Report from the Hadron Shower Simulation Workshop at Fermilab

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Geant4 Workshop and Users Conference
Lisbon, Portugal
9 October 2006

Outline

- Purpose
- Survey of simulation codes
- Validation Highlights from ATLAS and CMS
- “Grand Validation”
- Excerpts from R. Wigmans' talk on calorimetry
- Importance of hadronic simulation in other areas

Purpose of the Workshop

- Understand hadronic shower simulation relevant to:
  - hadron calorimetry at ILC and LHC
  - neutrino fluxes and atmospheric showers
- Get simulation experts together to:
  - evaluate available simulation codes
  - compare validations
  - identify problems
  - propose ways to go forward
- http://conferences.fnal.gov/hss06

Survey of Simulation Codes

- Geant4, Fluka, Mars, MCNPX, PHITS
- Feature comparison chart by Gregg McKinney

General	MCNPX	GEANT4	FLUKA	MARS	PHITS
Version	2.5.0	8.0 p1	2005	15	2.09
Lab. Affiliation	LANL	CERN IN2P3 INFN KEK SLAC TRIUMF ESA	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
User Manual	470 pages	280 pages	387 pages	150 pages	176 pages
Users	2500	~2000	~1000	220	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	~100	~100
Parallel Execution	Yes	Yes	Yes	Yes	Yes

Geometry	MCNPX	GEANT4	FLUKA	MARS	PHITS
Description	MCNP-based	STEP Solids (Boolean CSG)	MORSE-based	Solids MCNP-based User defined	MCNP-based MORSE-based
Extensions Twisted Nested Repeated Voxel	 No Yes (universes) Yes Lattice (rec, hex)	 Yes Yes (logical vol.) Yes Yes (rec, cyl)	 No No Yes Yes	 No Yes Yes Yes	 No Yes (universes) 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	Built-in: None External: Custom (X11) Others?	Built-in: 2-D Interactive Tcl/Tl 3-D Interactive OpenGL External: Custom	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	No	No	No
Fields (E/B)	2.6.0	Yes	Yes	Yes	Yes
Moving	2.6.0	Yes	Yes	No	Yes

Source	MCNPX	GEANT4	FLUKA	MARS	PHITS
Fixed					
General					
Explicit	Yes	Yes	Yes	Yes	Yes
Distribution	Yes	Yes	No	Yes	Yes
Dep. Dist.	Yes	GPS	No	Yes	Yes
External	SSW/SSR	Yes	No	Yes	Yes
User Sub.	Yes	Yes	Yes	Yes	Yes
Eigenvalue	Yes	No	No	No	No
Burnup	Yes (2.6.A)	No	No	No	No

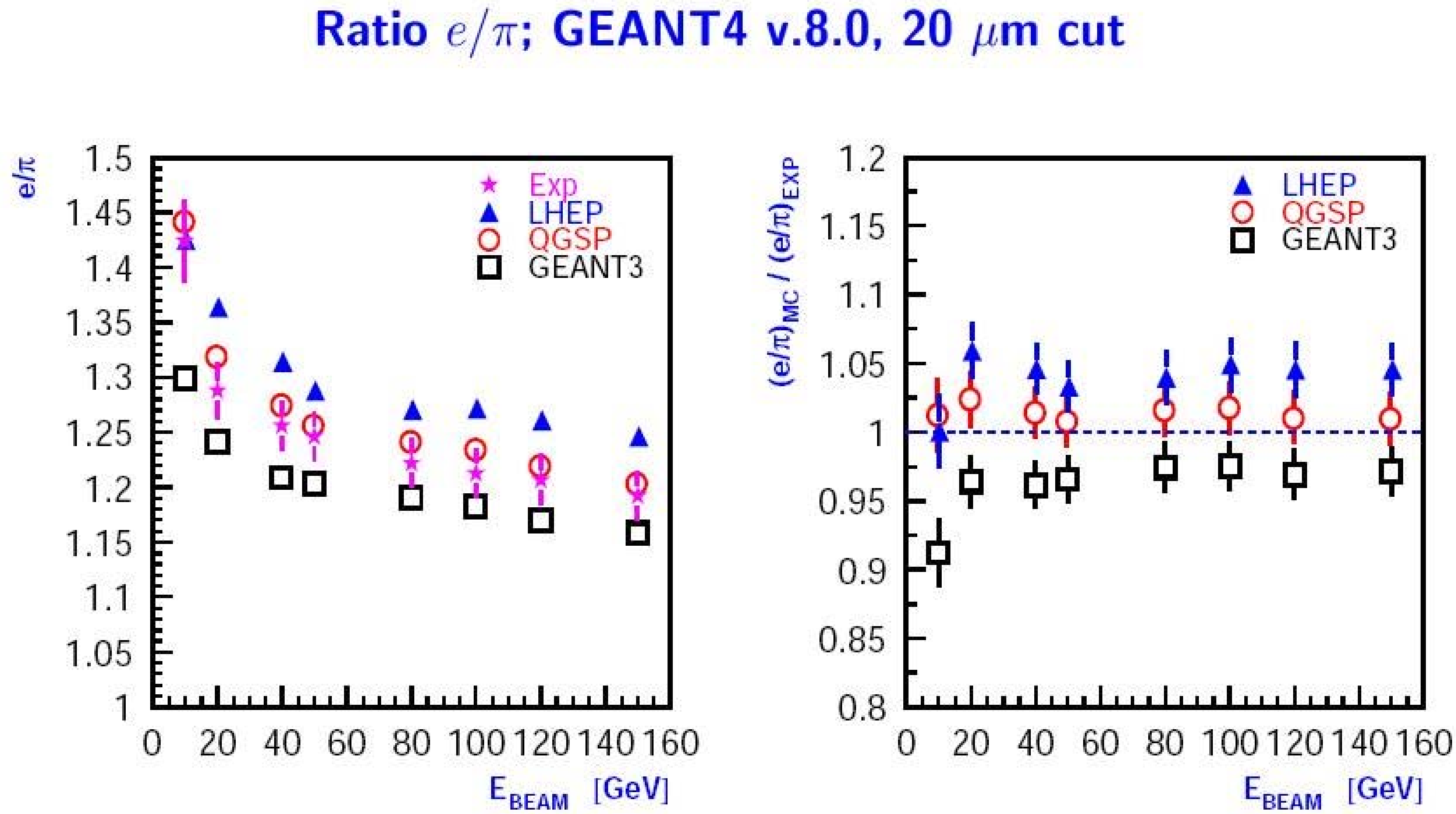
Physics	MCNPX	GEANT4	FLUKA	MARS	PHITS
Particles	34	68	68	41	38
Charged particles	CSDA	CSDA	CSDA	CSDA	CSDA
Energy loss	Bethe-Bloch	Bethe-Bloch	Bethe-Bloch	Bethe-Bloch	Bethe-Bloch
Scatter	Rossi	Lewis	Moliere	Moliere*	Moliere
Straggling	Vavilov	Urban	Custom	Custom	Vavilov
XTR/Cherenkov	No	Yes	No/yes	No	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.D)	Model list: Hadron-nucleous GHEISHA* INUCL(Bertini) BIC CHIPS QGS/FTF>8 GeV	Model list: PEANUT(GINC) DPM+Glauber > 5 GeV	Model list: Custom CEM LAQGSM DPMJET	Model list: Bertini JAM>3 GeV
Leptons					
Electrons	ITS 3.0	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	**MCNPX**	**GEANT4**	**FLUKA**	**MARS**	**PHITS**
Mesons	Models	Models	Models	Models	Models
Photons Optical x-ray/γ Photonuclear	 No ITS 3.0 Libraries (IAEA) CEM	 Yes EPDL97, EADL CHIPS	 Yes Custom+EPDL97 PEANUT VMDM	 No Custom Custom CEM	 No ITS 3.0 No
Ions	ISABEL LAQGSM (2.6.D)	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

