Hadronic Shower Simulation

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ILC Detector Test Beam Workshop
19 January 2007

Outline

- Selected highlights of the Hadronic Shower Simulation Workshop at Fermilab (September 2006)
    - comparison of code features
    - shower shape studies
    - Grand Validation
- Improving the codes: where do we go from here?
    - ILC detector needs
    - areas for improvement
    - new sources of data

Comparison of Code Features

- Slides by Gregg McKinney (presented in summary talk by Laurie Waters)
  - comparison of features for five physics simulation codes: FLUKA, GEANT4, MARS, MCNPX, PHITS
  - covers: general information, geometry, physics, sources, tallies/scoring and variance reduction

General information for various all-particle transport codes

General	MCNPX	GEANT4	FLUKA	MARS	PHITS
Version	2.5.0	8.1 p1	2005	15	2.09
Lab. Affiliation	LANL	CERN ESA IN2P3 PPARC INFN LIP KEK SLAC TRIUMF	CERN INFN	FNAL	JAEA RIST GSI Chalmers Univ.
Language	Fortran 90/C	C++	Fortran 77	Fortran 95/C	Fortran 77
Cost	Free	Free	Free	Free	Free
Release Format	Source & binary	Source & binary	Source & binary	Binary	Source & binary
Availability Conditions	RSICC Beta test team	Open web None		User's Agreement	
User Manual	470 pages	280 pages	387 pages	150 pages	176 pages
Users	~2000	~2000	~1000	~300	220
Web Site	mcnpx.lanl.gov	cern.ch/geant4	www.fluka.org	www-ap.fnal.gov/MARS	Under const.
Workshops	~7/year	~4/year	~1/year	~2/year	~1/year
Input Format	Free	C++ main Fixed geometry	Fixed or free	Free	Free
Input Cards	~120	N/A	~85	0 to 100	~100
Parallel Execution	Yes	Yes	Yes	Yes	Yes

Geometry Capabilities

Geometry	MCNPX	GEANT4	FLUKA	MARS	PHITS
Description	MCNP-based	Solids (CSG, Boolean, some BREP/STEP)	Combinatorial	Fixed shapes or MCNP-based	MCNP-based MORSE-based
Extensions					
Twisted	No	Yes	No	No	No
Nested	Yes (universes)	Yes (logical vol.)	No	Yes	Yes (universes)
Repeated	Yes	Yes	Yes	Yes	Yes
Voxel	Lattice (rec, hex)	Yes (rec, cyl)	Yes	Yes	Lattice (rec, hex)
Reflections	3 types	Yes	Yes	Yes	Neutron albedo
Viewer **Debugger**	Built-in: 2-D Interactive X-Windows External: Vised Moritz	Built-in: 3-D Interactive OpenGL OpenInventor RayTracer External: WIRED VRML DAWN Overlap tools	Built-in: None External: Custom (X11) Debugger built in	Built-in: 2-D Interactive Tcl/Tl 3-D Interactive OpenGL External: Built-in	Built-in: 2,3-D Command PS via Angel External: Angel PS
Setup GUI	Vised Moritz	GGE	No	Tcl/Tl	No
CAD	STEP via GUI	STEP via Tool	No	No	No
Fields (E/B)	2.6.D	Yes	Yes	Yes	Yes
Moving	2.6.D	Yes	Yes	No	Yes

Physics Capabilities

Physics	**MCNPX**	**GEANT4**	**FLUKA**	**MARS**	**PHITS**
Particles	34	68	68	41	38
Charged particles	CSDA	CSDA	CSDA	CSDA	CSDA
Energy loss	Bethe-Bloch	Bethe-Bloch	Bethe-Bloch	Bethe-Bloch	Bethe-Bloch
Scatter	Rossi	Lewis	Moliere improved	Moliere improved	Moliere
Straggling	Vavilov	Urban	Custom	Custom	Vavilov
XTR/Cheren.	No	Yes	No/yes	No	No
Baryons					
Neutron					
Low	Cont. (ENDF)	Cont. (ENDF)	Multigroup(72)	Cont. (ENDF)	Cont. (ENDF)
High	Models	Models	Models	Models	Models
Proton					
Low	Cont. (ENDF)	Models	Models	Models	Models
High	Models	Models	Models	Models	Models
Other	Model List: Bertini ISABEL CEM INCL FLUKA89>3 GeV LAQGSM (2.6.C)	Model list: Hadron-nucleous GHEISHA* INUCL(Bertini) BIC CHIPS QGS/FTF>8 GeV	Model list: PEANUT(GINC) +DPM+Glauber	Model list: Custom CEM LAQGSM DPMJET	Model list: Bertini JAM>3 GeV
Leptons					
Electrons	ITS 3.0	Models/EEDL, EADL	Custom	Custom	ITS 3.0
Muon	CSDA/decay	Models	Models	Models	CSDA/decay
Neutrino	Production	Production	Models	Models	Models
Other	Decay	Decay	Decay	Models	Models

Physics Capabilities, cont.

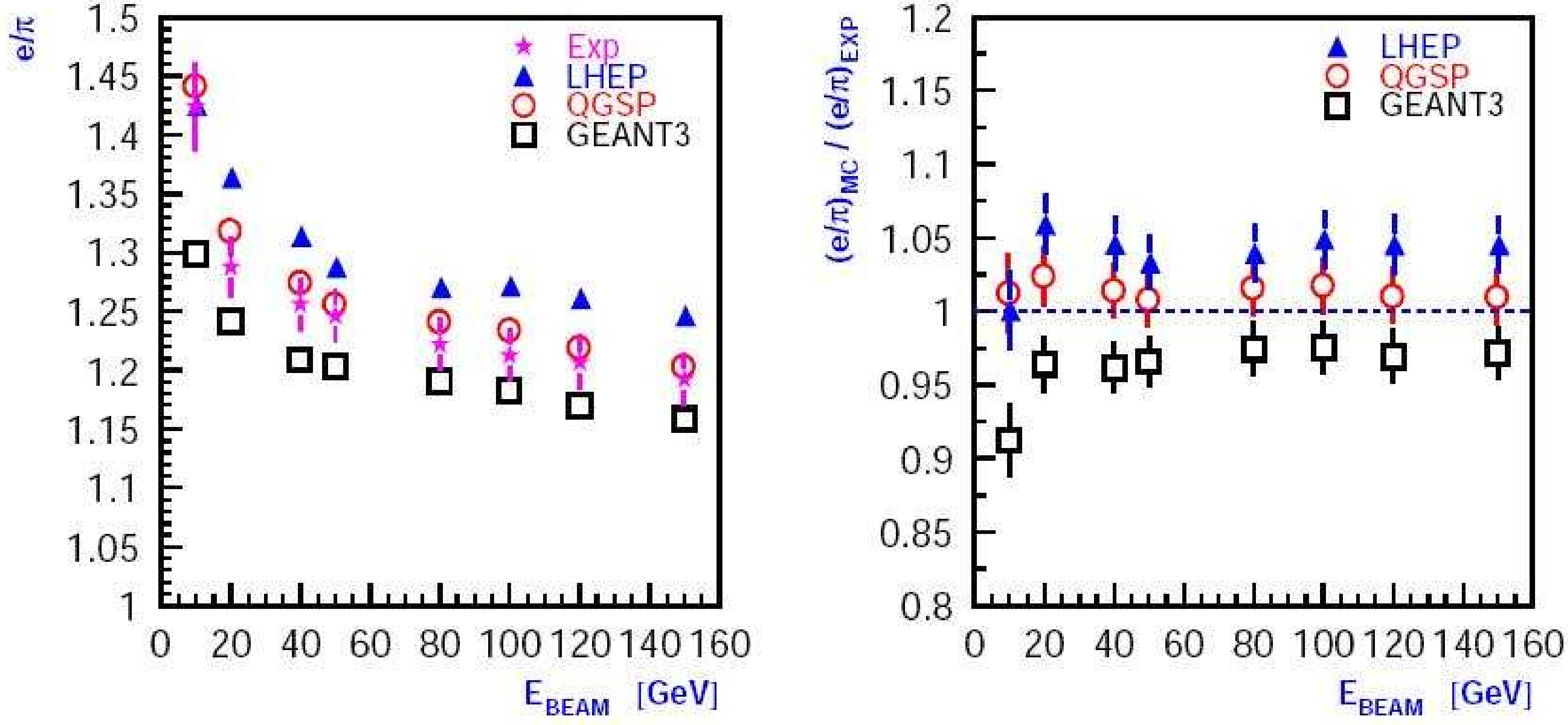
Mesons	Models	Models	Models	Models	Models
Photons Optical x-ray/g Photonuclear	No ITS 3.0 Libraries (IAEA) CEM	Yes Models or EPDL97, EADL CHIPS	Yes Custom+EPDL97 PEANUT VMDM	No Custom Custom CEM	No ITS 3.0 No
Ions	ISABEL LAQGSM (2.6.C)	AAM EDM BLIC	RQMD-2.4 DPMJET-3	LAQGSM	JQMD JAMQMD > 3 GeV/u
Delayed	n,γ (2.6.C)	α , β , γ ?	β , γ	γ	n

