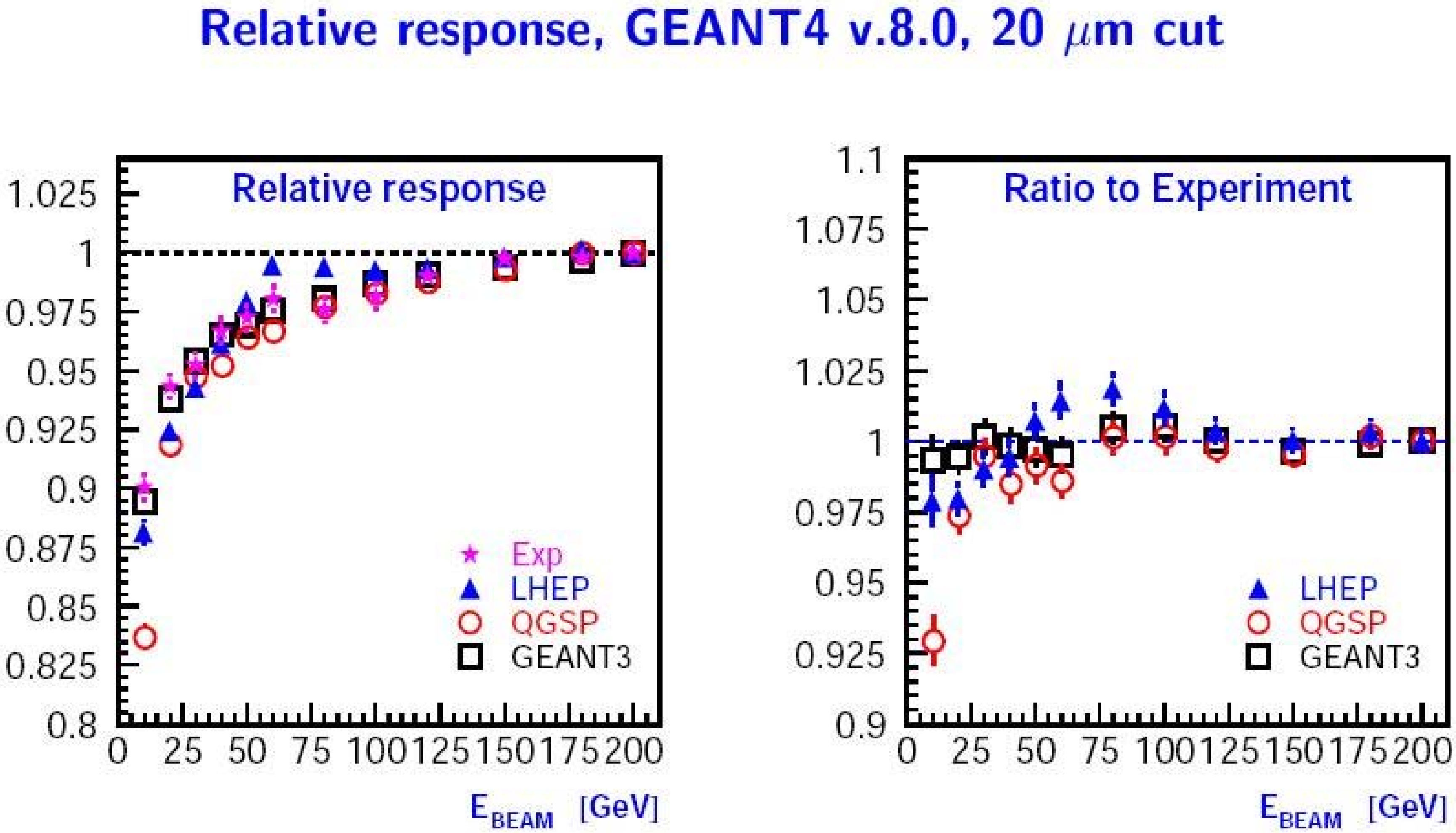
Shower Shape Comparisons

- Data from ATLAS and CMS test beams
  - almost all data is longitudinal profile information
- Transverse profile information would be very useful
- Data compared to two physics lists
  - LHEP
    - collection of low and high energy parameterized models (descendants of GHEISHA)
  - QGSP
    - mostly theory-based models which obey conservation

Atlas (HEC)

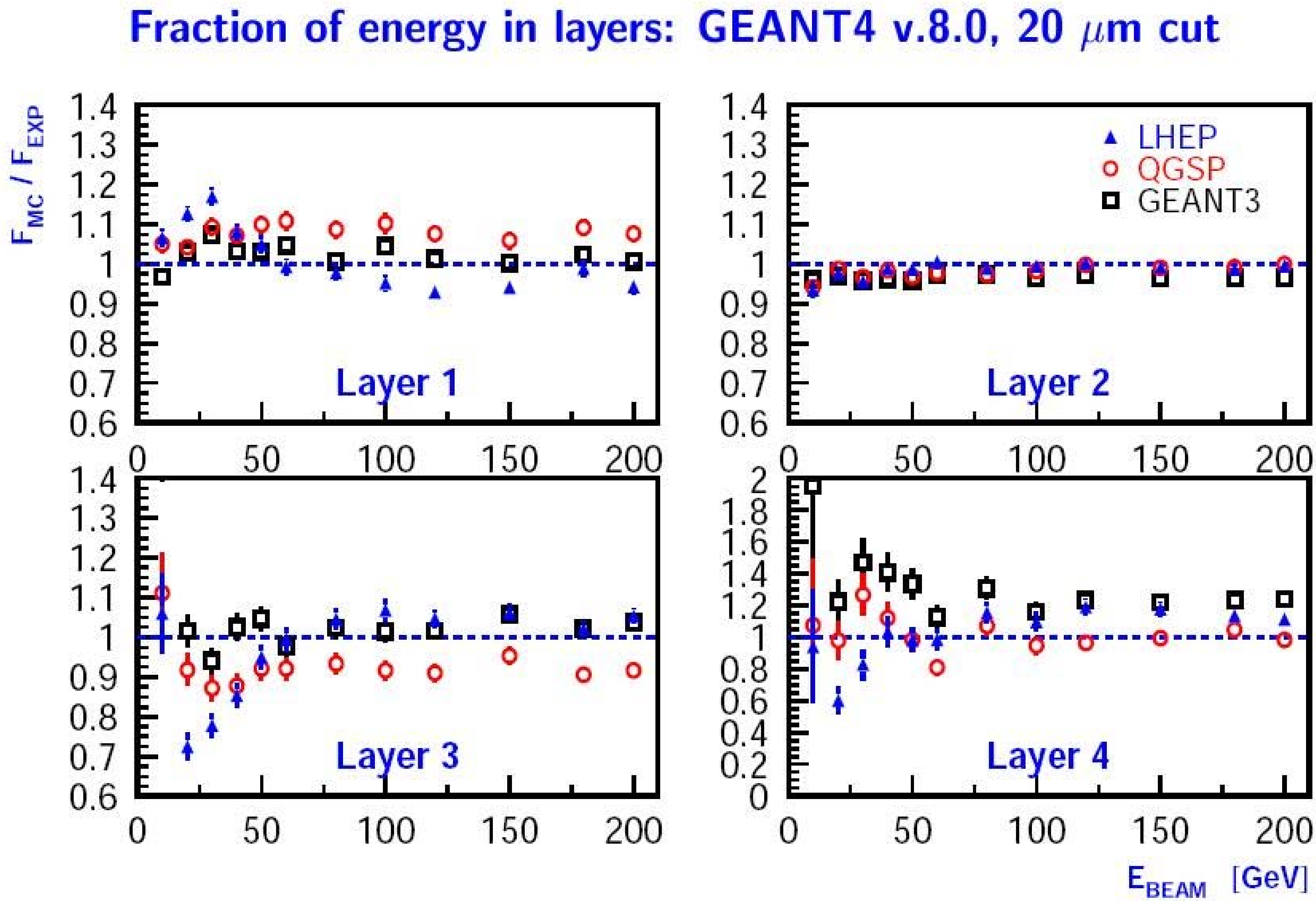

Ratio e/π; GEANT4 v.8.0, 20 μm cut
e/π
Exp
LHEP
QGSP
GEANT3
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0 20 40 60 80 100 120 140 160
E_BEAM [GeV]
(e/π)_MC / (e/π)_EXP
LHEP
QGSP
GEANT3
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0 20 40 60 80 100 120 140 160
E_BEAM [GeV]

Atlas (HEC)

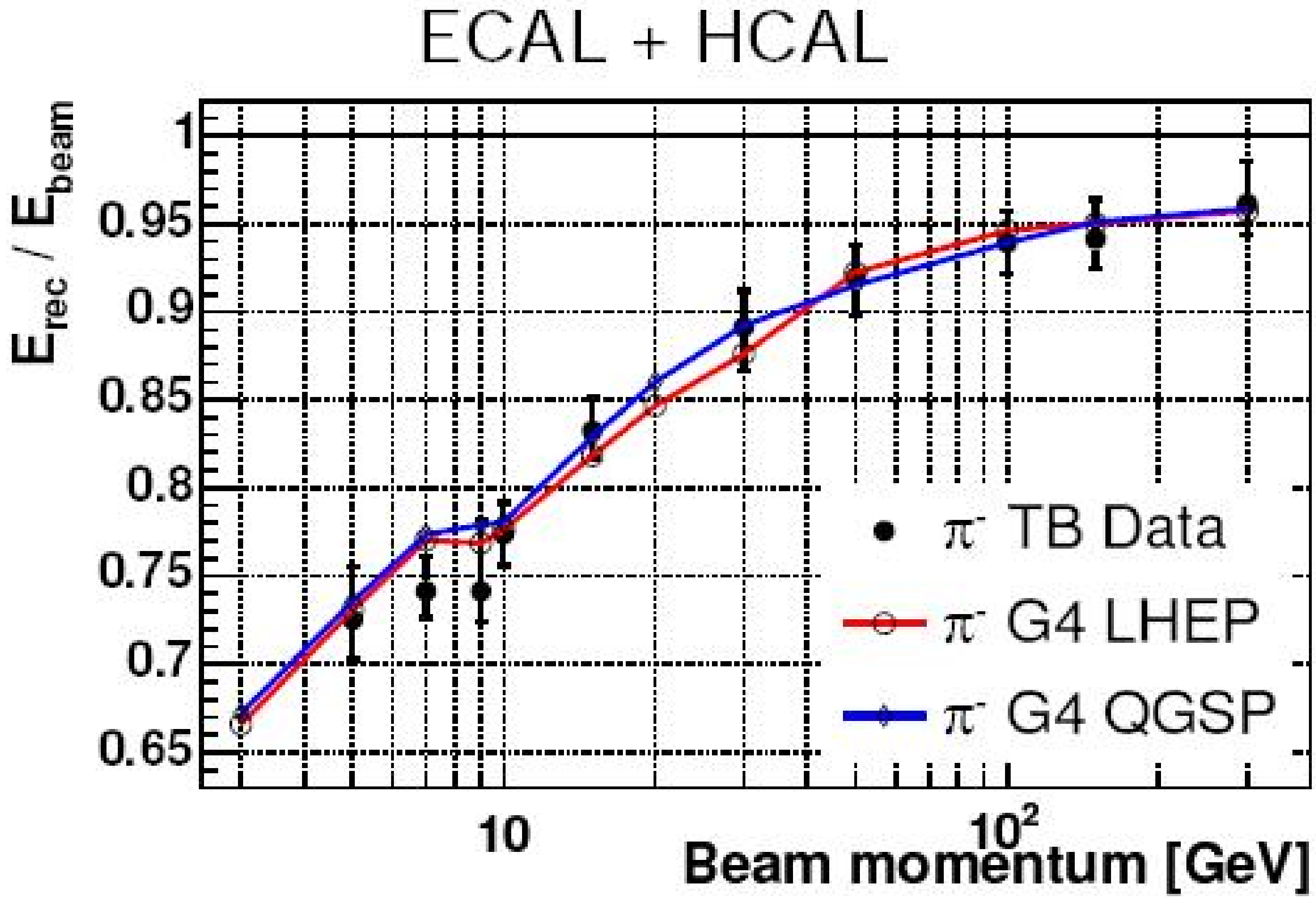


Relative response, GEANT4 v.8.0, 20 μm cut
Relative response
Ratio to Experiment
Exp
LHEP
QGSP
GEANT3
E_BEAM [GeV]

Atlas (HEC)