Tallies	**MCNPX**	**GEANT4**	**FLUKA**	**MARS**	**PHITS**
Standard					
Flux					
Volume	Yes	Yes	Yes	Yes	Yes
Surface	Yes	Limited	Yes	Yes	Yes
Point/ring	Yes	No	No	Yes (neutrons)	No
Current	Yes	Limited	Yes	Yes	Yes
Charge	Yes	Yes	Yes	Yes	Yes
Kinetic energy	Yes	Yes	Yes	Yes	Yes
Particle density	Yes	Yes	No	No	No
Reaction rates	Yes	No	Star (inelastic)	Yes	Yes
Energy deposition	Yes	Yes	Yes	Yes	Yes
Rapidity	No	Yes	Yes	Yes.	No
DPA	HTAPE3X	??	Some	Yes	Yes
Momentum	No	Yes	Yes	Yes	No
Pulse-height	Yes	User input	Yes	No	Yes
Termination	Partial	??	Yes	Partial	Yes
Modifiers	9	2	2	2	2
Special					
Mesh	rec, cyl, sph	rec, cyl	rec, cyl	rec, cyl, sph	rec,cyl
Coincidence	Yes	No	Yes	Yes	Yes
Residuals	Yes	No	Yes	Yes	Yes
Activation	2.5.D	??	Yes	Yes	No
Event logs	Yes	Yes	Yes	Yes	Yes
Convergence Tests	10	Error	Error	Error	Error

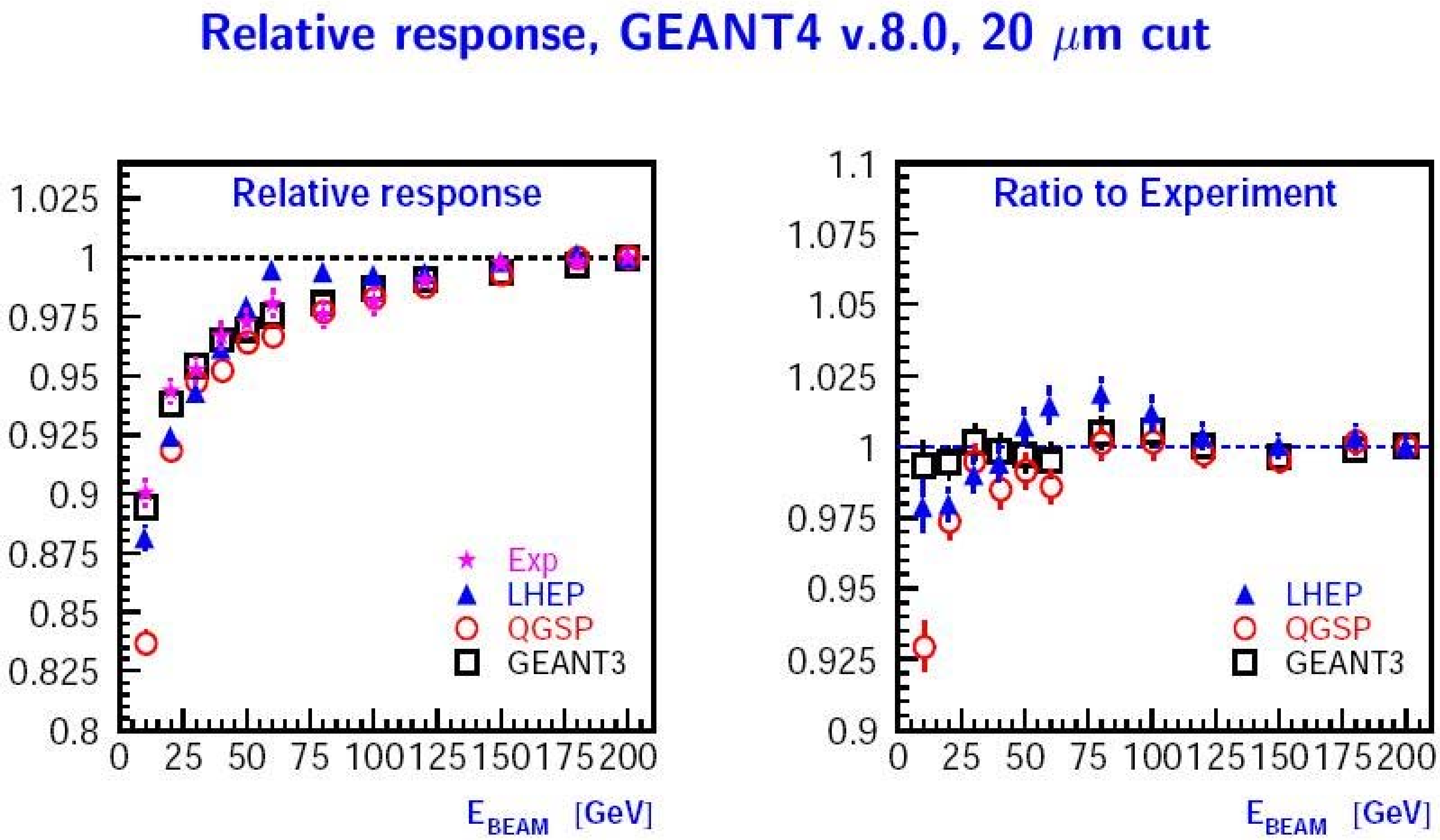
Tallies	**MCNPX**	**GEANT4**	**FLUKA**	**MARS**	**PHITS**
Viewer	Built-in: 1-D, 2-D Custom X-Windows External: IDL Tecplot GNUplot PAW	Built-in: No External: JAS PI Open Scientist	Built-in: None External: Custom (X11) GNUplot PAW ROOT	Built-in: Custom External: PAW	Built-in: Angel External: Angel
Variance Reduction					
Population control Region biasing Weight cutoff Weight window mesh Energy biasing	 Yes Yes Yes Yes	 Yes Yes Yes No	 Yes Yes Yes Yes	 Yes Yes Yes Yes	 Yes Yes Yes Yes
Modified sampling Source biasing Implicit capture Exp. transform Production biasing Angular bias	 Yes Yes Yes Yes Via DXTRAN	 RDM Yes No Yes ??	 Yes Yes Yes Yes Yes	 Yes Yes Yes Yes Yes	 Yes Yes No Yes Yes
DXTRAN	Yes	No	No	No	No
Viewer	2-D contour	No	No	No	No

Atlas (HEC)