Shower Shape Comparisons

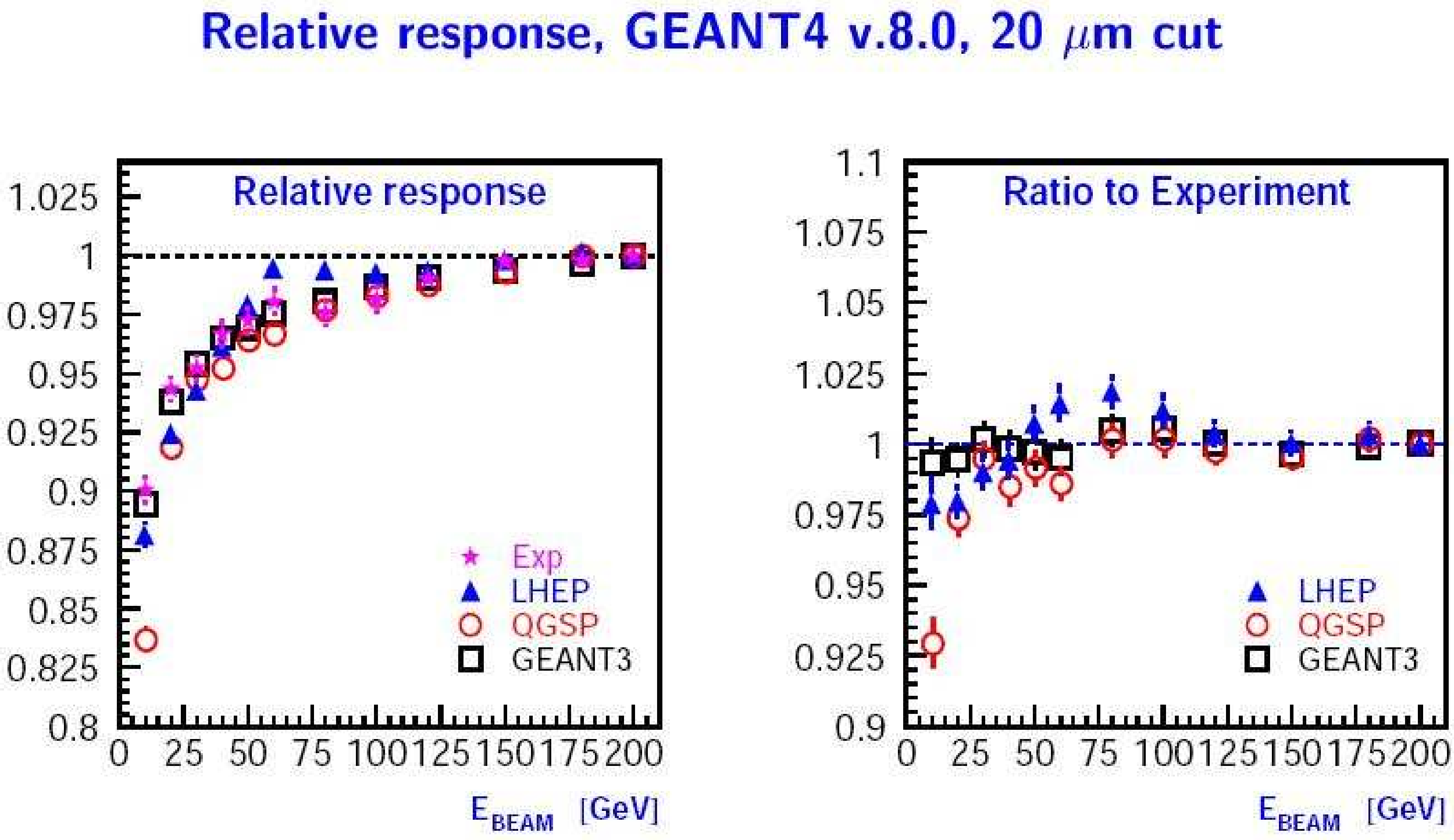
- Data from ATLAS and CMS test beams
  - almost all data is longitudinal profile information
- Transverse profile information would be very useful
- Data compared to two physics lists
  - LHEP
    - collection of low and high energy parameterized models (descendants of GHEISHA)
  - QGSP
    - mostly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

Atlas (HEC)

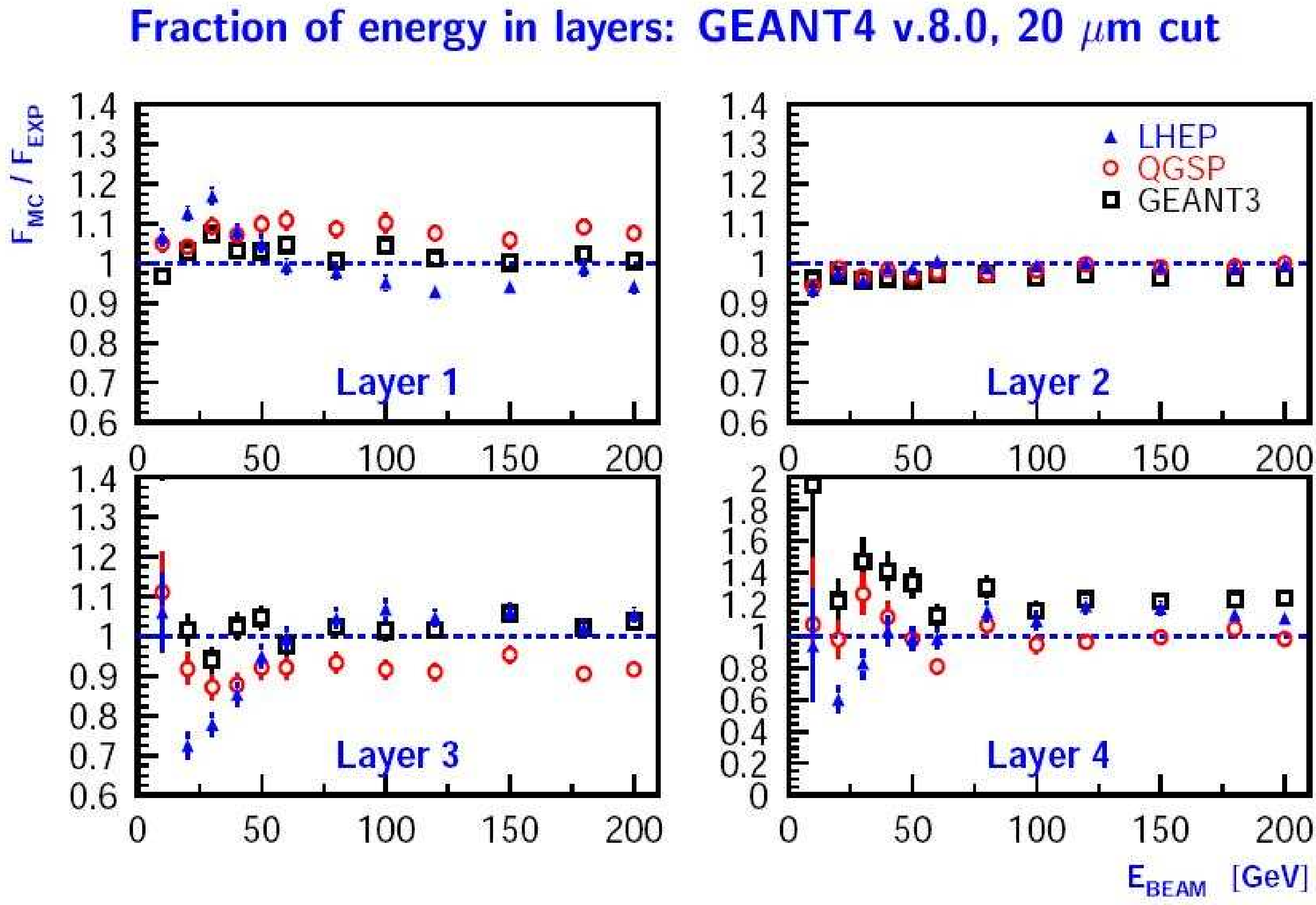
Ratio e/π; GEANT4 v.8.0, 20 μm cut



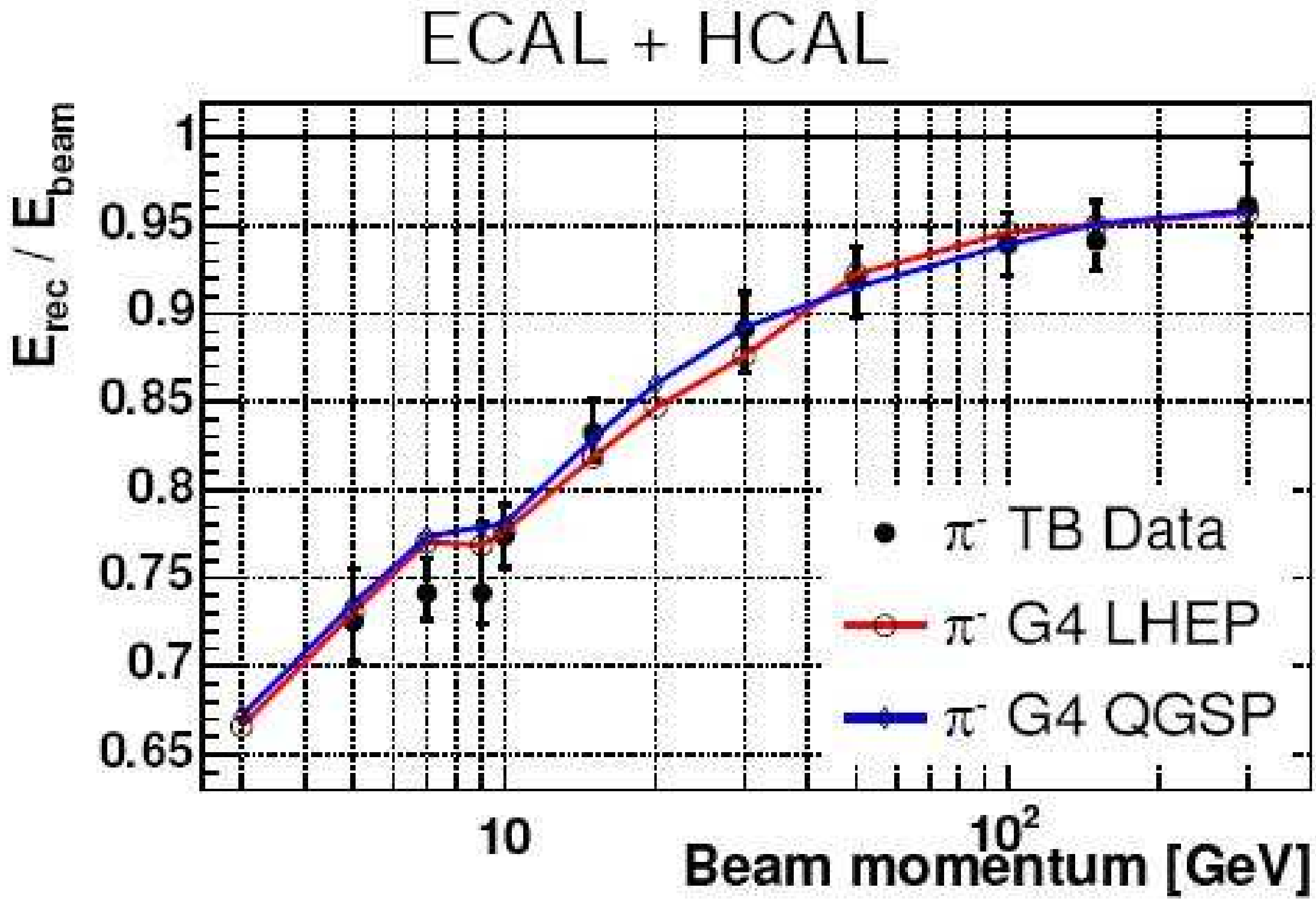
Atlas (HEC)