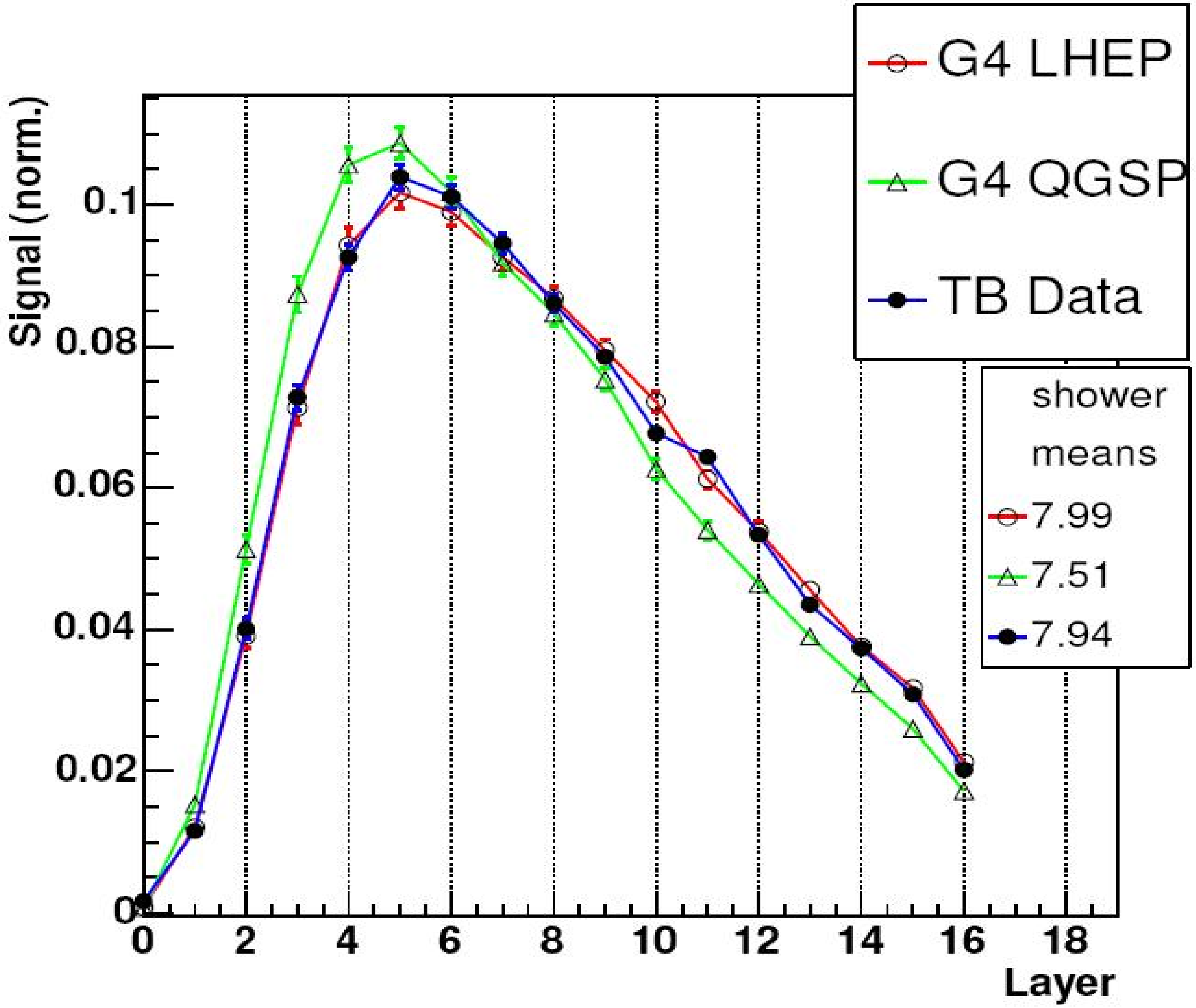

Fraction of energy in layers: GEANT4 v.8.0, 20 μm cut
F_MC / F_EXP
LHEP
QGSP
GEANT3
Layer 1
Layer 2
Layer 3
Layer 4
E_BEAM [GeV]
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200

CMS



ECAL + HCAL
E_{rec} / E_{beam}
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
10
10^2
Beam momentum [GeV]
π⁻ TB Data
π⁻ G4 LHEP
π⁻ G4 QGSP

CMS



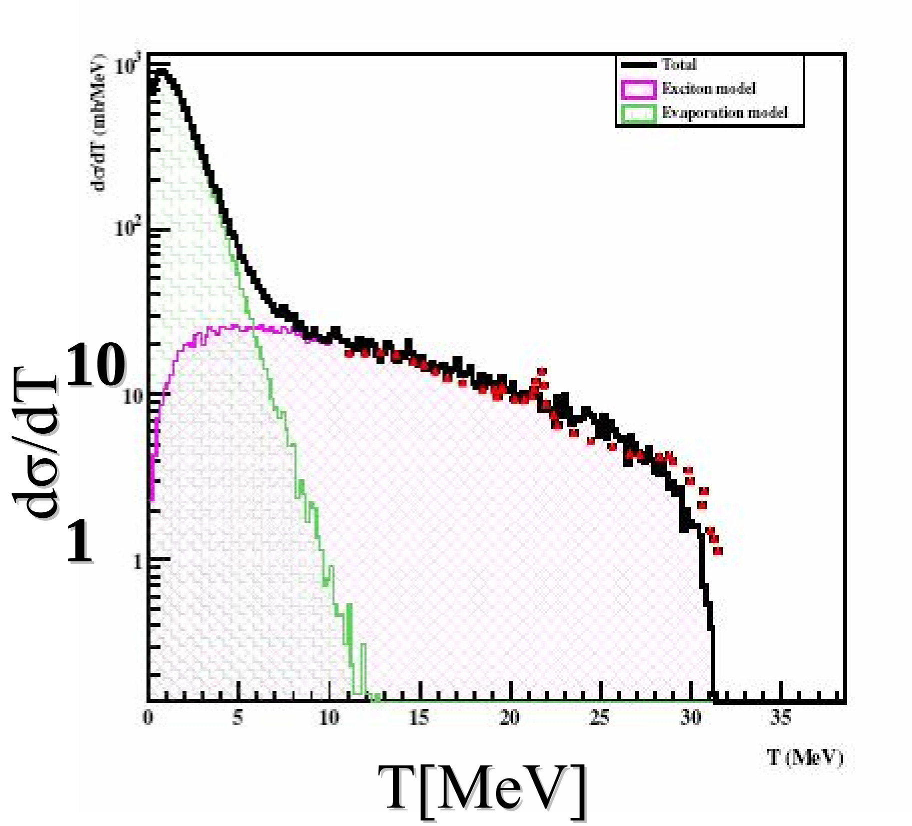
300 GeV pions, leaving MIP in ECAL and L0.

Thin Target Comparisons

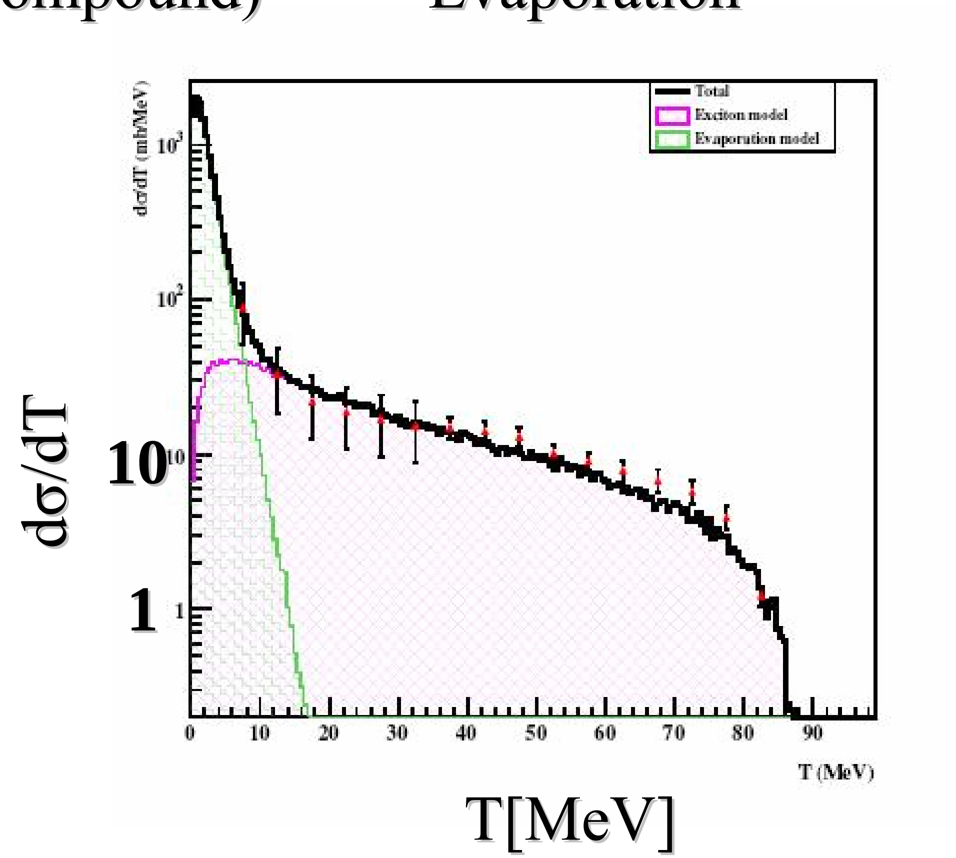
- Tests which compare data to a single hadronic model in isolation
- Mostly tests at intermediate energies (100 MeV to 3 GeV)