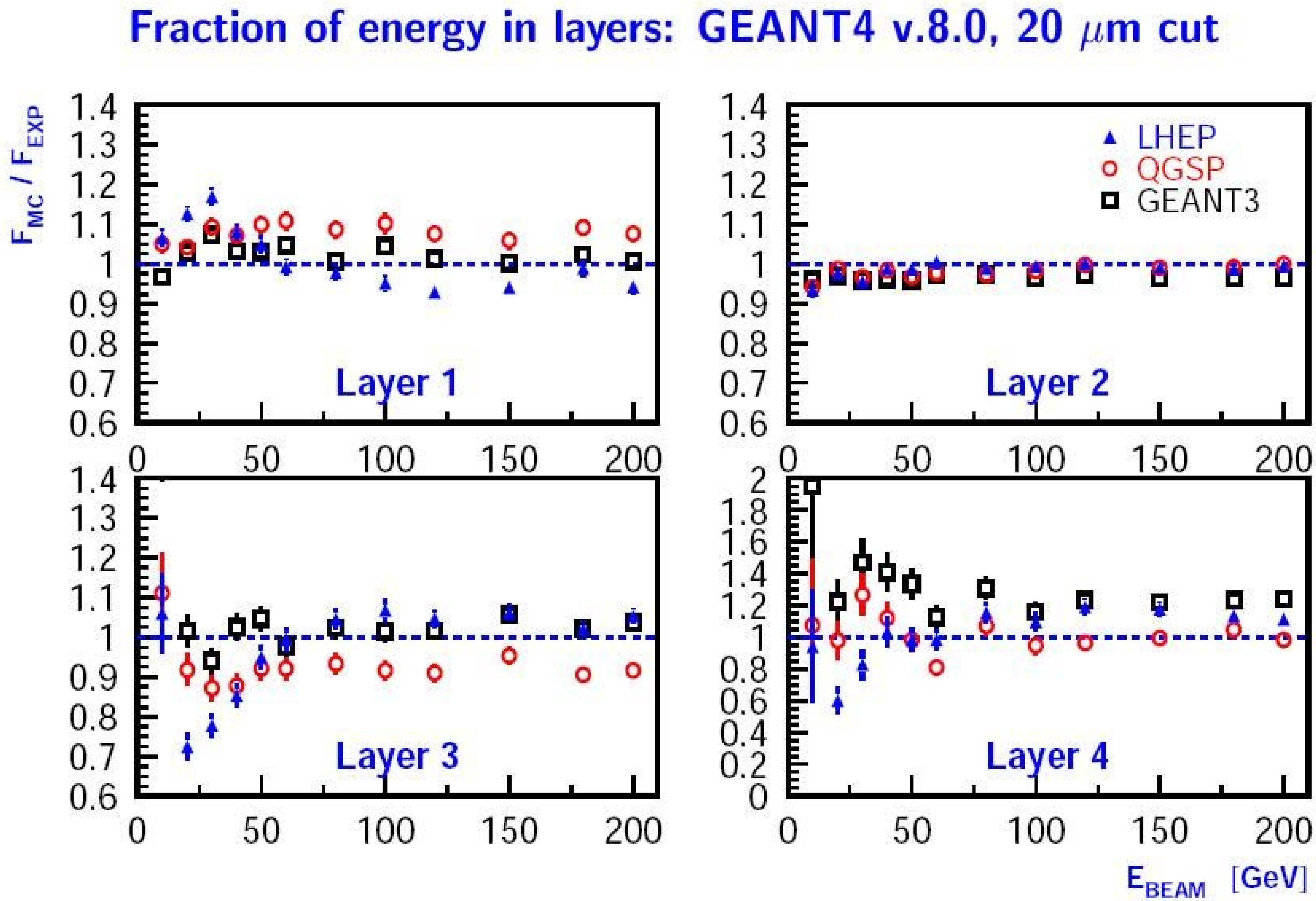
Ratio e/π; GEANT4 v.8.0, 20 μm cut
e/π
Exp
LHEP
QGSP
GEANT3
E_{BEAM} [GeV]
$(e/\pi)_{MC}$ / $(e/\pi)_{EXP}$
LHEP
QGSP
GEANT3
E_{BEAM} [GeV]

Atlas (HEC)



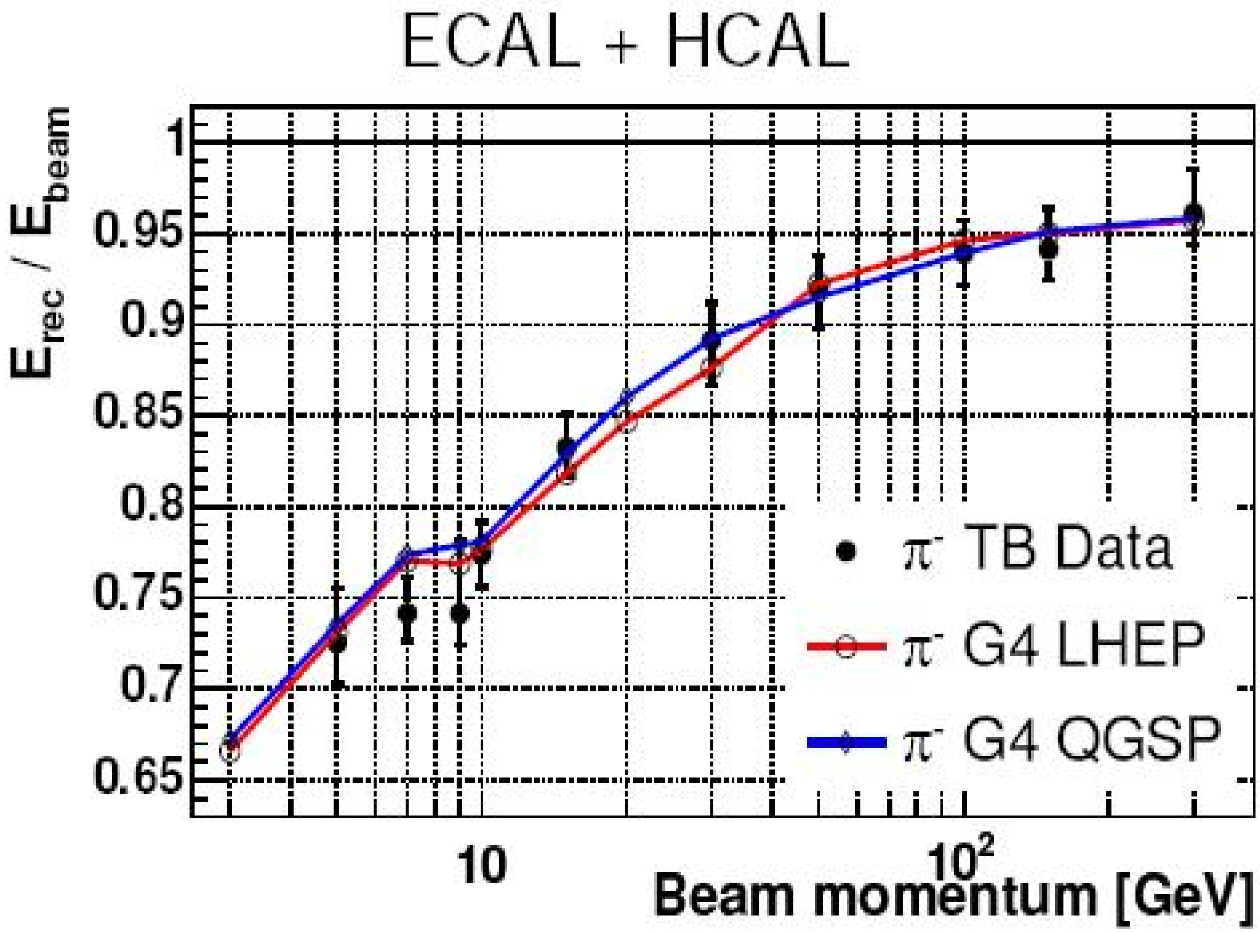
Relative response, GEANT4 v.8.0, 20 μm cut
Relative response
1.025
1
0.975
0.95
0.925
0.9
0.875
0.85
0.825
0.8
0 25 50 75 100 125 150 175 200
Exp
LHEP
QGSP
GEANT3
E_BEAM [GeV]
Ratio to Experiment
1.1
1.075
1.05
1.025
1
0.975
0.95
0.925
0.9
0 25 50 75 100 125 150 175 200
LHEP
QGSP
GEANT3
E_BEAM [GeV]