Relative response, GEANT4 v.8.0, 20 μm cut
Relative response
1.025
1
0.975
0.95
0.925
0.9
0.875
0.85
0.825
0.8
0
25
50
75
100
125
150
175
200
E_{BEAM} [GeV]
★ Exp
▲ LHEP
○ QGSP
□ GEANT3
Ratio to Experiment
1.1
1.075
1.05
1.025
1
0.975
0.95
0.925
0.9
▲ LHEP
○ QGSP
□ GEANT3

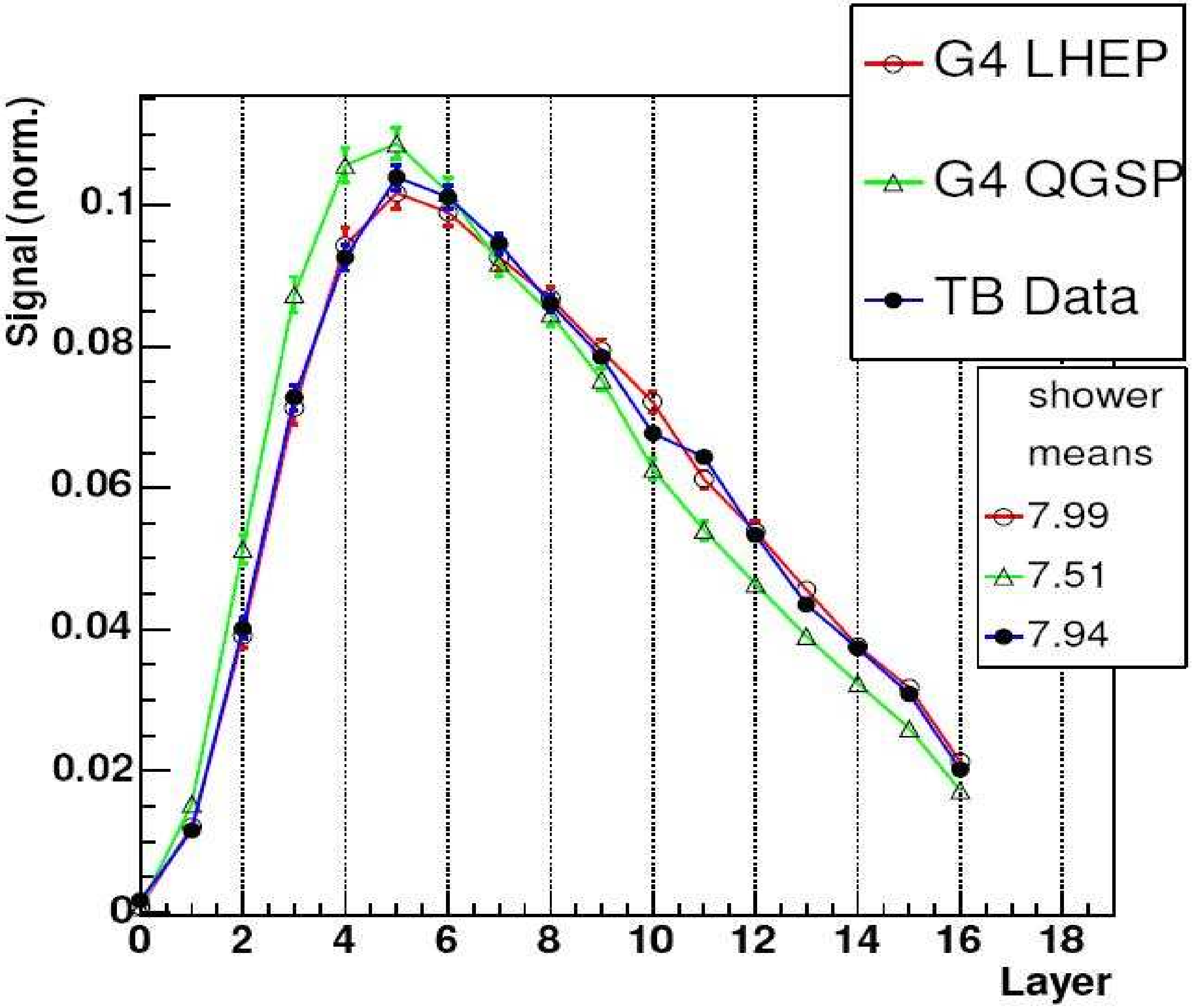
Atlas (HEC)


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

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



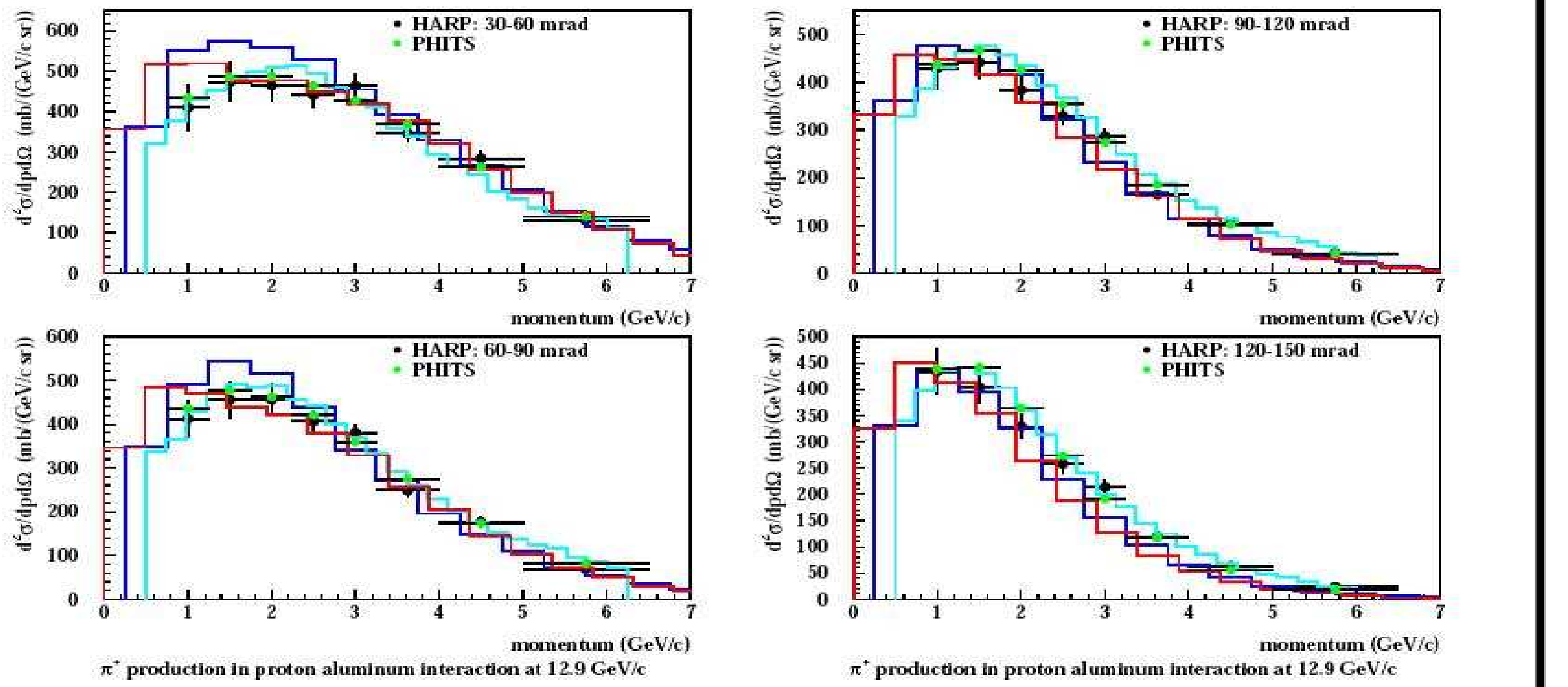
300 GeV pions, leaving MIP in ECAL and L0.