Neutron Production Cross Section

Secondary neutrons are created in
Exciton (Pre-compound) Evaporation

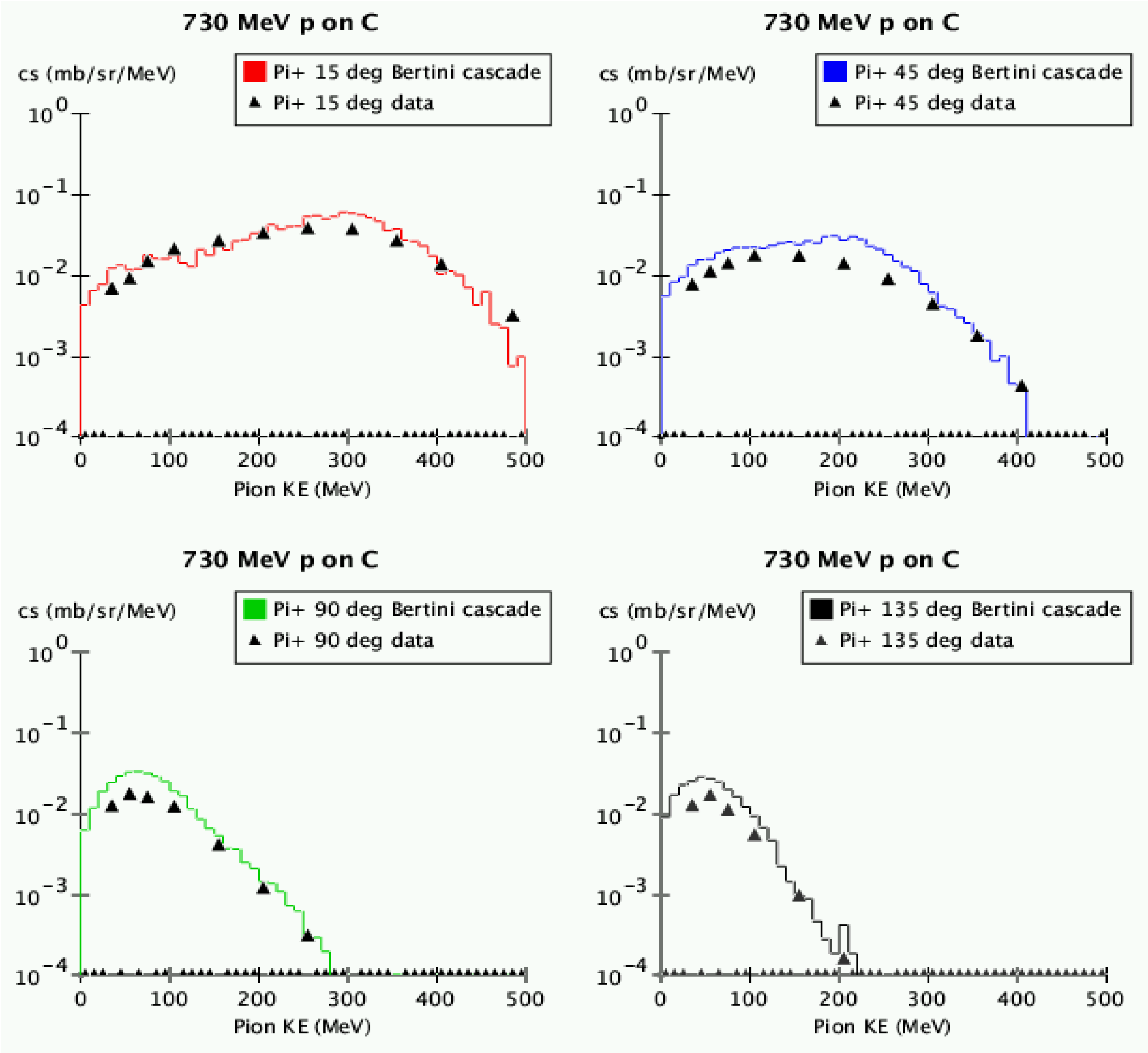


Sn (p, X n) 35MeV



Bi (p, X n) 90MeV

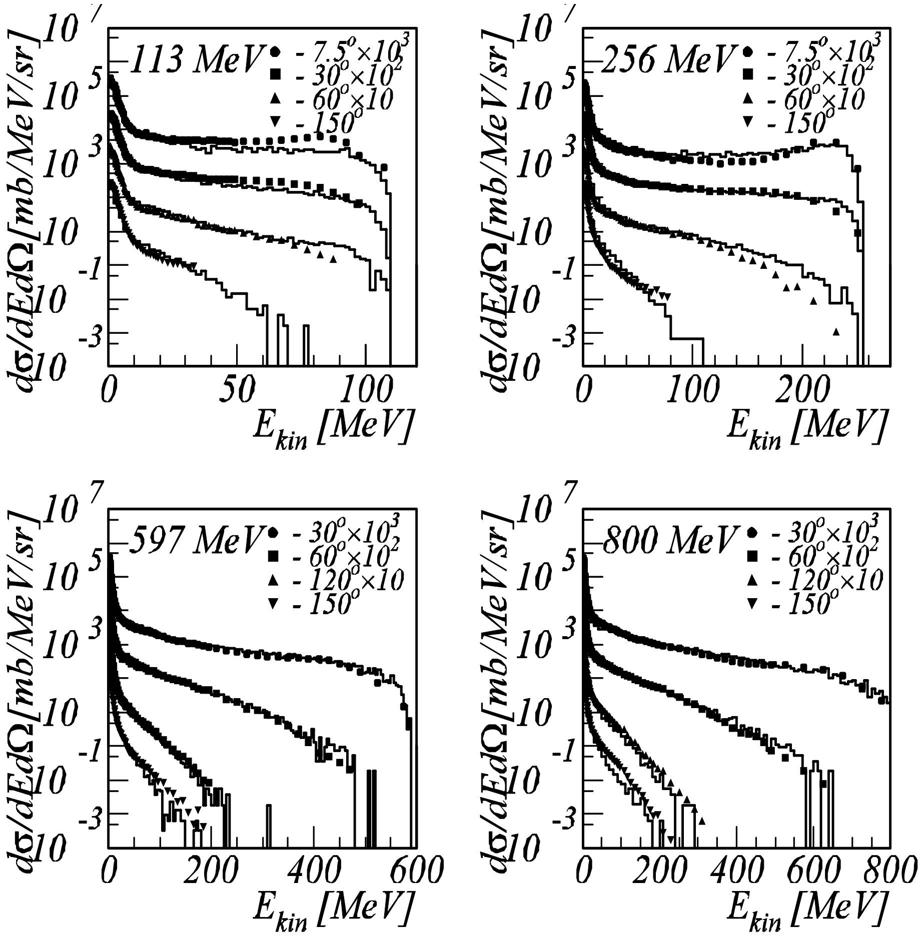
π^+ production from 730 MeV protons



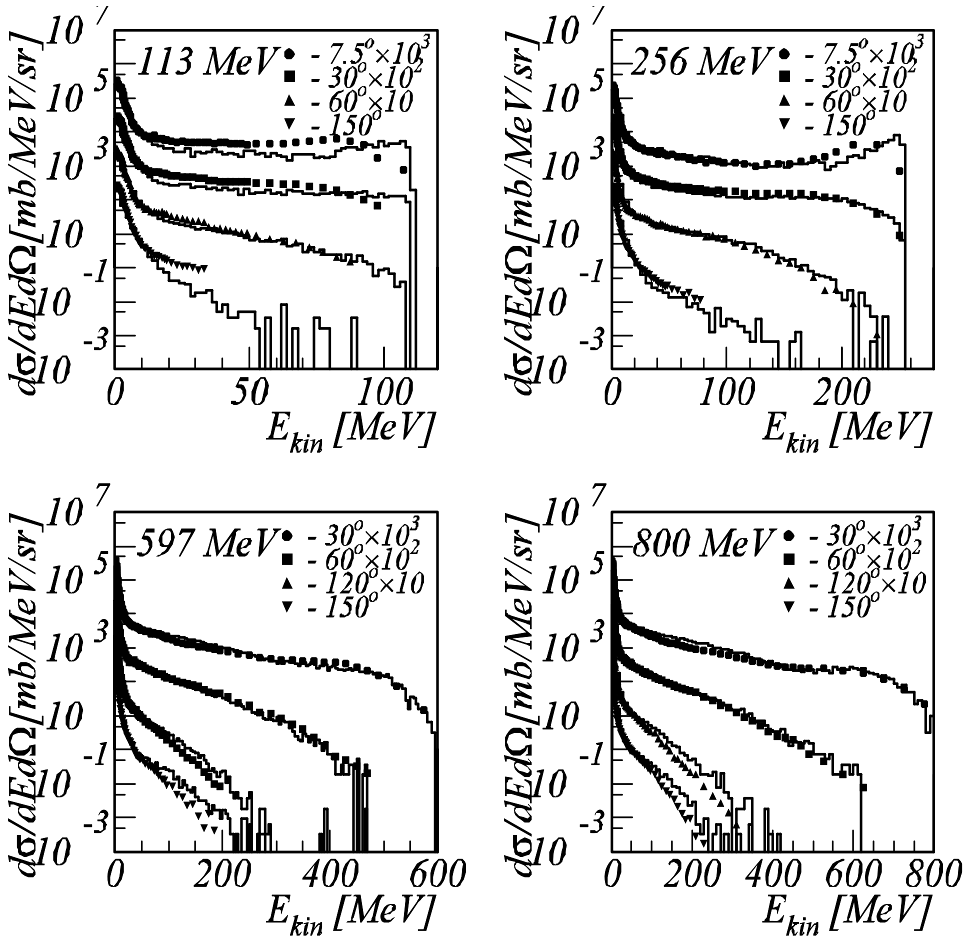
Bertini Cascade

Neutron spectra by protons in Lead (113 – 800 MeV)