Atlas (HEC)

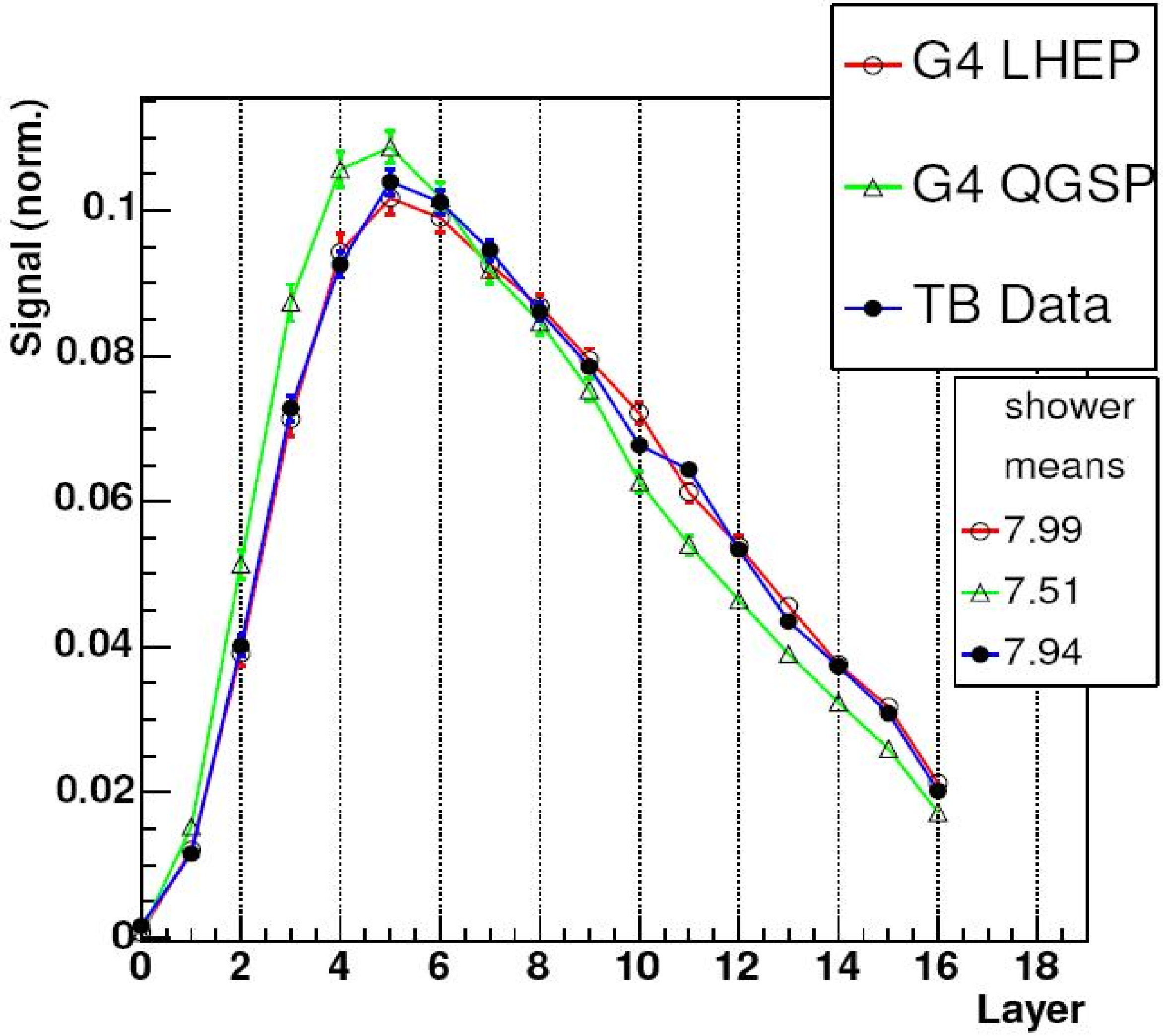


Fraction of energy in layers: GEANT4 v.8.0, 20 μm cut
F_MC / F_EXP
LHEP
QGSP
GEANT3
Layer 1
Layer 2
Layer 3
Layer 4
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
E_BEAM [GeV]