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

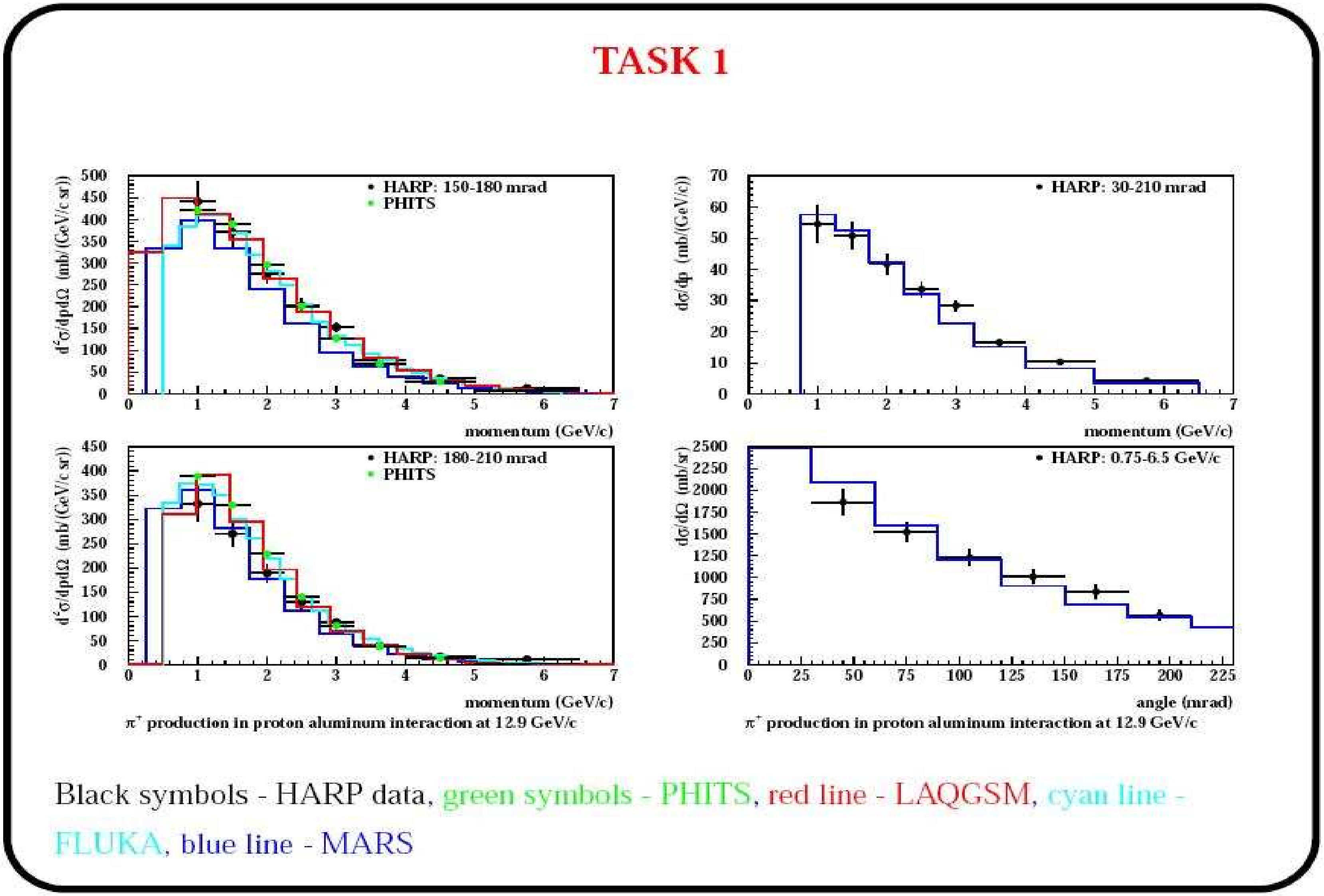
Task 1: 12.9 GeV/c p on Al

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



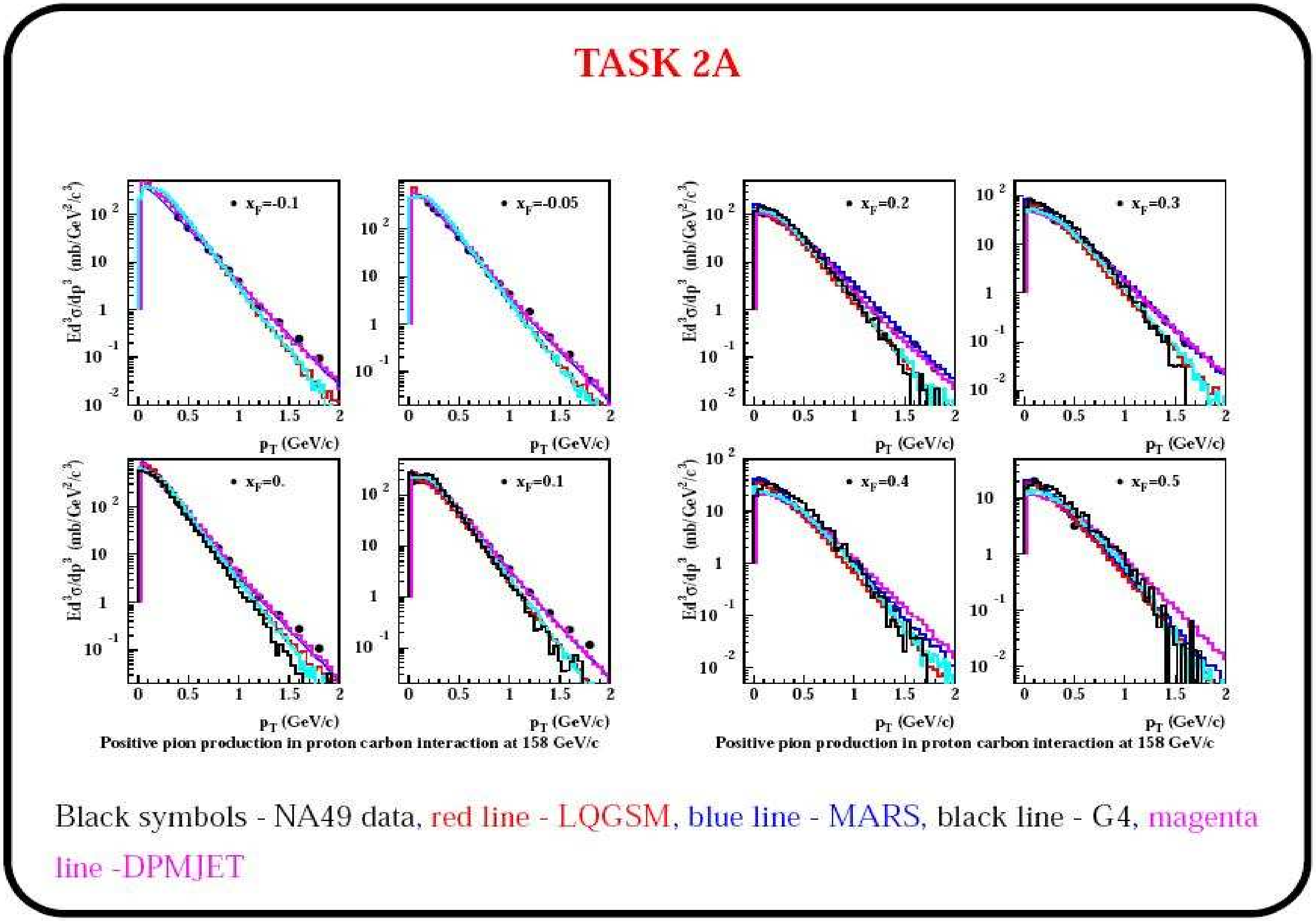
TASK 1

π^+ production in proton aluminum interaction at 12.9 GeV/c

π^+ production in proton aluminum interaction at 12.9 GeV/c

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

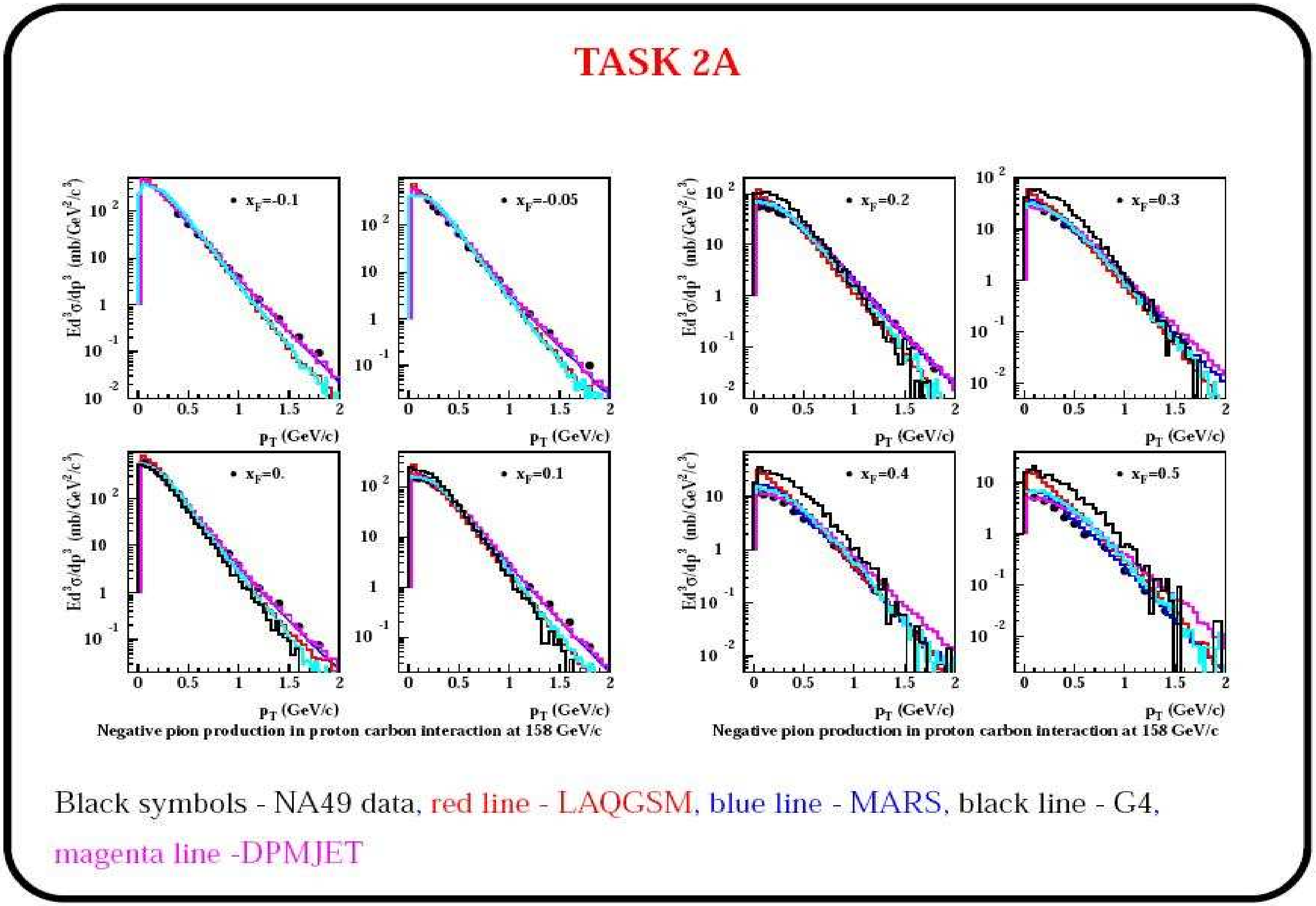
Positive pion production in proton carbon interaction at 158 GeV/c