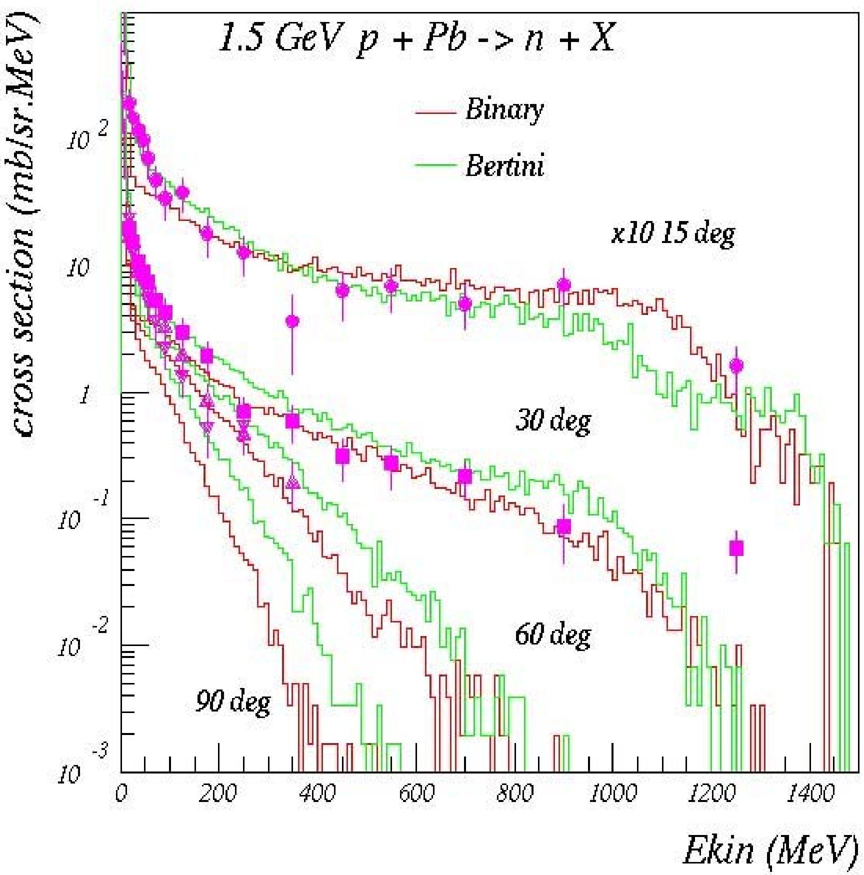
Binary Cascade

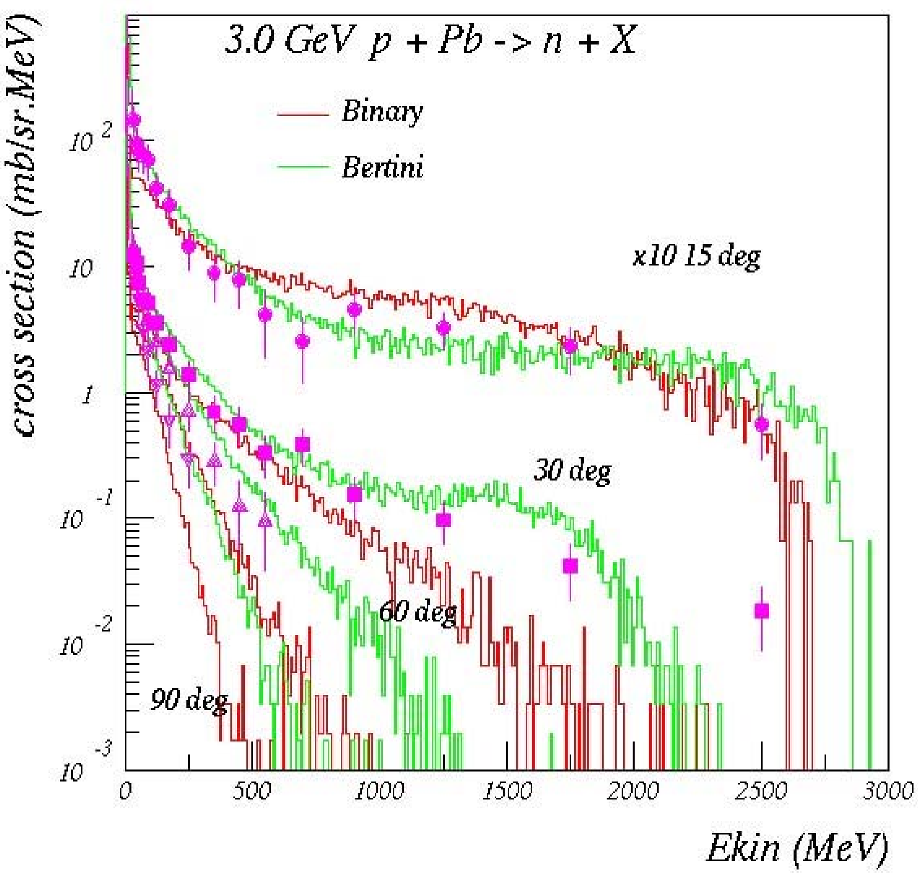


Bertini Cascade



Neutron spectra by 1.5 and 3 GeV protons



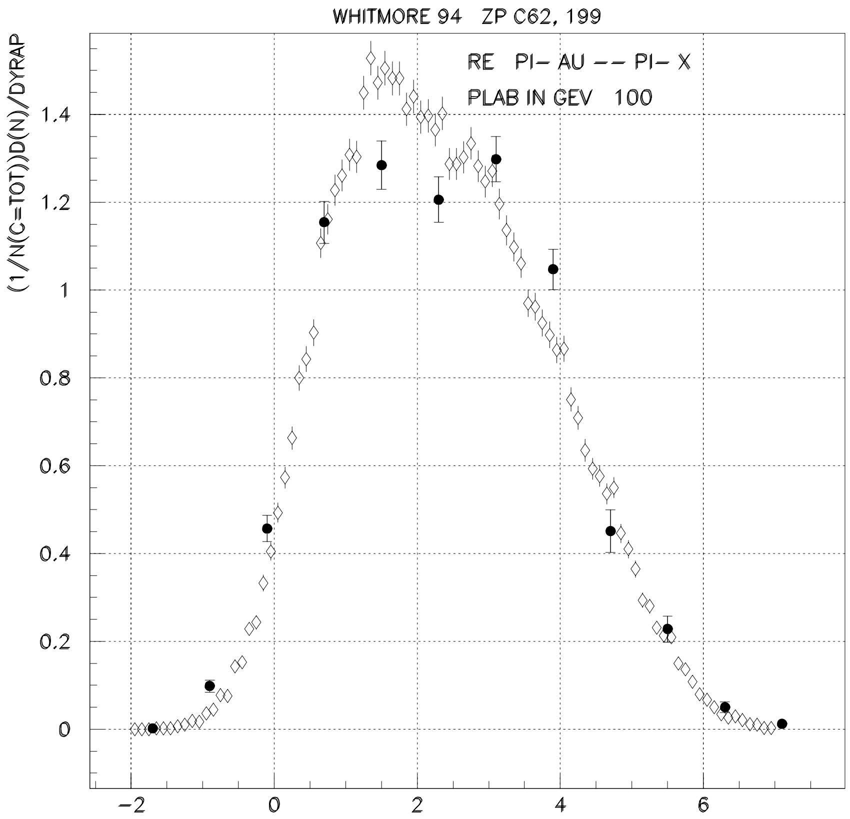


K. Ishibashi et al., J,NST,34,(6),529,199706

QGS Model

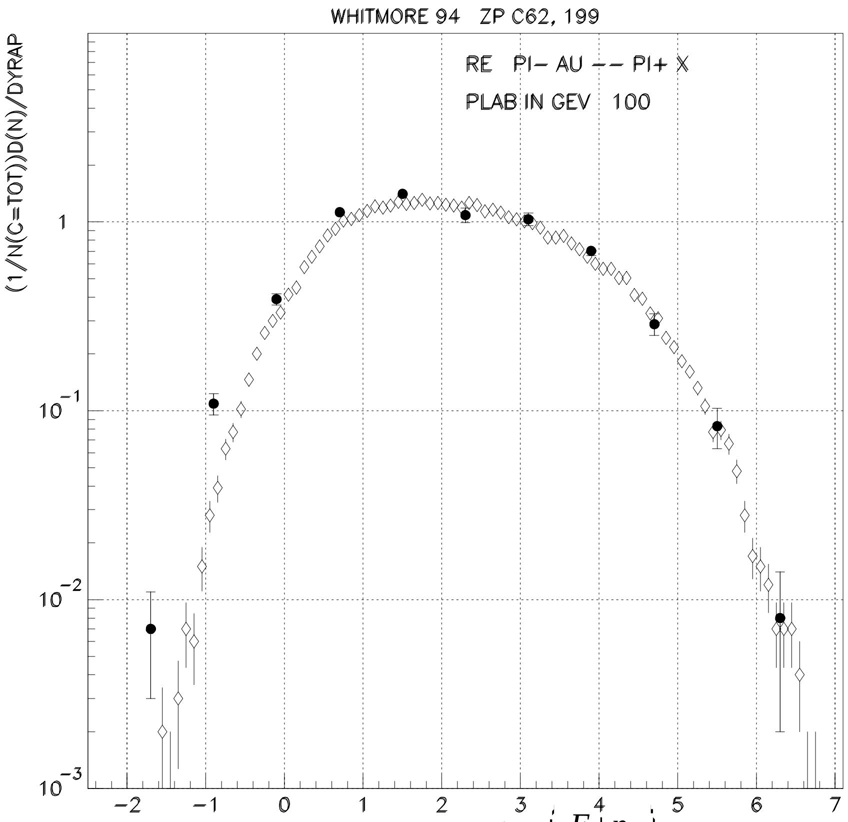
Pi- Scattering on Au, Plab 100 GeV/c

PI- AU -> PI- X



Rapidity $\eta - \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

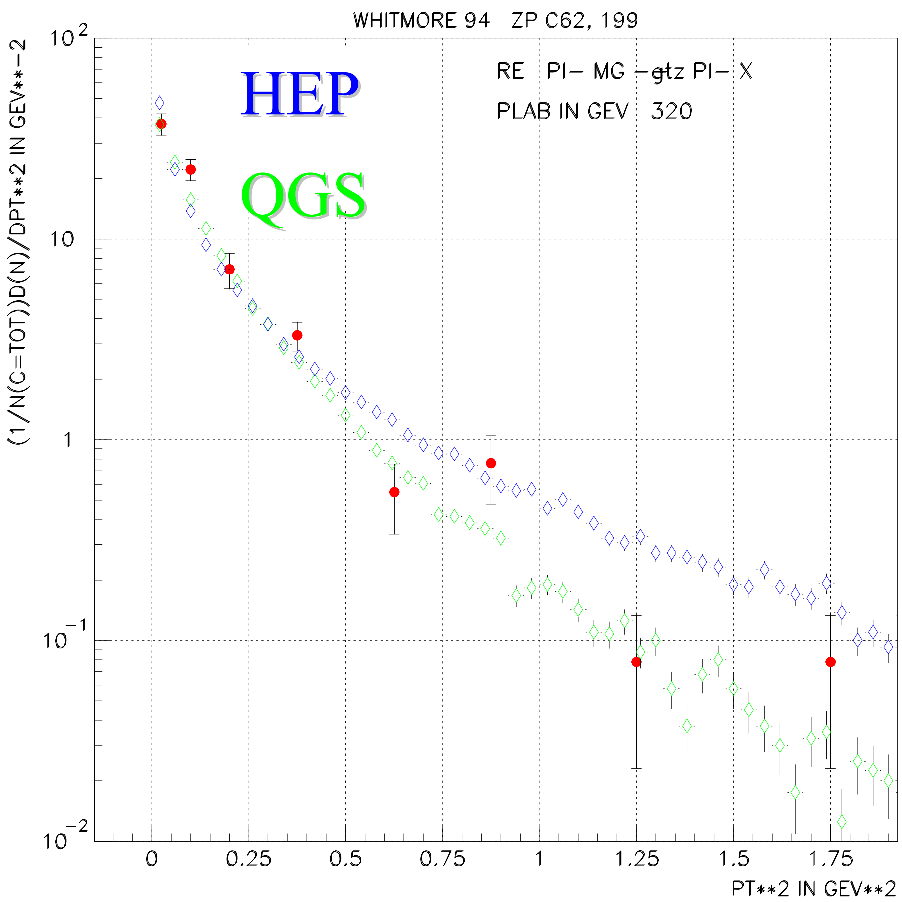
PI- AU -- PI+ X



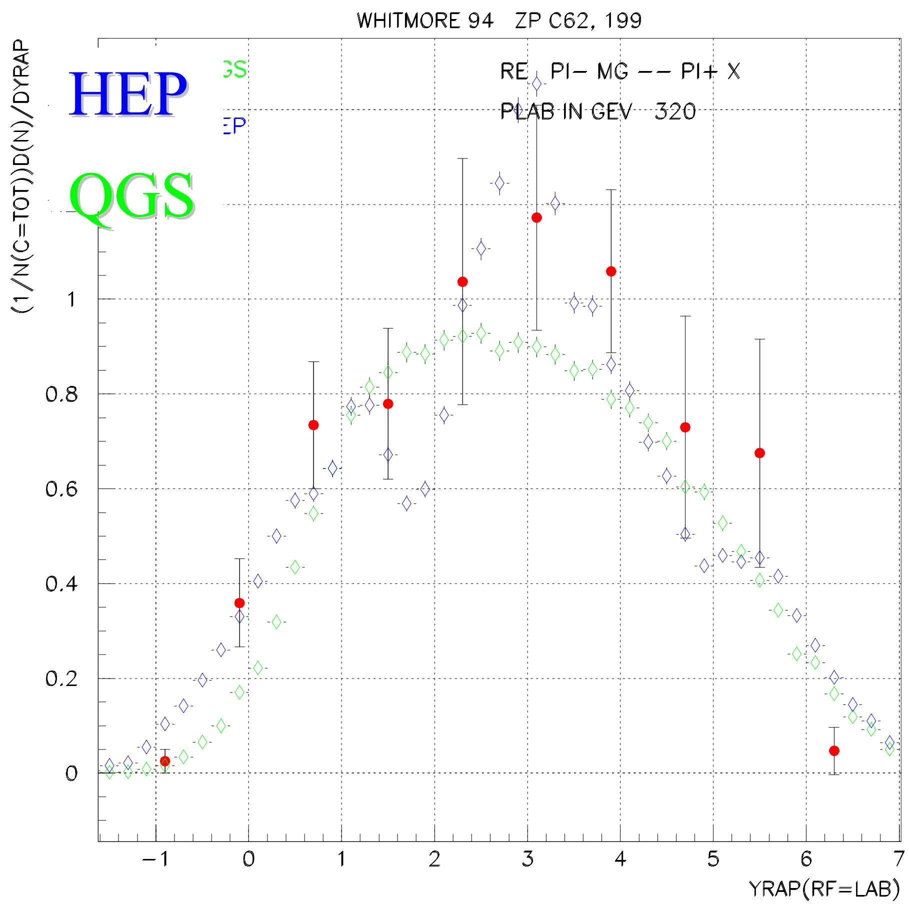
Rapidity $\eta - \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

J.J.Whitmore et.al., Z.Phys.C62(1994)199

$\pi^- + Mg \rightarrow \pi^- + X$, $p_{lab} = 320$ GeV/c



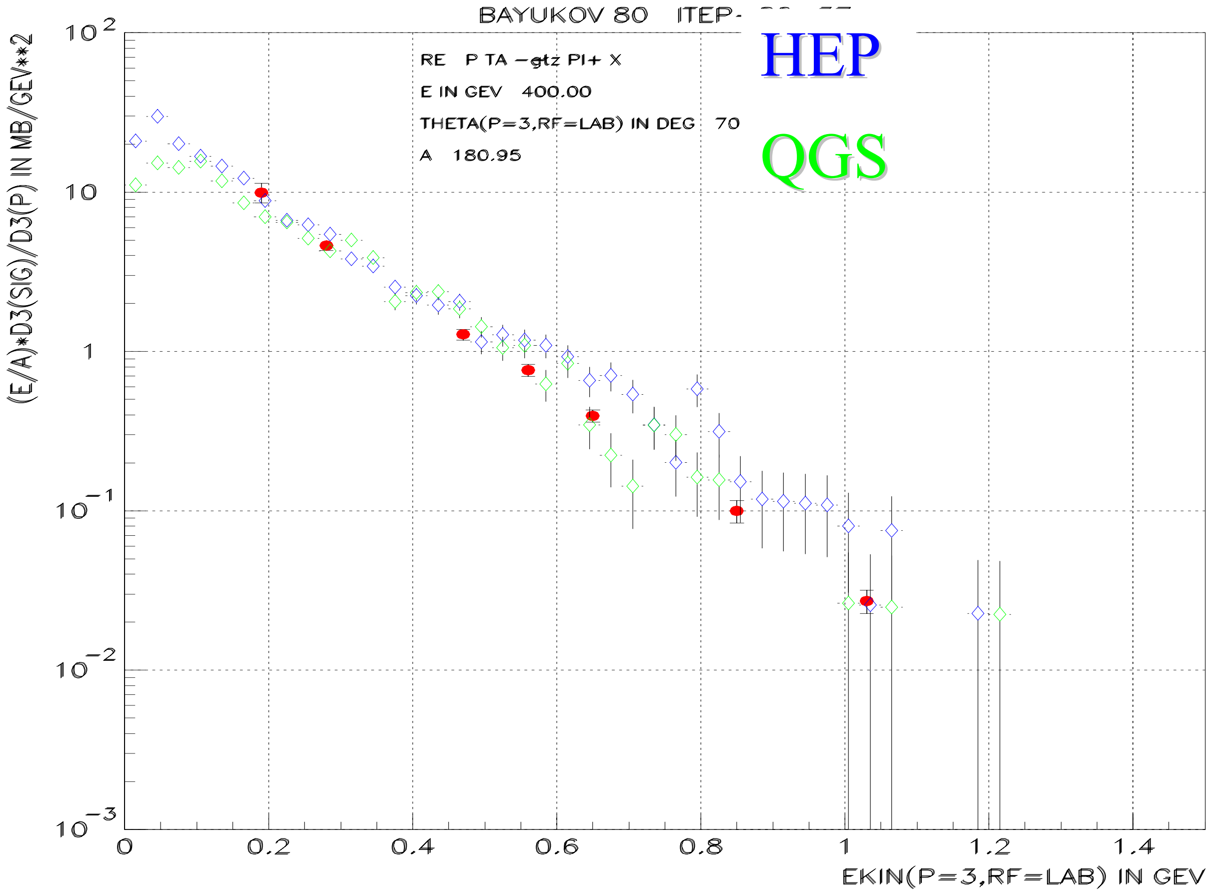
P_t^2 [GeV^2]



Rapidity $\eta = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

Z.Phys.C62(1994)199

p + Ta -> $\pi^+(70^0)$, T = 400GeV

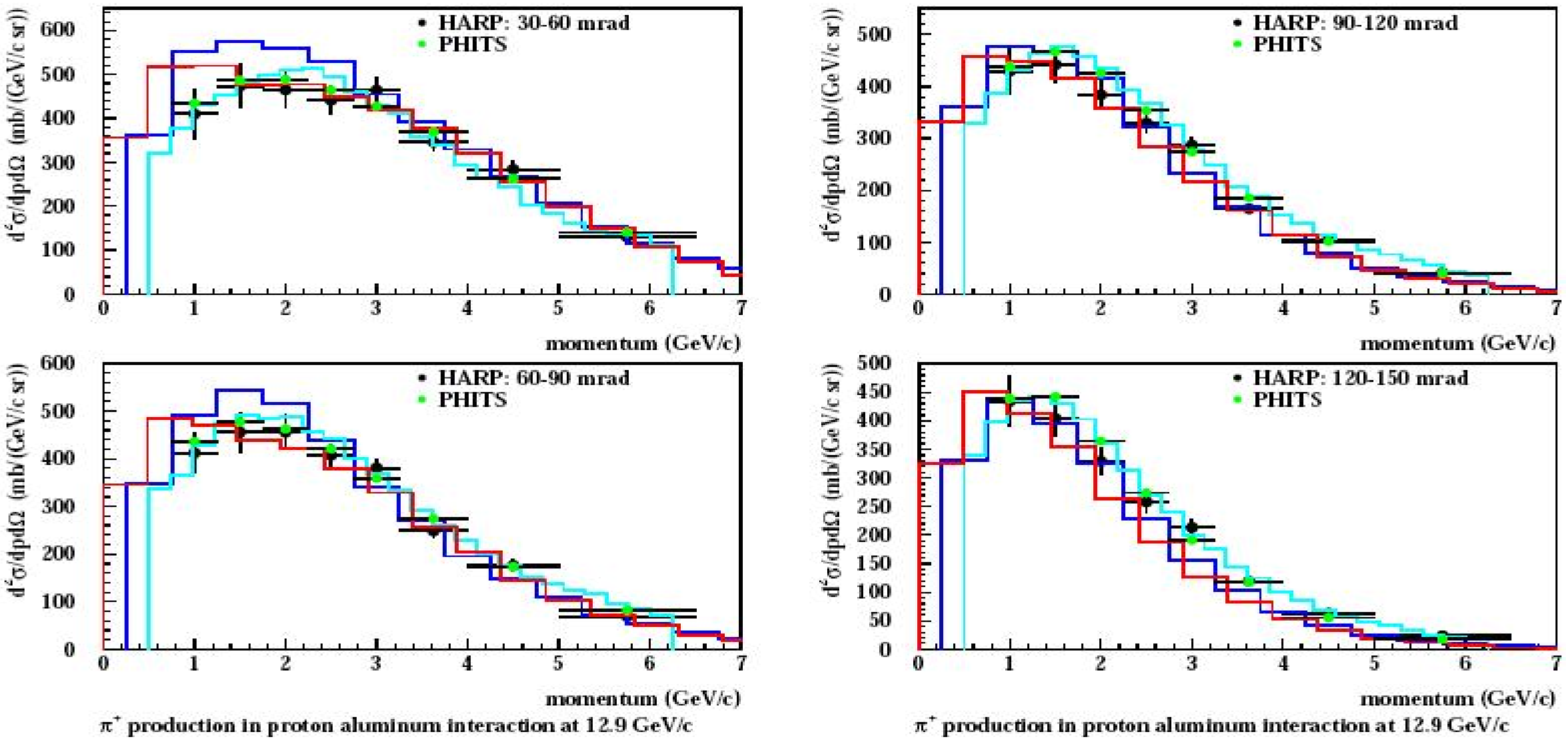


Inter-comparison with Other Codes

- 7 validation tests proposed for Hadronic Shower Simulation Workshop at Fermilab, September 06
  - covered wide energy range
  - head-to-head comparison of (5-6) simulation codes for each test
  - data sets agreed upon beforehand
  - voluntary participation
- Due to short time scale, not all tasks could be completed
- Agreed to make this a regular exercise