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

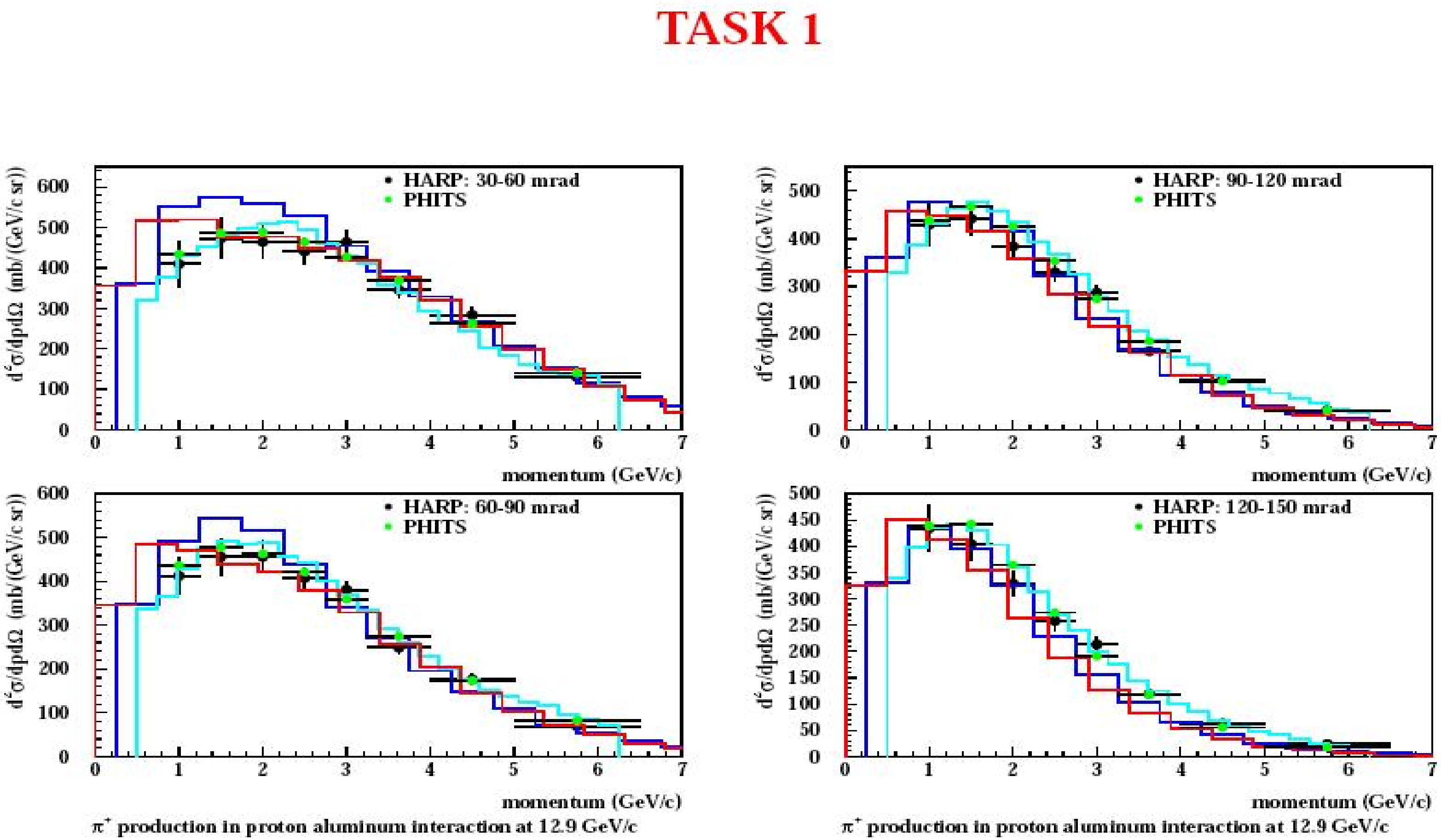


300 GeV pions, leaving MIP in ECAL and L0.

Grand Validation

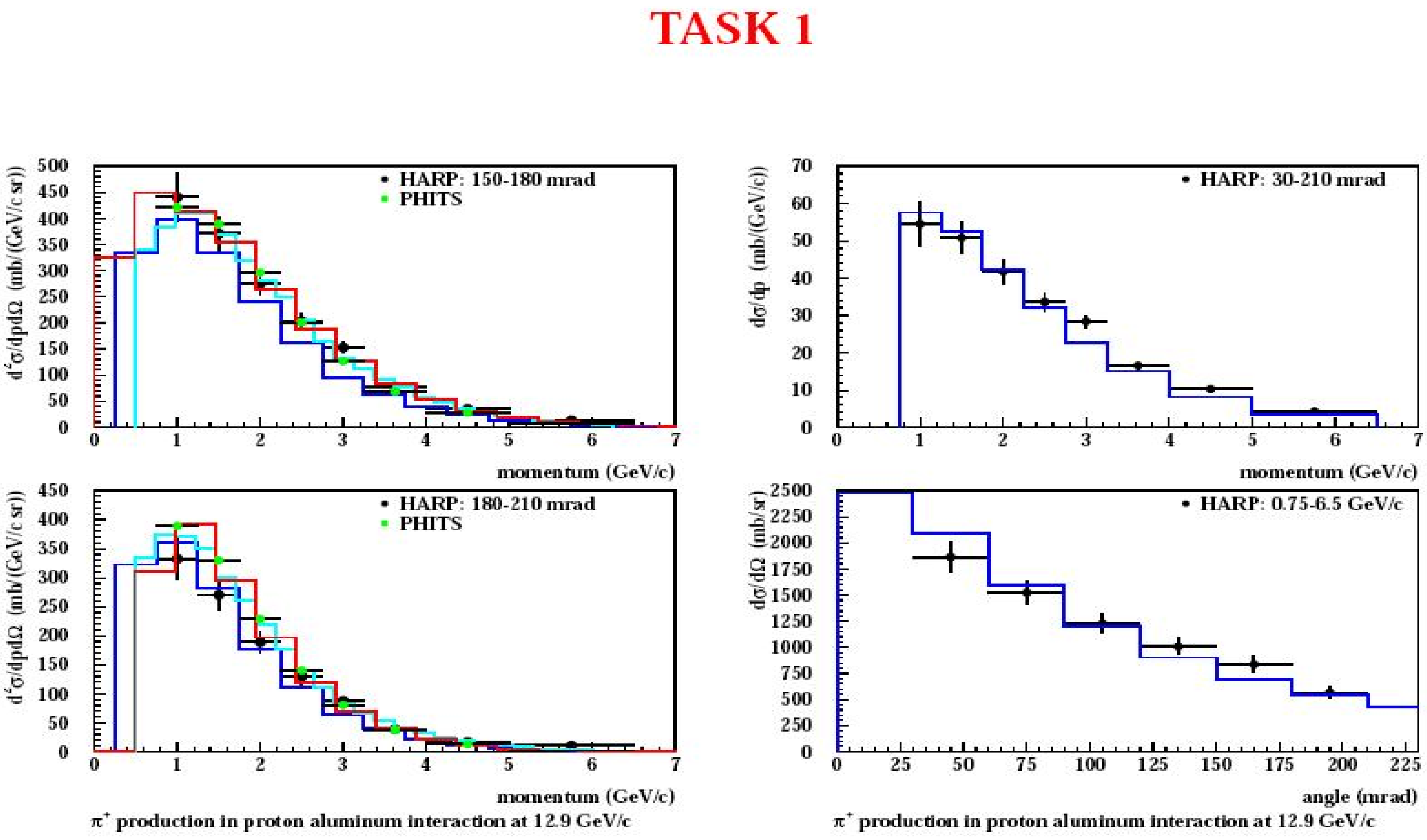
- 7 validation tests
  - covered wide energy range
  - head-to-head comparison of (5-6) simulation codes for each test
  - data sets agreed upon beforehand
  - voluntary participation
- Due to short time scale, not all tasks could be completed
- Agreed to make this a regular exercise