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

Fermilab

S. Striganov

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

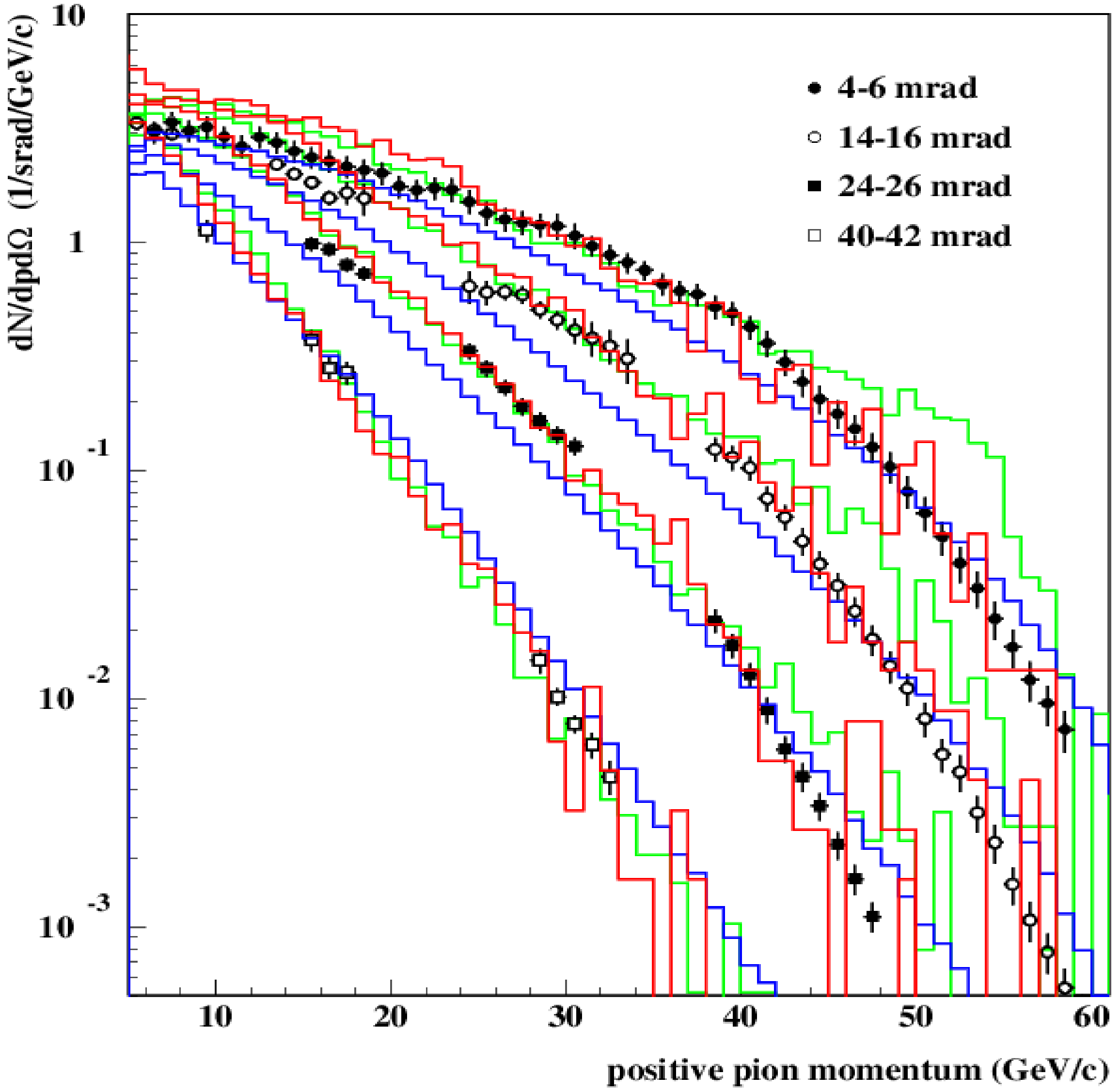
Black symbols - NA49 data, red line - LAQGSM, blue line - MARS, black line - G4, magenta line -DPMJET