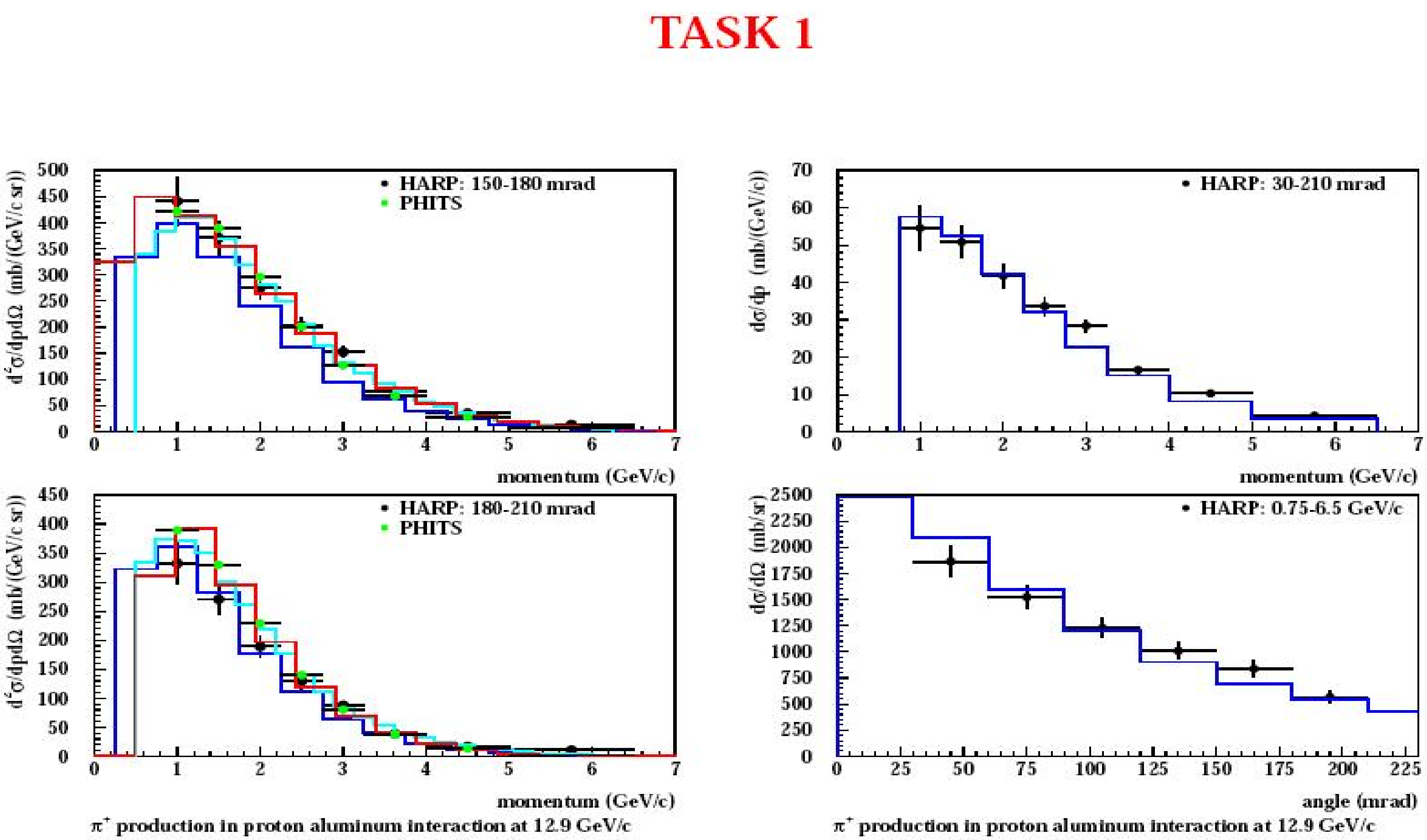
Task 1: 12.9 GeV/c p on Al

TASK 1



Black symbols - HARP data, green symbols - PHITS, red line - LAQGSM, cyan line - FLUKA, blue line - MARS

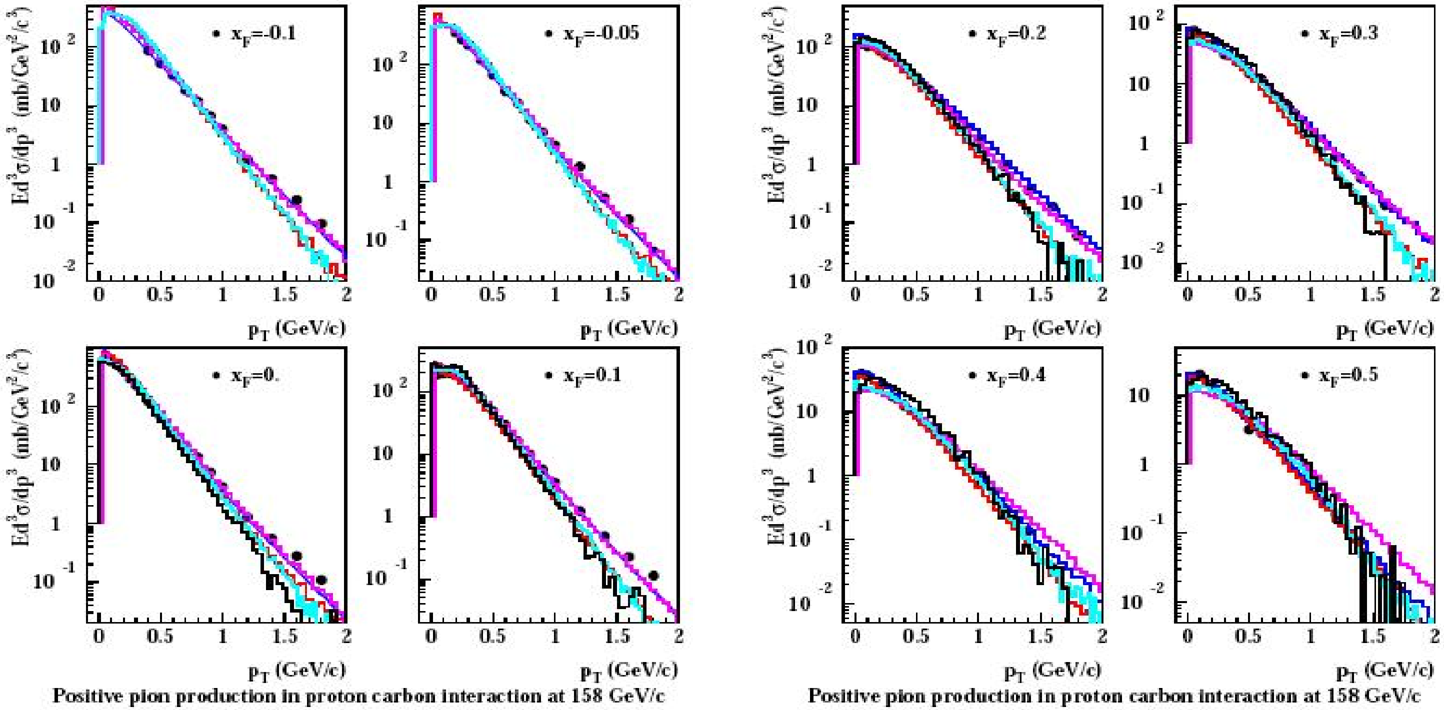
Task 1: 12.9 GeV/c p on Al



Black symbols - HARP data, green symbols - PHITS, red line - LAQGSM, cyan line - FLUKA, blue line - MARS

Task2a: π^+ from 158 GeV/c p on C

TASK 2A



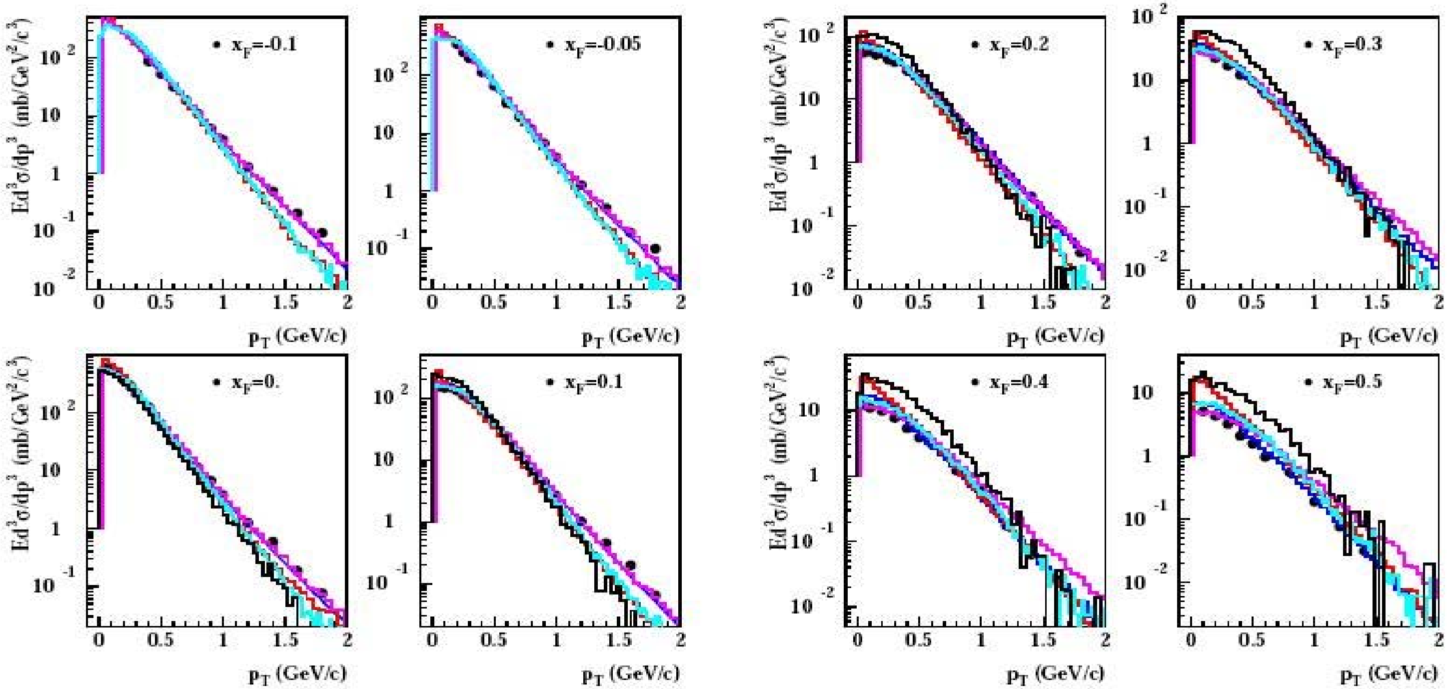
Positive pion production in proton carbon interaction at 158 GeV/c

Positive pion production in proton carbon interaction at 158 GeV/c

Black symbols - NA49 data, red line - LQGSM, blue line - MARS, black line - G4, magenta line -DPMJET