Task 1: 12.9 GeV/c p on Al



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

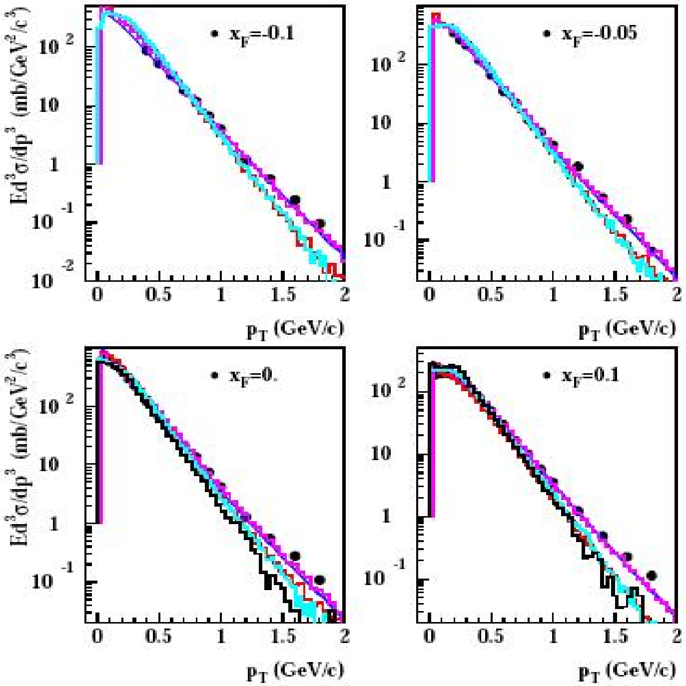
Task 1: 12.9 GeV/c p on Al

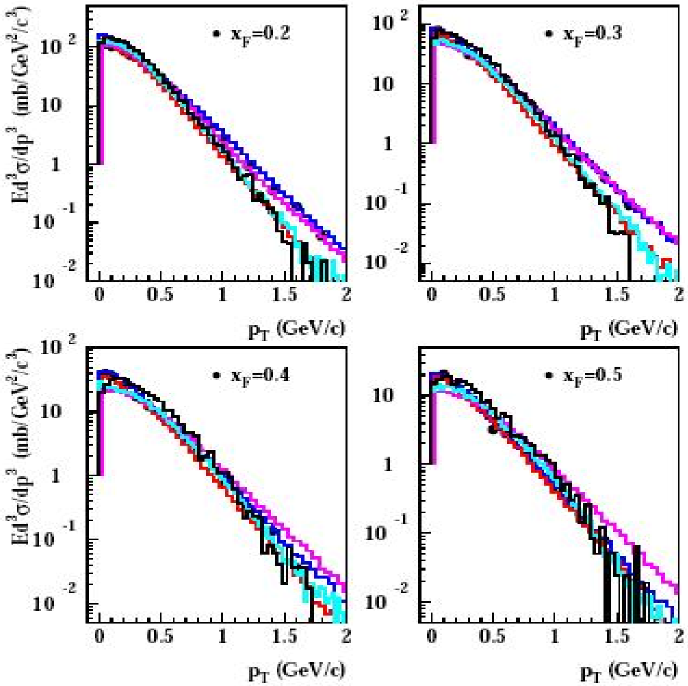


Black symbols - HARP data, green symbols - PHITS, red line - LAQGSM, cyan line - FLUKA, blue line - MARS