Fermilab

S. Striganov

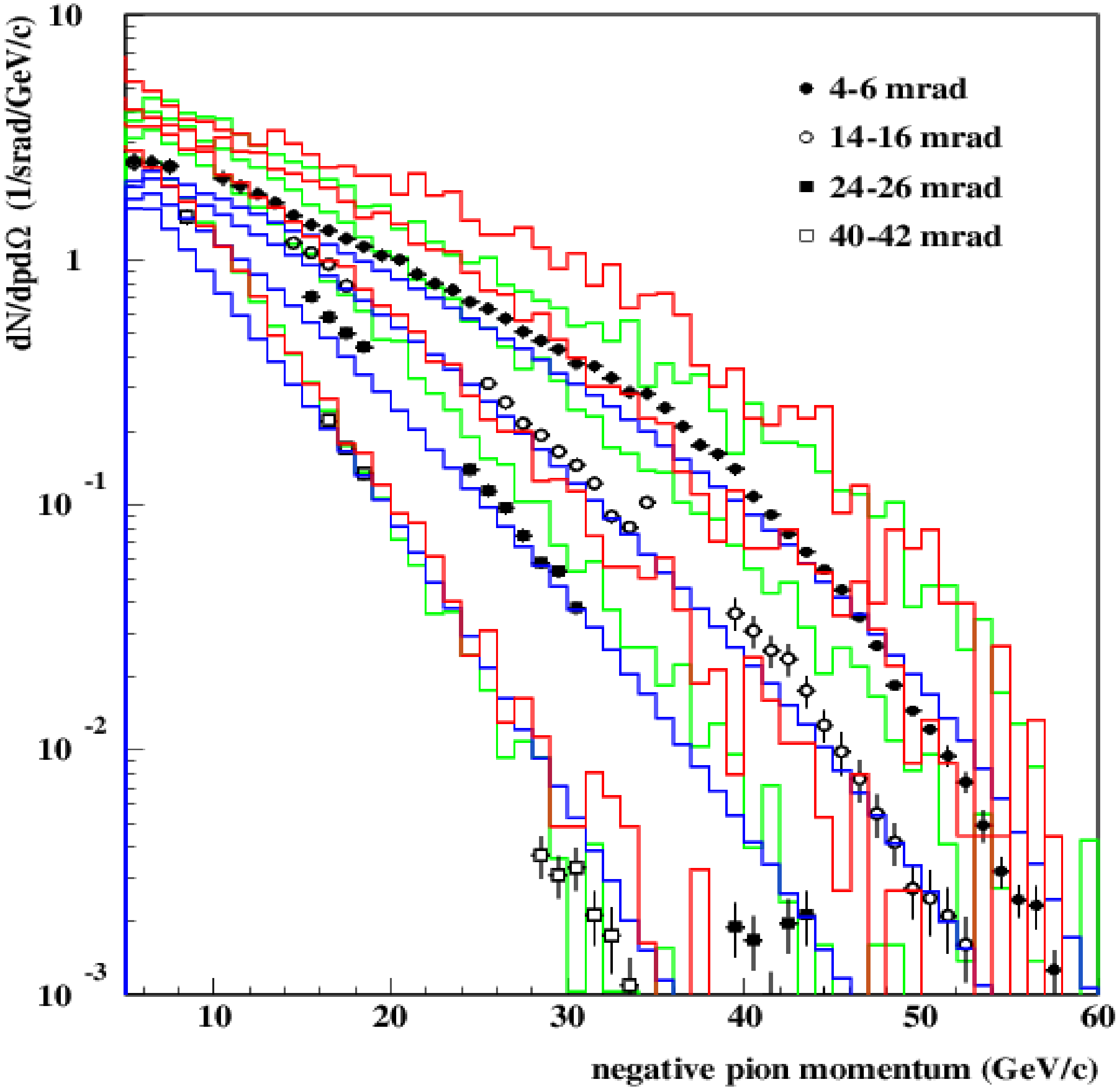
Task3: p + Al at 67 GeV/c -> π^+ X

red: Geant4, blue: MARS, green: PHITS



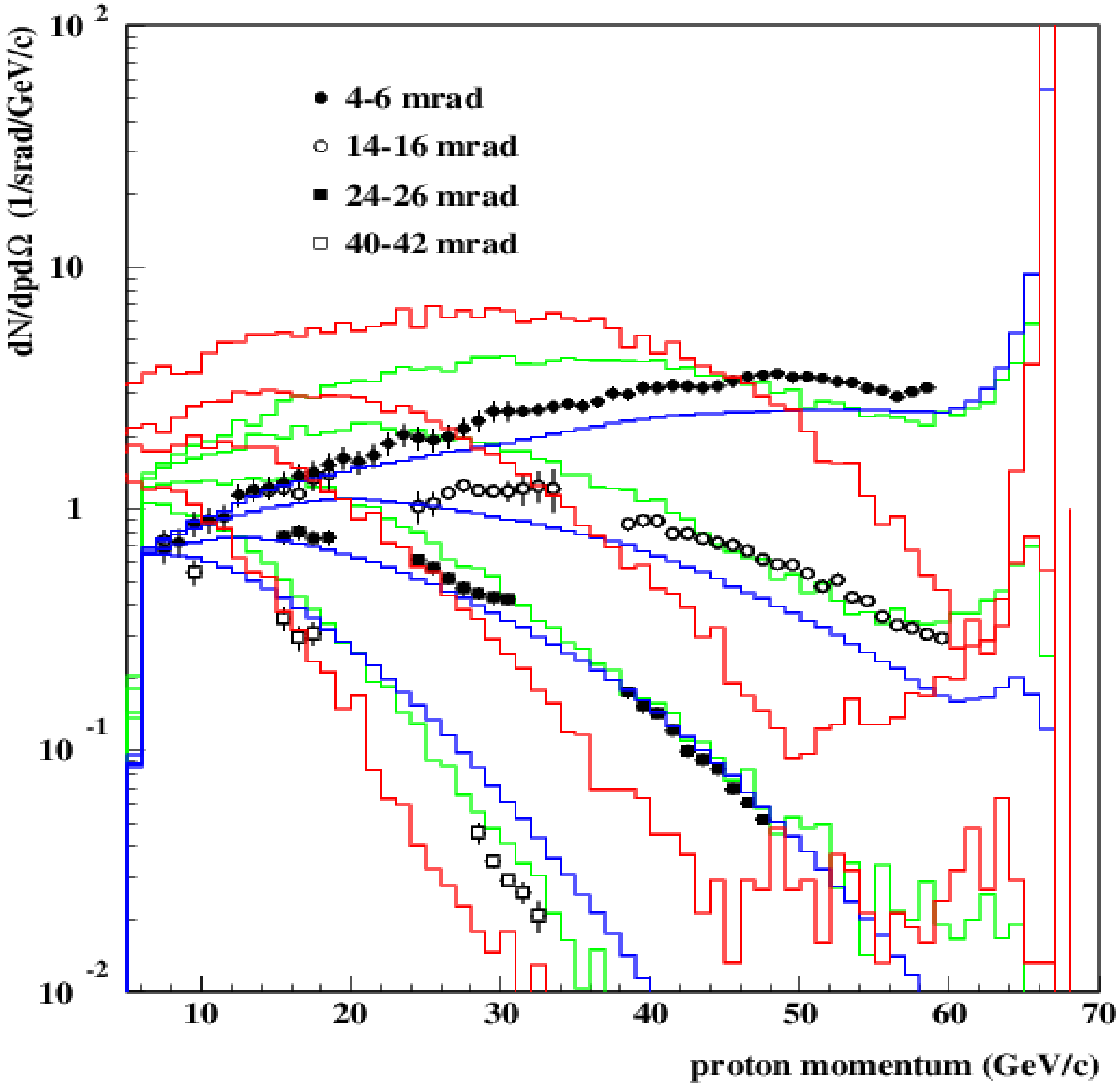
Task3: p + Al at 67 GeV/c -> π^- X

red: Geant4, blue: MARS, green: PHITS

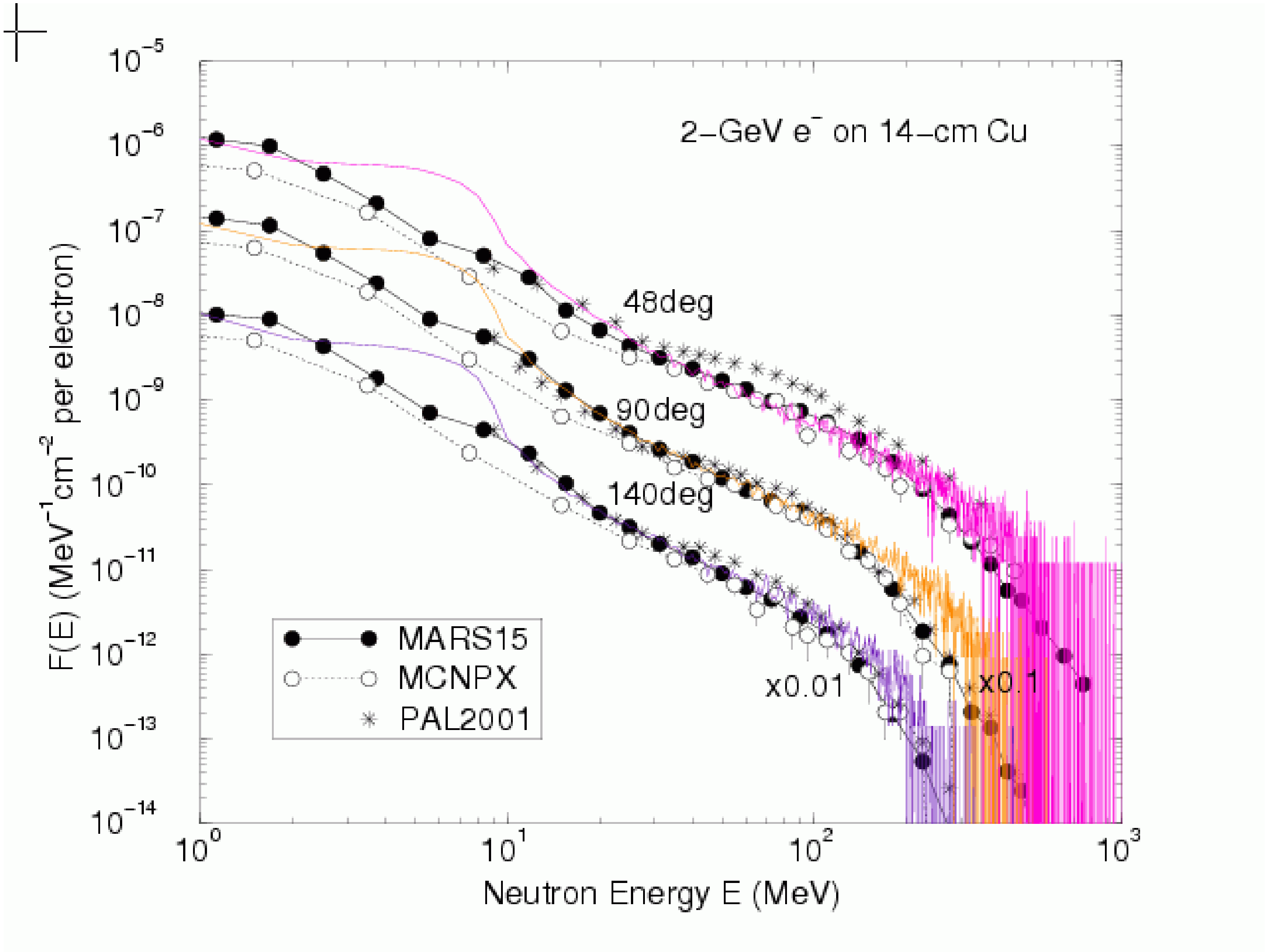


Task 3: p + Al at 67 GeV/c -> p X

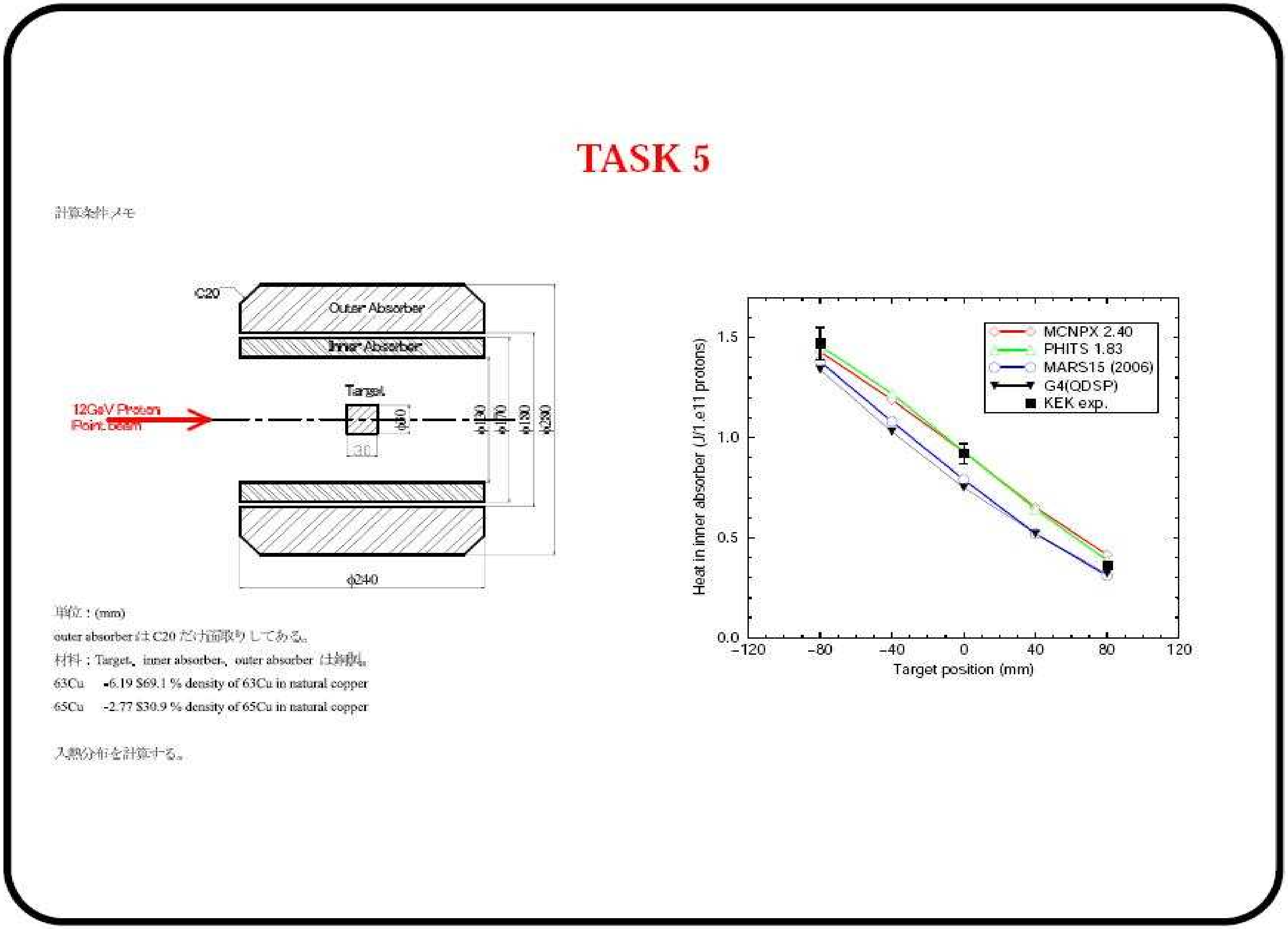
red: Geant4, blue: MARS, green: PHITS



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。

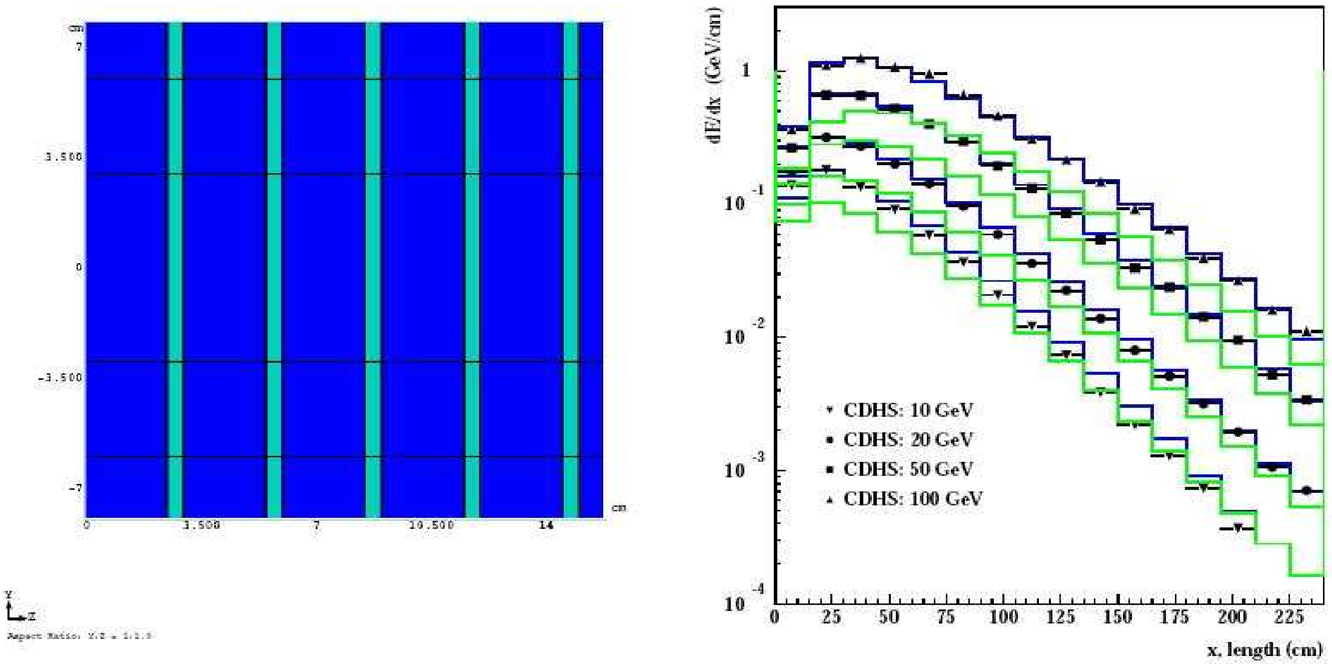
63Cu -6.19 $69.1 % density of 63Cu in natural copper