Task2a: π^- from 158 GeV/c p on C

TASK 2A

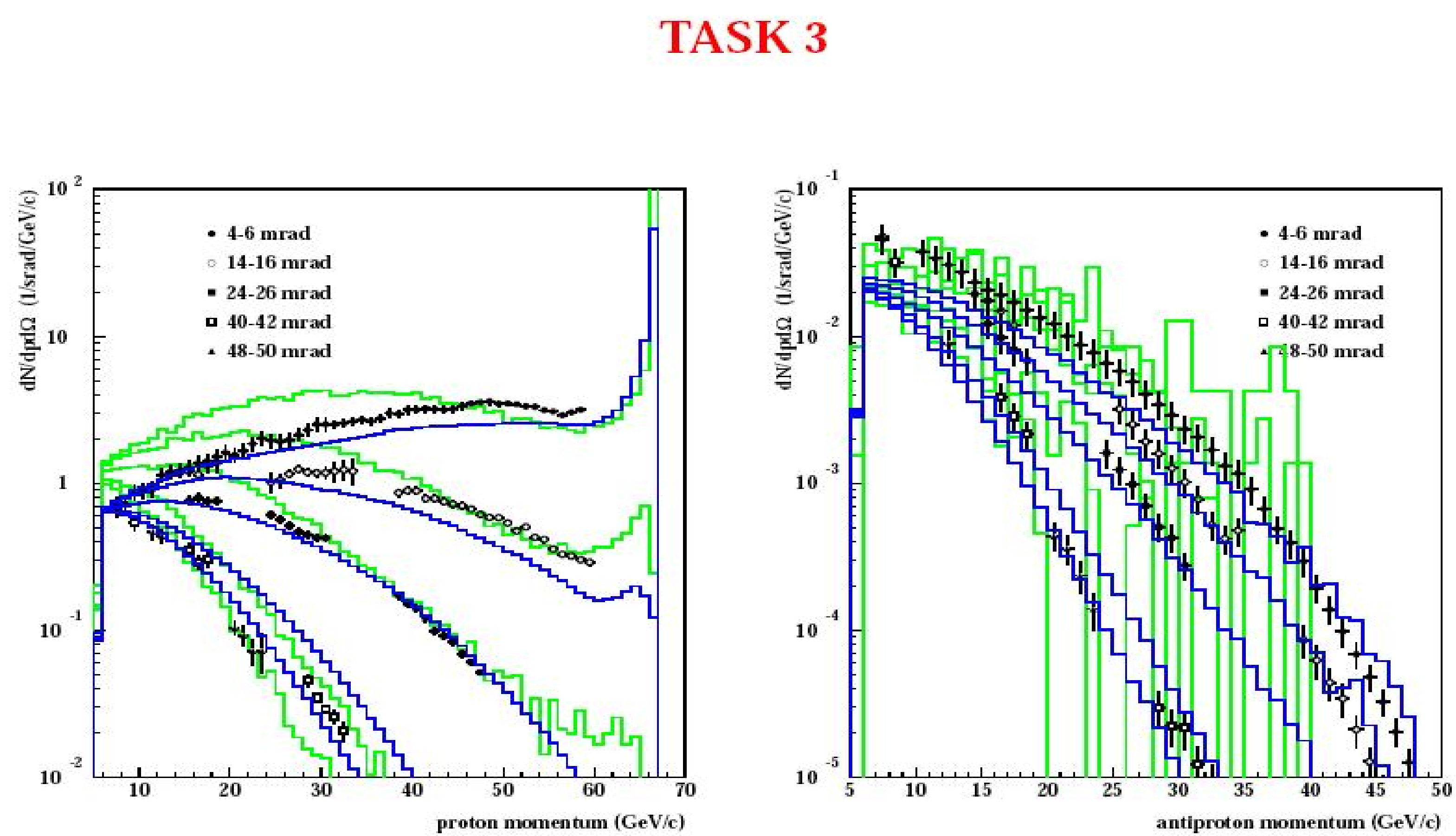


Negative pion production in proton carbon interaction at 158 GeV/c

Negative pion production in proton carbon interaction at 158 GeV/c

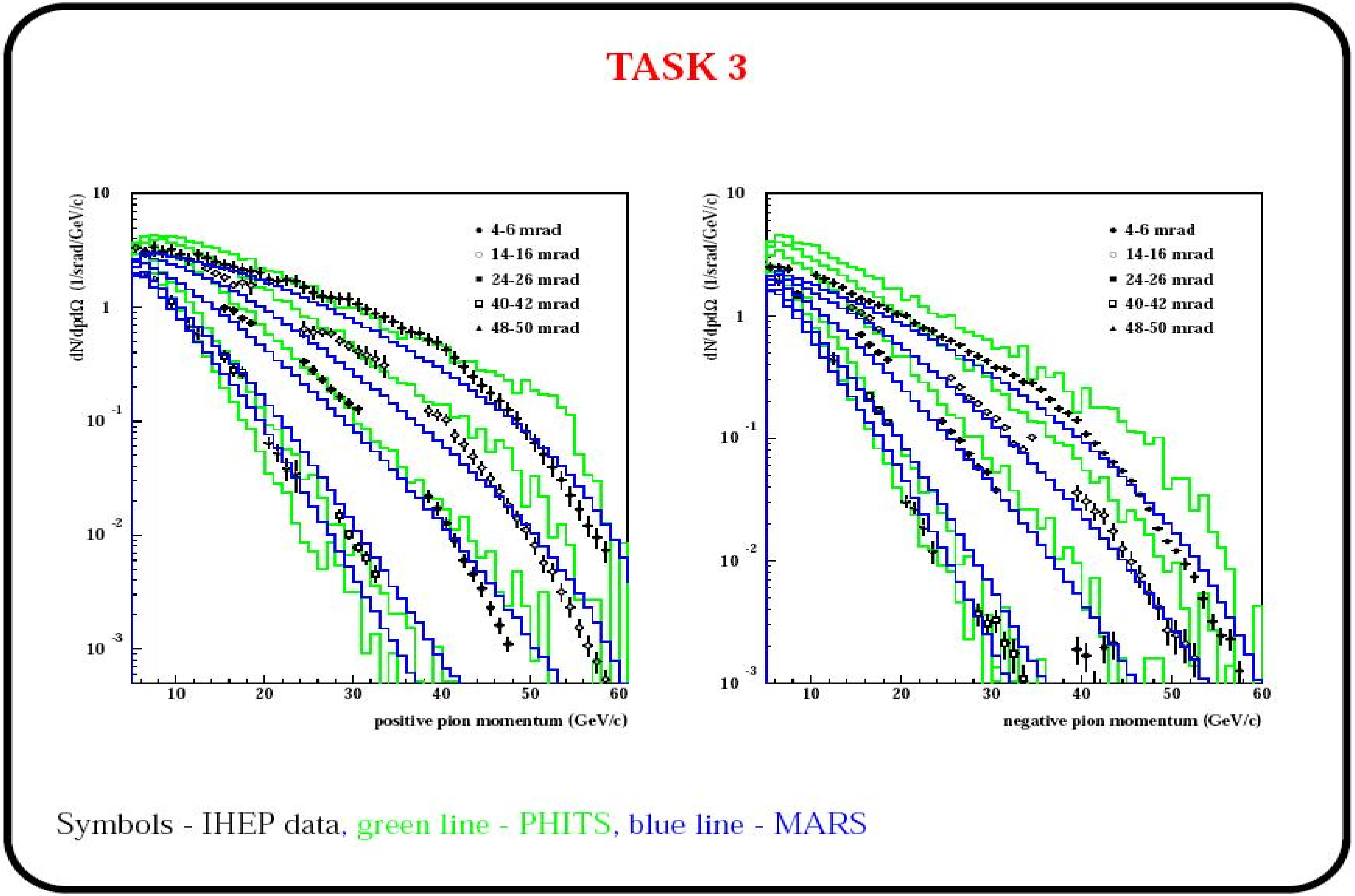
Black symbols - NA49 data, red line - LAQGSM, blue line - MARS, black line - G4, magenta line -DPMJET

Task 3: p, p-bar from 67 GeV/c p on Al



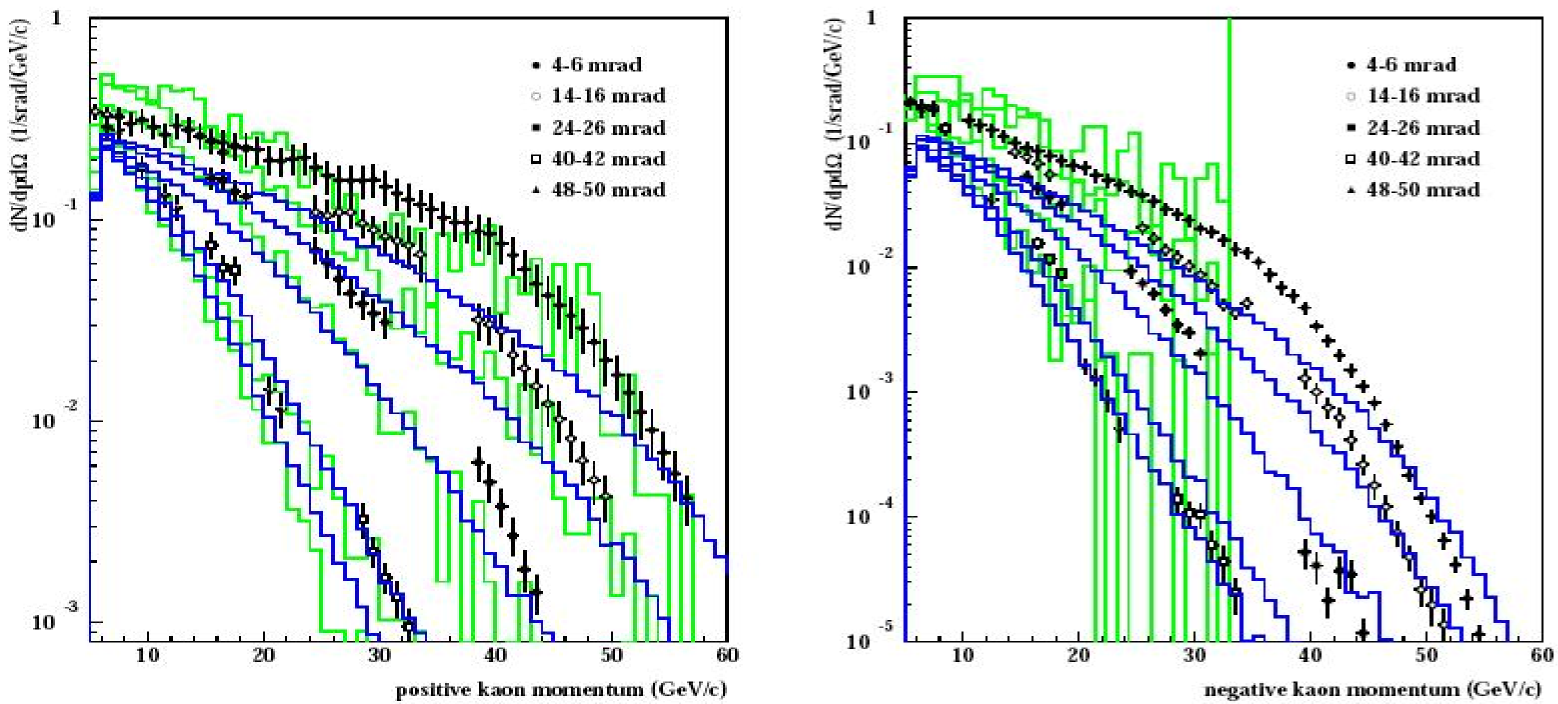
Symbols - IHEP data, green line - PHITS, blue line - MARS