Task2a: π^+ from 158 GeV/c p on C

TASK 2A

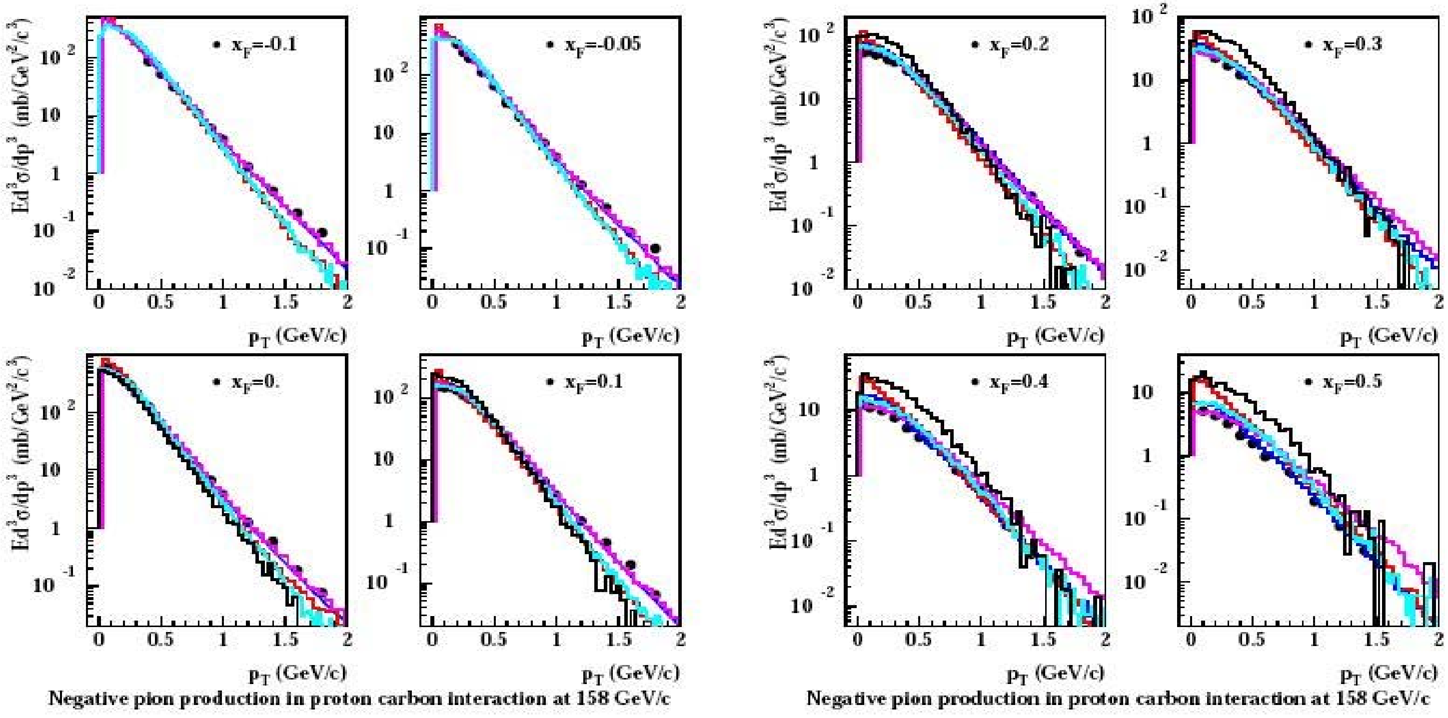

Positive pion production in proton carbon interaction at 158 GeV/c


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

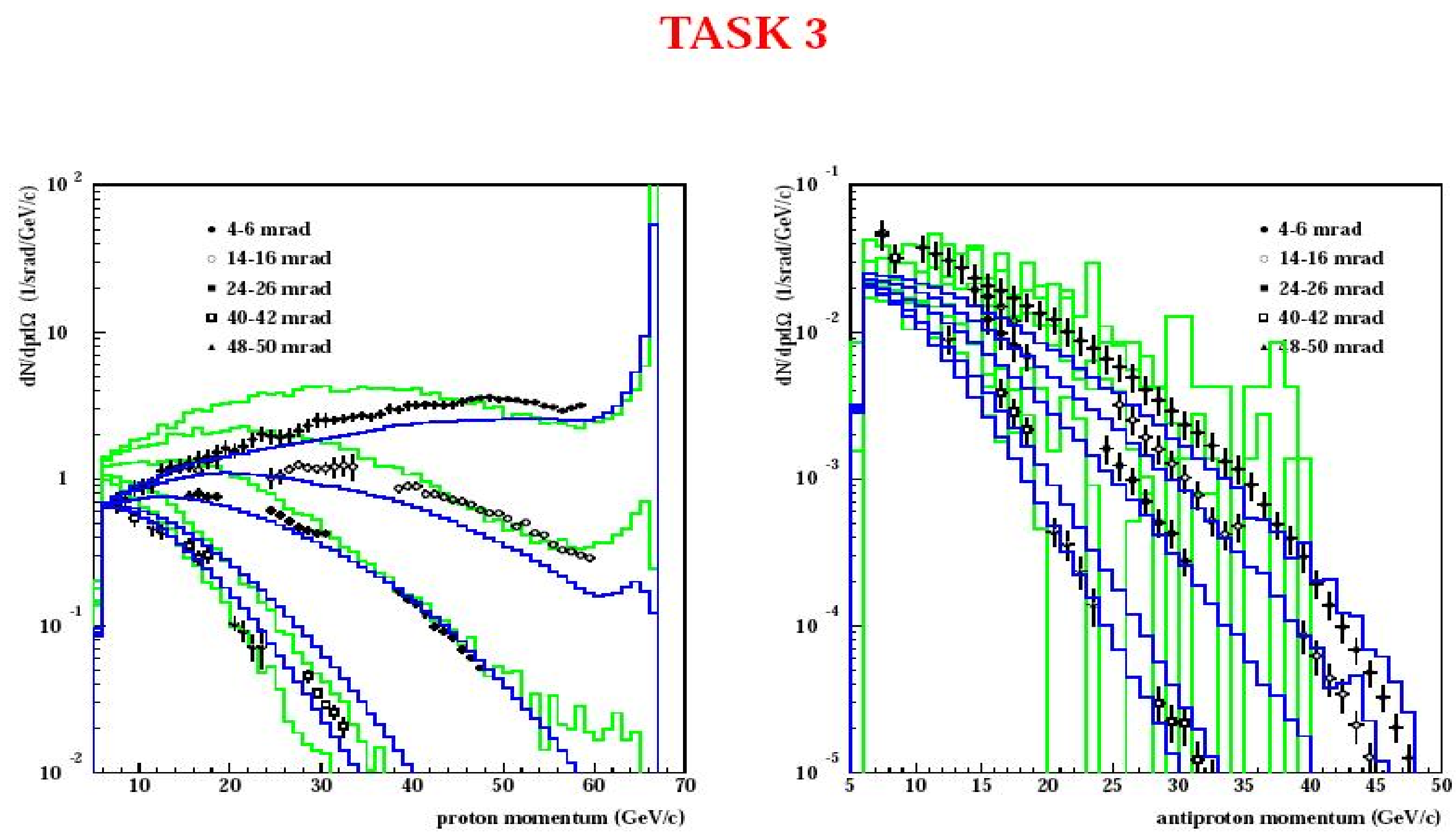
Task2a: π^- from 158 GeV/c p on C

TASK 2A



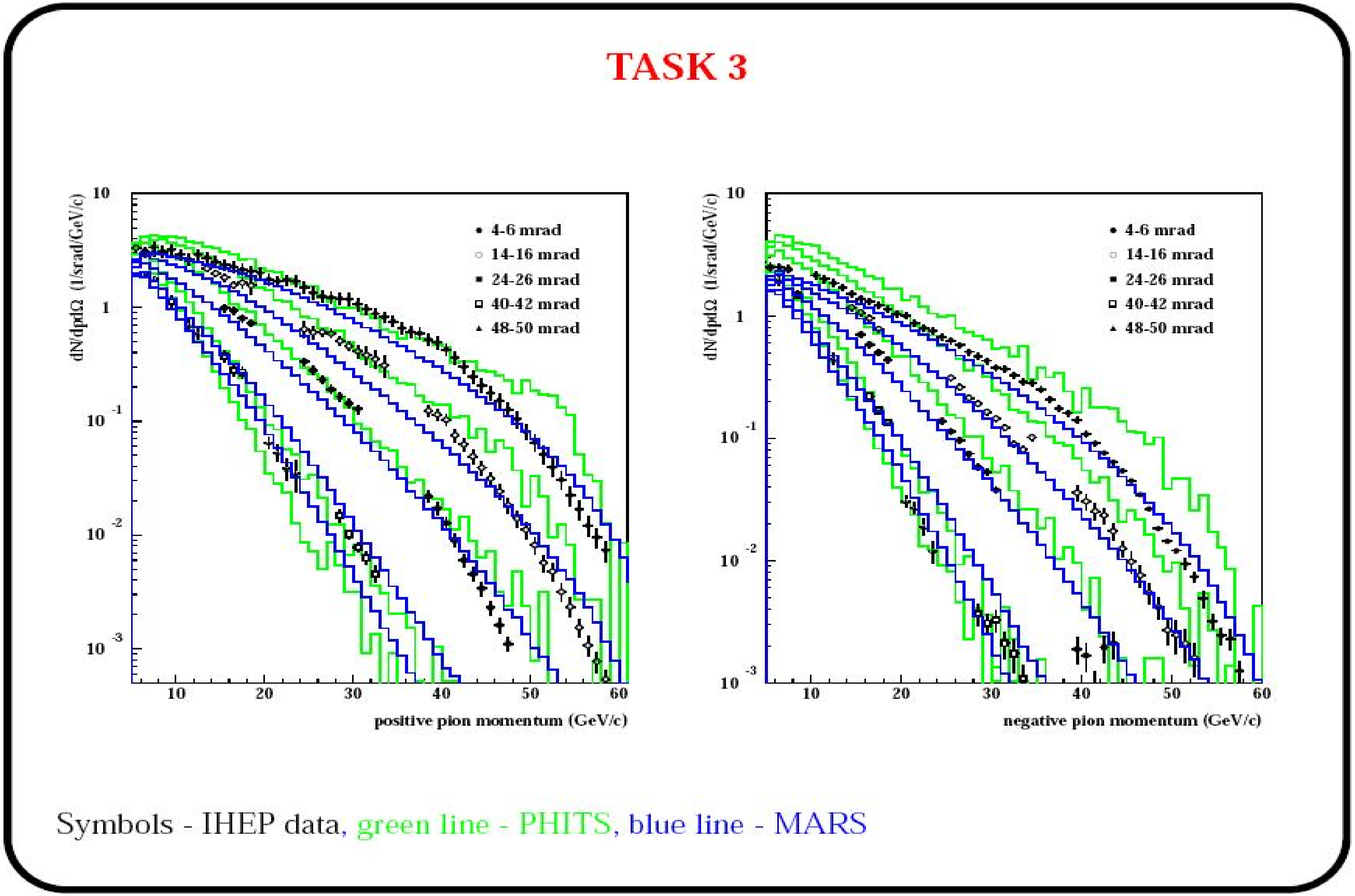
Black symbols - NA49 data, red line - LAQGSM, blue line - MARS, black line - G4, magenta line -DPMJET