65Cu -2.77 $30.9 % density of 65Cu in natural copper

入熱分布を計算する。

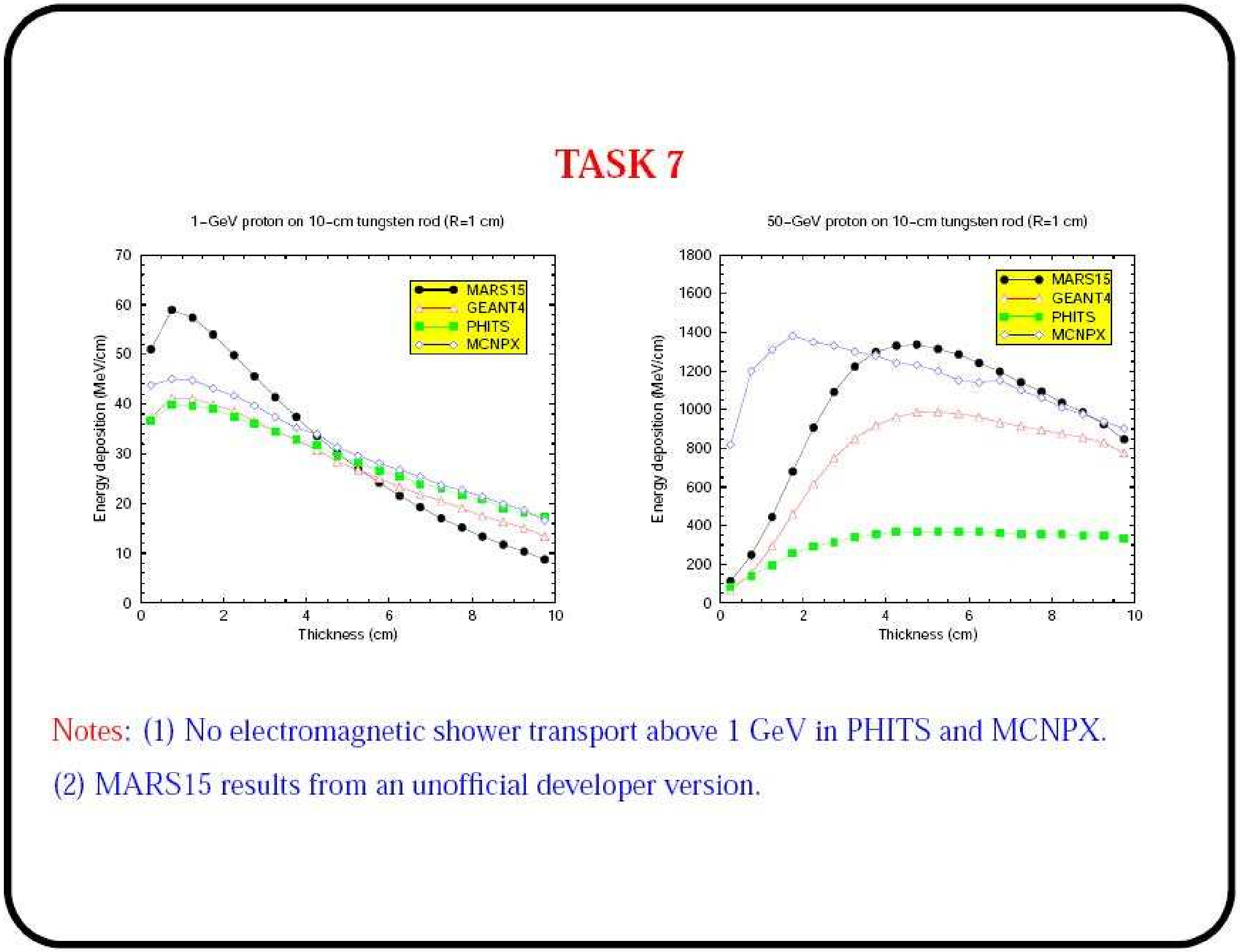
Task6: π^- in Fe-Scint Calorimeter

TASK 6



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

Task 7: Energy Deposited in W Rod



TASK 7

1-GeV proton on 10-cm tungsten rod (R=1 cm)

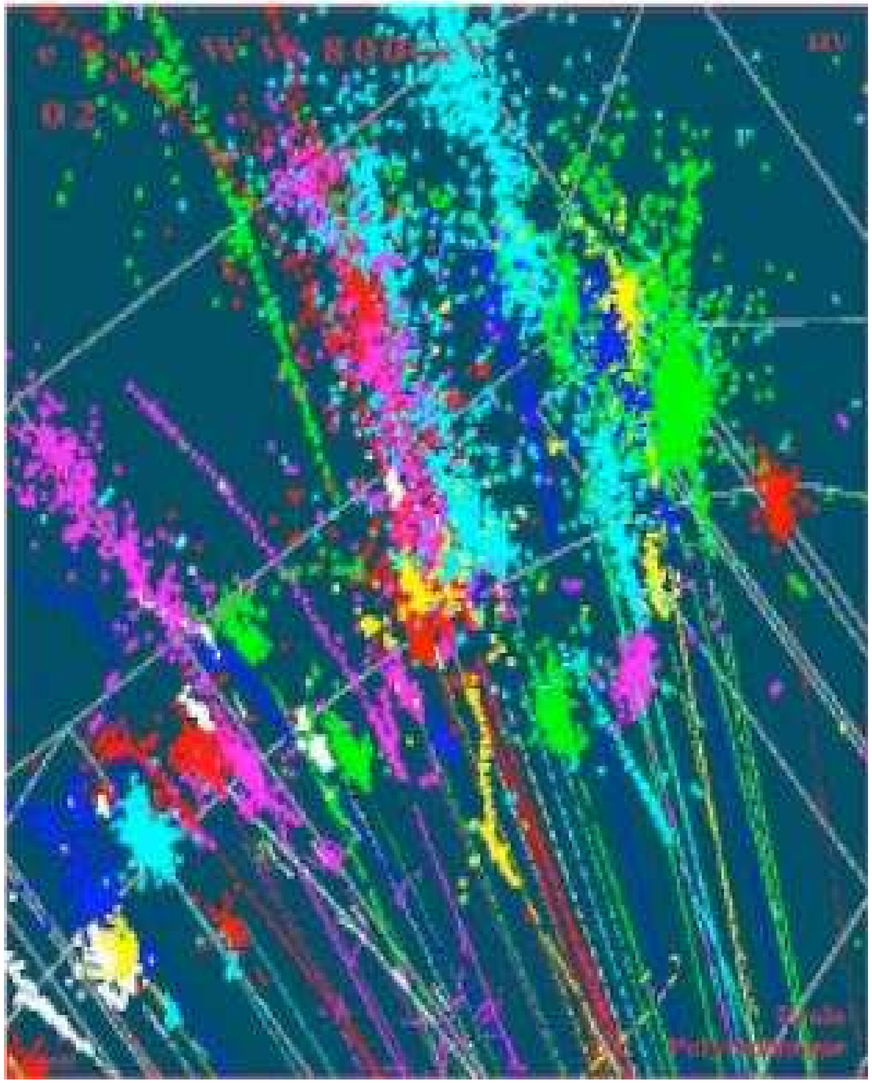
50-GeV proton on 10-cm tungsten rod (R=1 cm)

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

(2) MARS15 results from an unofficial developer version.

What ILC Detectors Require from Hadronic Codes (1)

- Detector conditions:
  - high jet density
  - high granularity
  - excellent hermeticity
- Implied requirements for simulation code:
  - good shower shape reproduction
  - good energy and baryon conservation
  - proper handling of transport and interaction of neutral hadrons



What ILC Detectors Require from Hadronic Codes (2)

- Shower shapes:
  - lateral distribution most important
  - dominated by EM processes, but hadronic code is important. Must pay attention to:
    - diffraction, pomeron trajectory parameters
    - ~100 MeV protons, π^0 fraction, neutrons below 10 MeV
- Energy/momentum, baryon number conservation
  - detailed models handle these correctly, some fast parameterized models handle it only averaged over many events
- Interaction of neutrals
  - models must rely on isospin arguments (very little data)

Areas for Improvement of Hadronic Code

- Problem: large differences from one hadronic code to another
  - as it stands now, this imposes a significant limitation for ILC calorimeter design
- Solutions:
  - continued inter-code comparisons
  - more interaction between experts to exploit apparent complementarity in codes
  - more data for validation
    - thin target (especially in few GeV to 20 GeV range)
    - full setup (especially transverse shower shape)

Areas for Improvement of Hadronic Code

- Re-examine treatment of low energy protons (~100 MeV) and neutrons (< 10 MeV)
- Develop new model for the few GeV region
  - theoretically difficult region (between cascade and string)
  - some codes blend models to cover this range
- Improve models for incident neutral hadrons
  - n, K^0_L especially important for ILC detectors

New Sources of Data Required for Hadronic Code 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 required (HARP, MIPP ?)
  - full setup
    - data from complete, or test beam detectors used as integration tests of all physics, but never for tuning
    - ATLAS and CMS longitudinal shower shape data available
    - transverse shower shape data would be very useful

MIPP Upgrade

- Will provide thin target data
  - event libraries, double differential cross sections
- Provide beams of 9 particle species
  - $\pi^{+/-}$, $K^{+/-}$, p, pbar, n, nbar, and K^0_L
  - 90 GeV/c down to maybe 1 GeV/c
- 40 target nuclei
  - excellent coverage of periodic table
- Proposal made to FNAL PAC
  - deferred