Task 3: π^+, π^- from 67 GeV/c p on Al



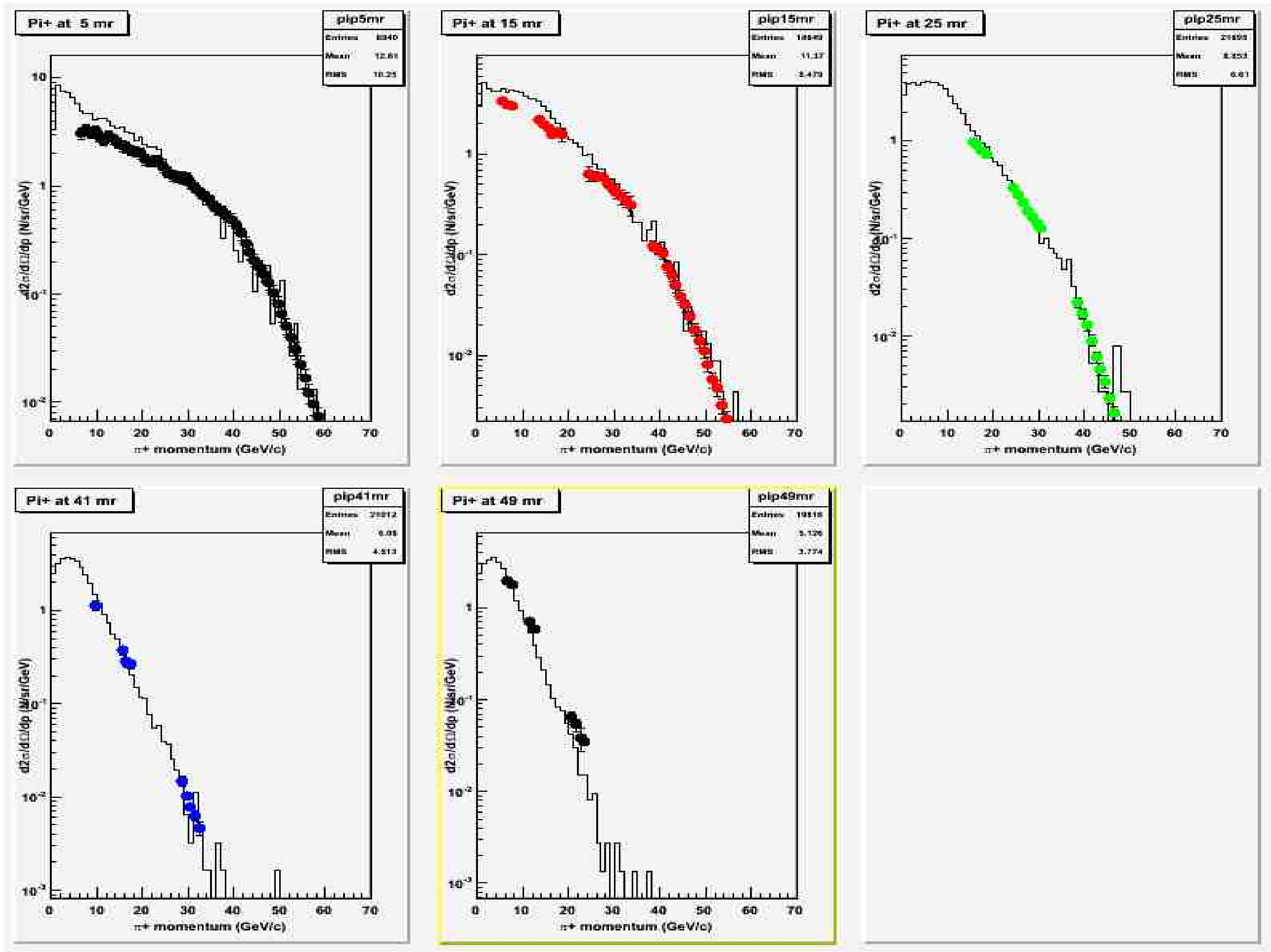
Task 3: K^+, K^- from 67 GeV/c p on Al

TASK 3

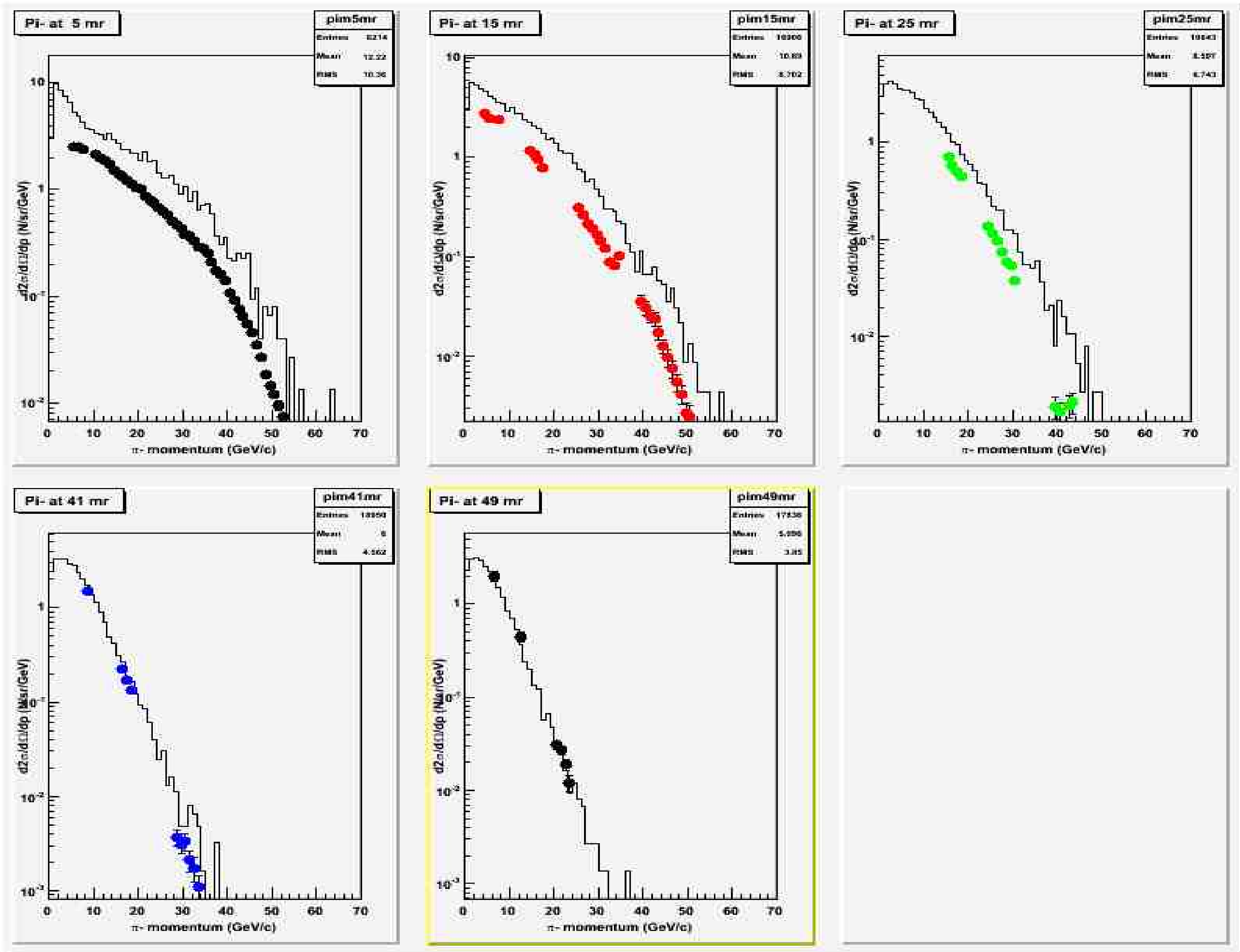


Symbols - IHEP data, green line - PHITS, blue line - MARS

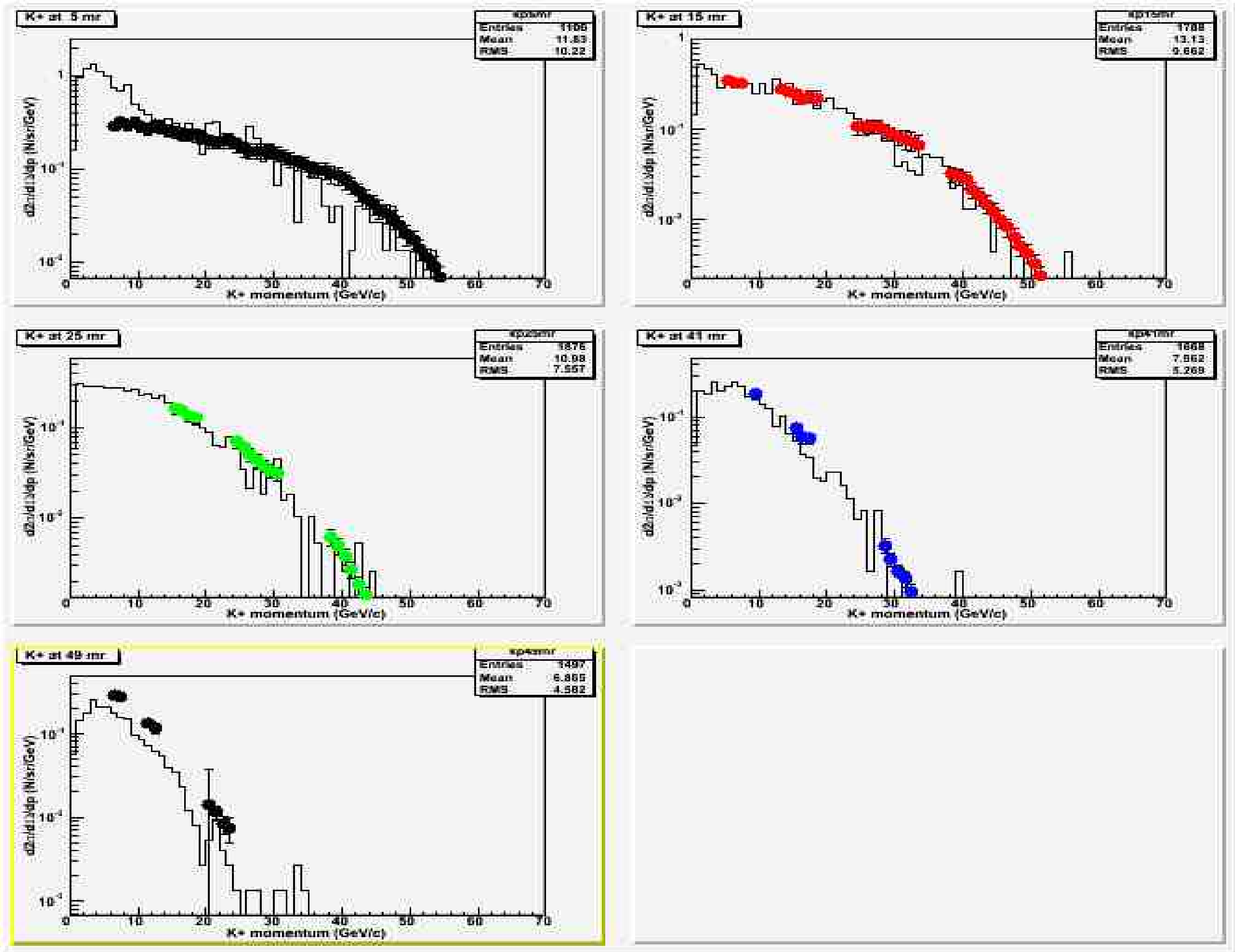
p + Al -> π^+ X at 67 GeV/c



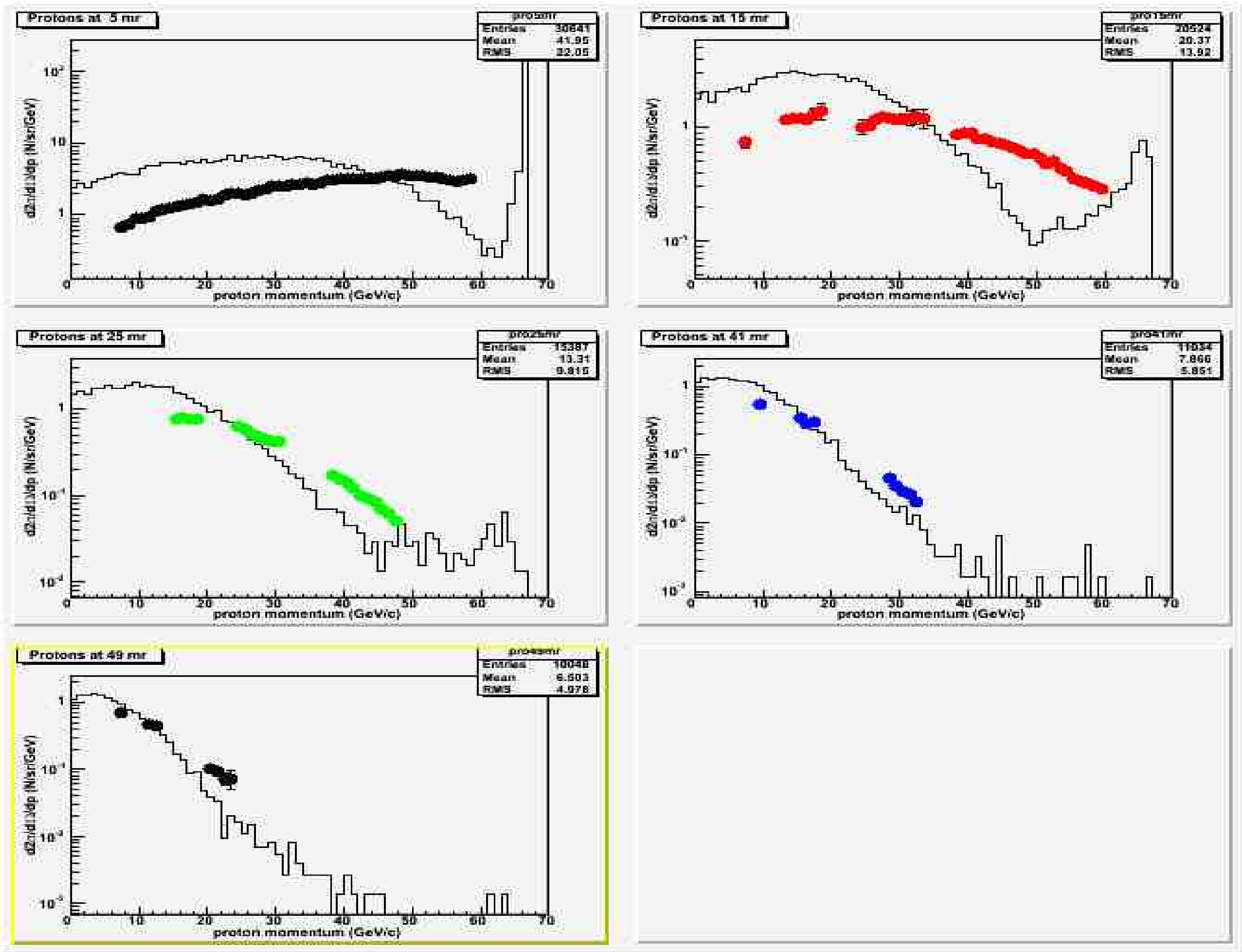
p + Al -> π^- X at 67 GeV/c



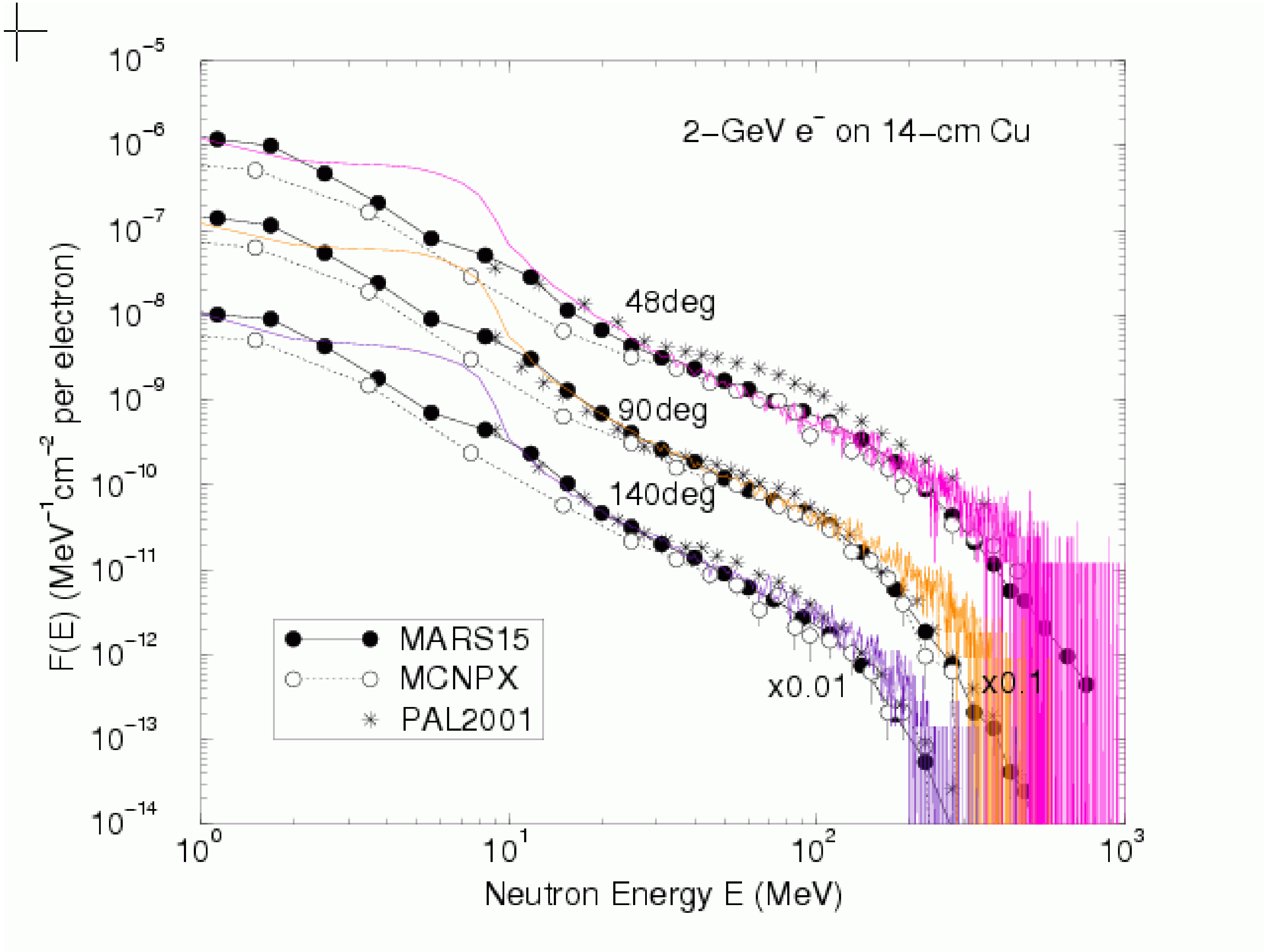
p + Al -> K^+ X at 67 GeV/c



p + Al -> p X at 67 GeV/c



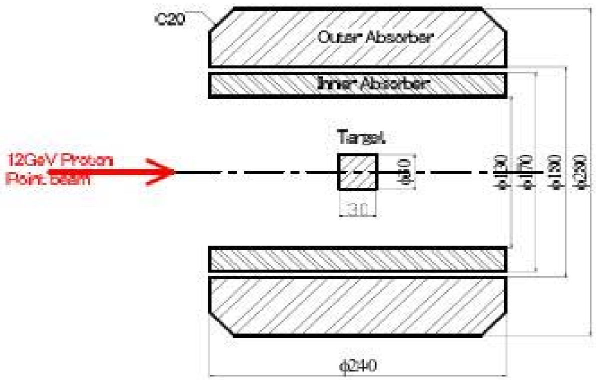
Task4: PAL with Geant4 prediction



Task 5: Total Energy in a Cu Absorber

TASK 5

計算条件メモ



単位：(mm)

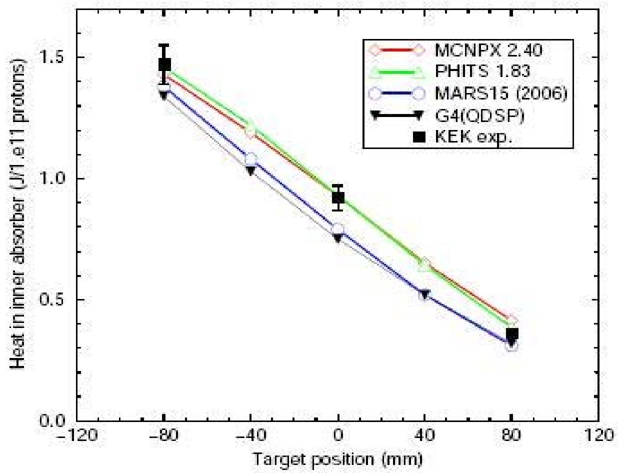
outer absorberはC20だけ面取りしてある。

材料：Target、inner absorber、outer absorberは銅製。

63Cu -6.19 S69.1 % density of 63Cu in natural copper

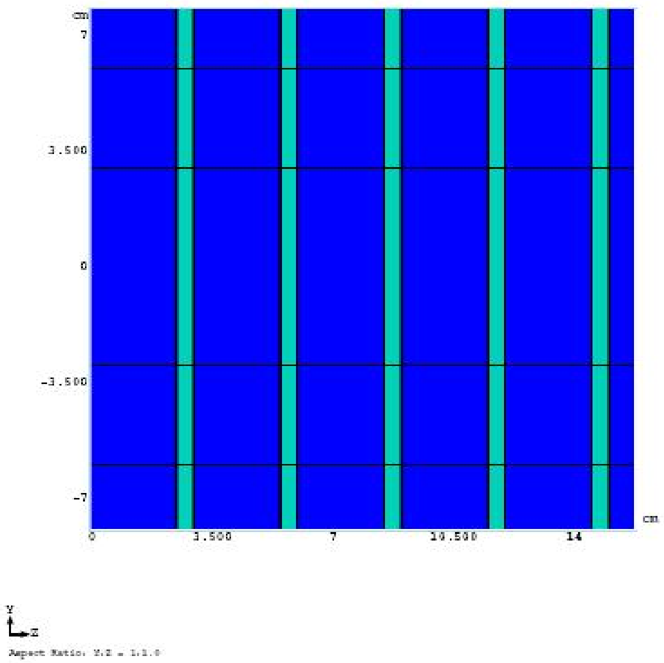
65Cu -2.77 S30.9 % density of 65Cu in natural copper

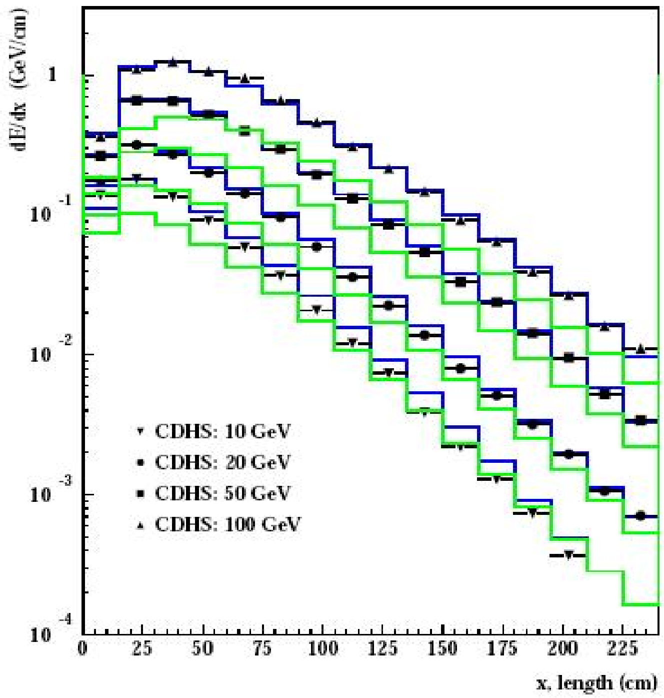
入熱分布を計算する。



Task6: π^- in Fe-Scint Calorimeter

TASK 6

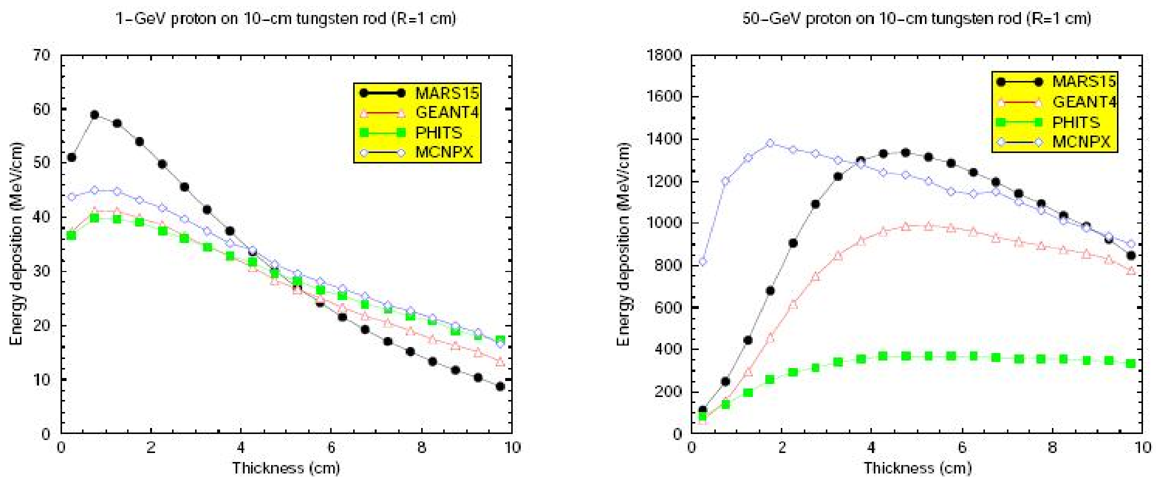




Black symbols - CDHS data, green line - PHITS, blue line - MARS

Task 7: Energy Deposited in W Rod

TASK 7



Notes: (1) No electromagnetic shower transport above 1 GeV in PHITS and MCNPX.

(2) MARS15 results from an unofficial developer version.

Geant4 Hadronics: Strengths

- Low energy: good performance for p, n by precompound model < 170 MeV
- Cascade models (Binary and Bertini) do a good job for p, n, π between 100 MeV and 1 GeV
- LEP models now have improved (but not perfect) baryon and energy conservation
- QGS model does well at highest energies 300-400 GeV
  - also good for rapidity, invariant cross sections, double differential cross sections between 50 – 300 GeV
- Shower shapes are well-reproduced by LHEP models
  - not bad for QGSP either, but some problems remain

Geant4 Hadronics: Weaknesses

- Some discrepancies in shower shape due to quark-gluon string (QGS)
  - also known problems with diffraction (too little) give disagreement with p_T distributions at 158 GeV
- No detailed (theory-based) model to cover energy range 3-20 GeV
  - currently use LEP models
- No detailed model to handle anti-baryons at any energy
  - currently use LEP, HEP models
- Treatment of kaons, hyperons, anti-baryons is not well-tested
  - not much data

Geant4 Hadronics Development/Improvement: QGS model

- Shower shapes the main focus for this model
- Observed deviations possibly due to:
  - simplistic p_T sampling which leads to incorrect diffraction
  - departures from original Dubna QGS model
  - parameterized pomeron cross sections
  - sea quarks not properly taken into account
- Recently improved cross sections have helped a little
- Review of the code is underway to bring it closer to Dubna model

Geant4 Hadronics Development/Improvement: Energy/momentum/baryon conservation

- Recent improvements made in LEP models which enforce baryon number conservation
- Energy conservation also improved, but to do better, energy/momentum conservation has to be enforced at a basic level
  - this will disturb the old GHEISHA parameterization
  - new parameterization (fits to data) will be required
- HEP models also have energy/baryon number conservation issues
  - fix the worst ones now
  - re-parameterize in the future

Geant4 Hadronics Development/Improvement: Models for the energy range 3 - 20 GeV

- This is a difficult region:
  - too high for most cascade models
  - too low for quark string/fragmentation models
- One option: extend Bertini cascade
  - this model depends mostly on partial cross sections and parameterized angular distributions, so it is easy to extend as long as there is enough thin target data
  - Binary cascade could also be extended, but it is limited by the number of nucleon resonances that must be included
- Another option: create a medium energy parameterized model
  - like LEP, HEP models, but with conservation enforced

Geant4 Hadronics Development/Improvement: Treatment of Low Energy Nucleons

- Effort has so far been concentrated on high and medium energy, but we know low energy protons and neutrons are important
  - Wigmans' slides from HSSW talk:

The crucial elements of hadronic shower simulations (3)

The *non-electromagnetic* shower component

A very large fraction (> 80%) of the calorimeter signal from this component is caused by *protons* and other nuclear fragments. Pions and other mips play, at best, only a minor role.

It is, therefore, crucial to simulate the processes in which these protons are being produced, as accurately as possible.

→ *Nuclear breakup* processes determine many aspects of the hadronic calorimeter performance

The crucial elements of hadronic shower simulations (4)

Where do these protons come from?

1) Nuclear spallation.

Spallation protons typically carry ~ 100 MeV kinetic energy.
Their range is typically of the order of the thickness of sampling layers in hadron calorimeters.

2) Nuclear reactions induced by neutrons, e.g. (*n,p)* reactions

These protons have kinetic energies comparable to those of the (evaporation) neutrons that generated them (< 10 MeV)
These neutrons outnumber spallation protons by an order of magnitude

Measurements of neutron production in hadronic showers:
> 40 per GeV in some materials (NIM A252 (1986) 4)

Geant4 Hadronics Development/Improvement: Continued Validation

- Two kinds of validation required:
  - thin target
    - double differential, or invariant cross section measurements on thin, simple targets used to tune (and sometimes develop) models
    - choosing which of several models is best can only be done in this way
    - more data always required (HARP, MIPP ?)
  - full setup
    - data from complete, or test beam detectors used as integration tests of all physics, but never for tuning
    - currently have access to ATLAS and CMS data

Backup Slides

- -

The non-electromagnetic shower component (1)

How do we know that protons dominate non-em signal?

1) Because of the small hadronic signals (i.e. large e/h values) of calorimeters that are blind to these protons.

In quartz-fiber calorimeters ($n = 1.46$), only particles with $\beta > 0.69$ emit Čerenkov light, i.e. $E_{kin} > 0.2$ MeV for electrons and > 350 MeV for protons

2) Because of the absence of correlations between the signals from adjacent active layers in fine-sampling hadron calorimeters

The calorimeter from the example had 0.06 λ_{int} thick sampling layers.
A mip would lose on average 12.7 MeV traversing these layers.

- All neutrino flux problems (NUMI, MiniBoone, K2K, T2K, Nova, Minerva) and all calorimeter design problems and all jet energy scale systematics (not including jet definition ambiguities here) can be reduced to one problem – the current state of hadronic shower simulators.
  - Rajendran Raja (HSSW 06)