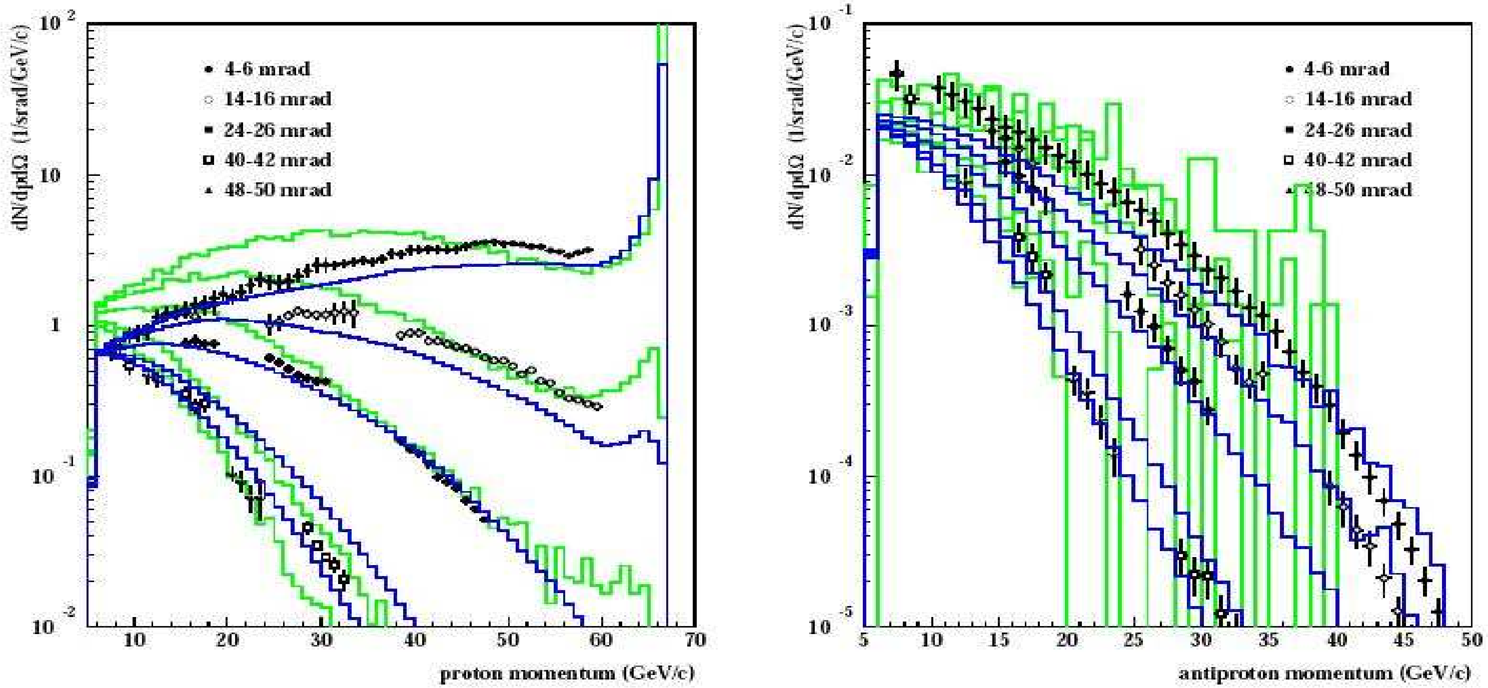
Summary

- Hadronic Shower Simulation workshop brought together experts in many different simulation codes
- Inter-comparison of codes was very useful and will be continued
- Codes were shown to differ widely
  - this is a potential limiting problem for ILC detector design
- Ways forward:
  - more validation data
  - new models
  - re-examination of old models

Backup Slides

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

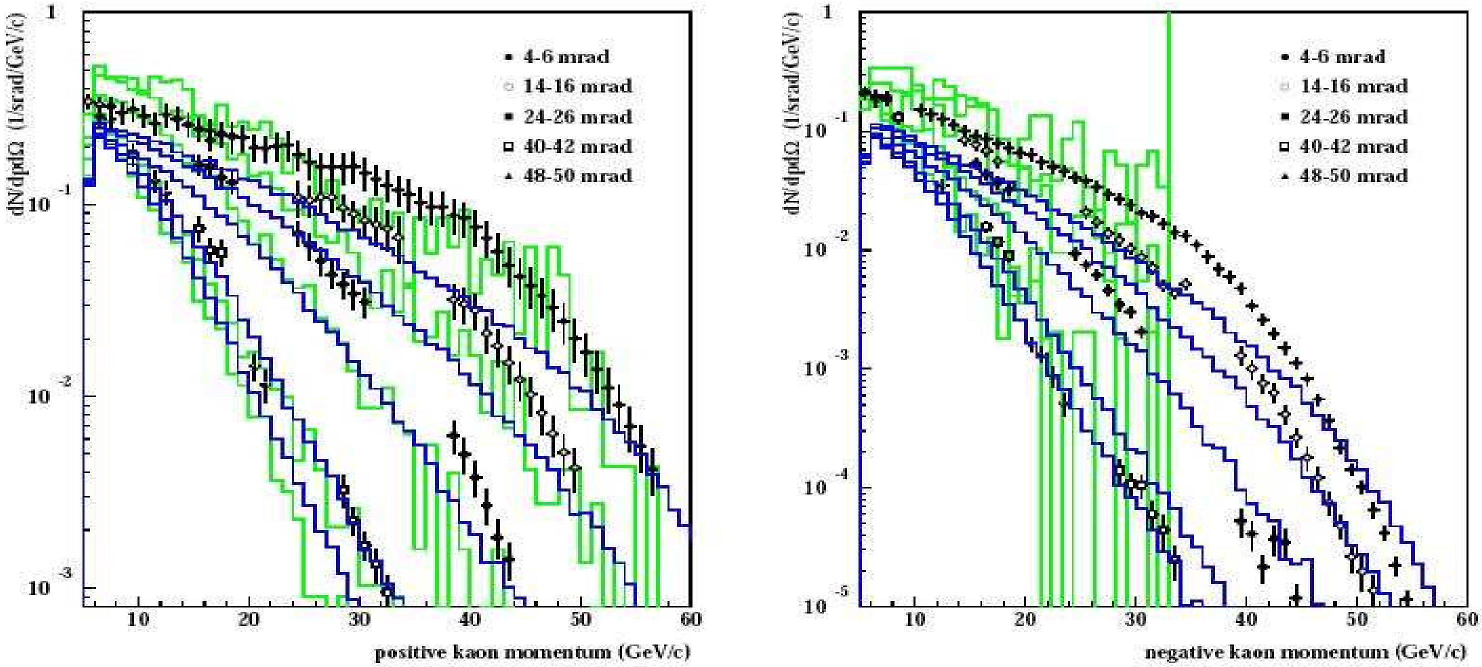
TASK 3



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

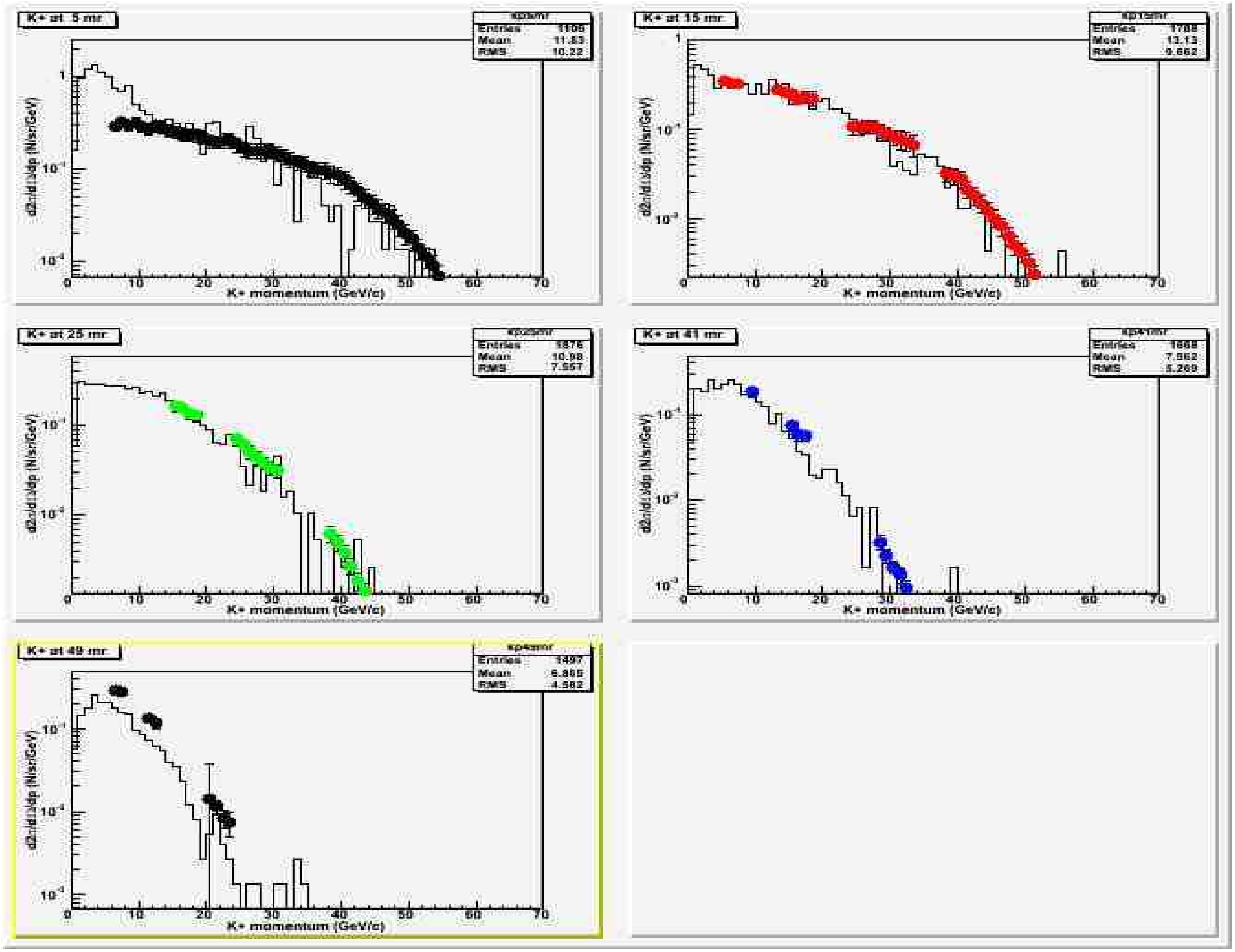
Task 3: K^+ ,K^- from 67 GeV/c p on Al

TASK 3



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

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



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)

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.