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

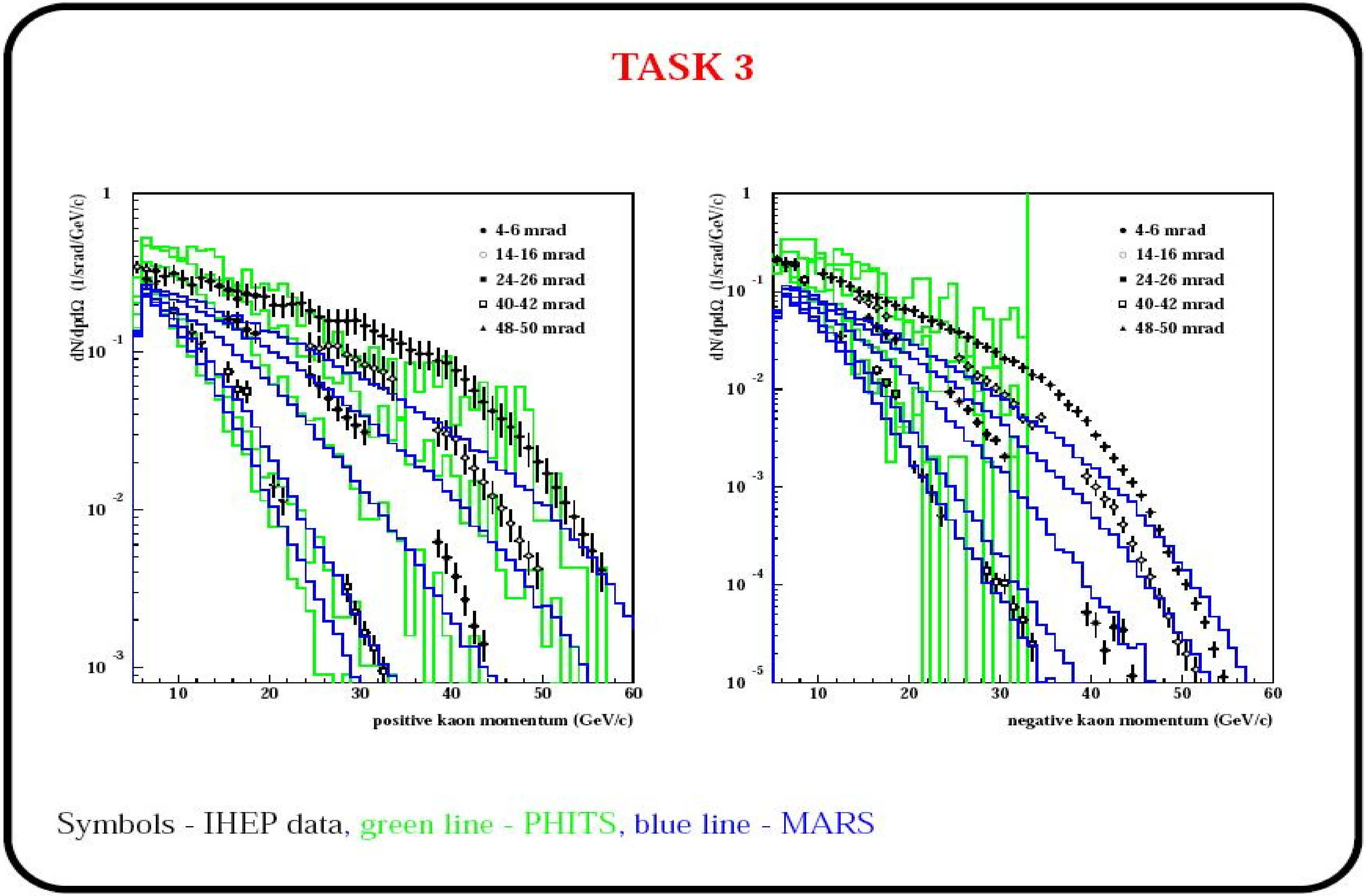


Symbols - IHEP data, green line - PHITS, blue line - MARS

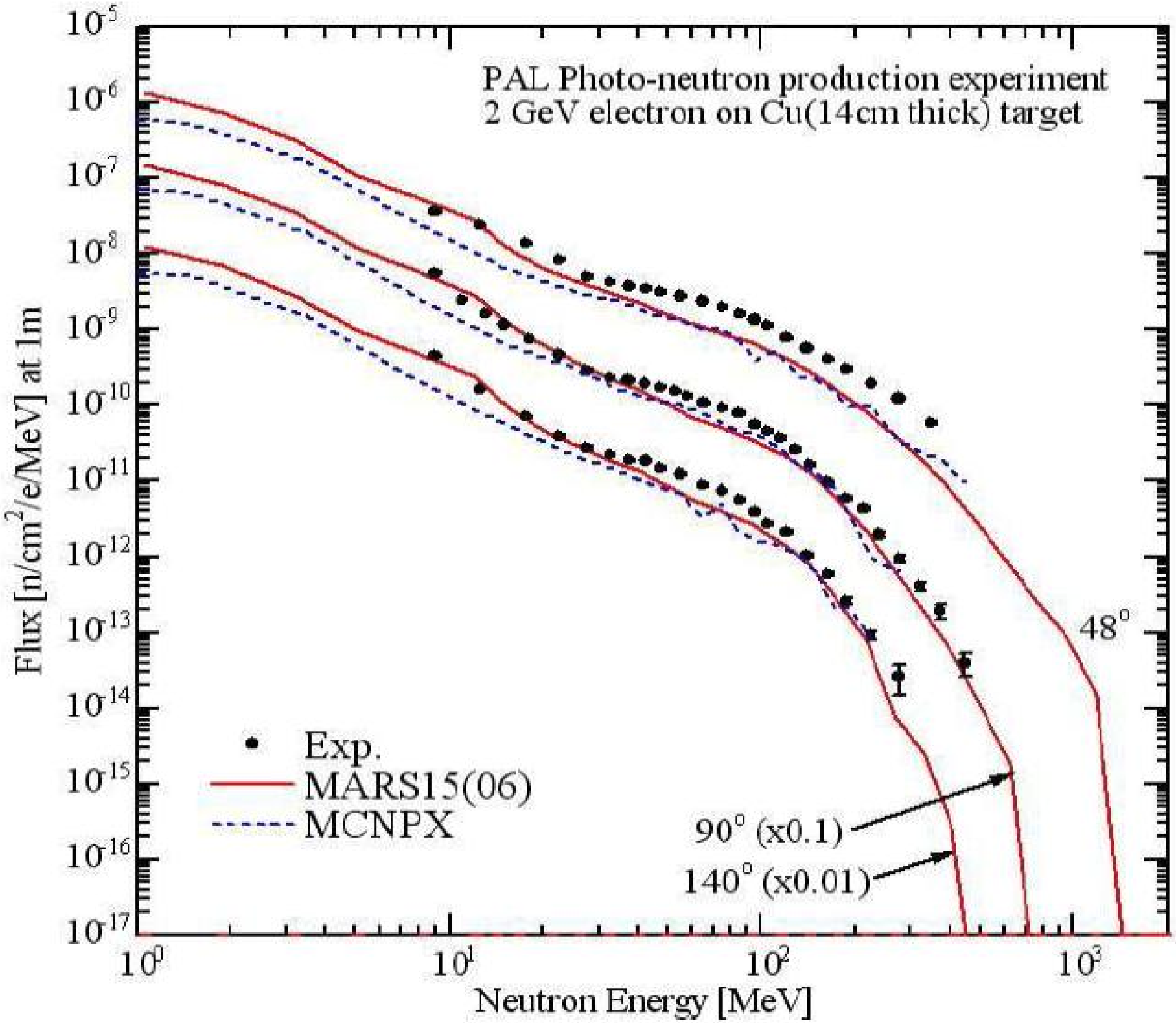
Task 3: π^+, π^- from 67 GeV/c p on Al



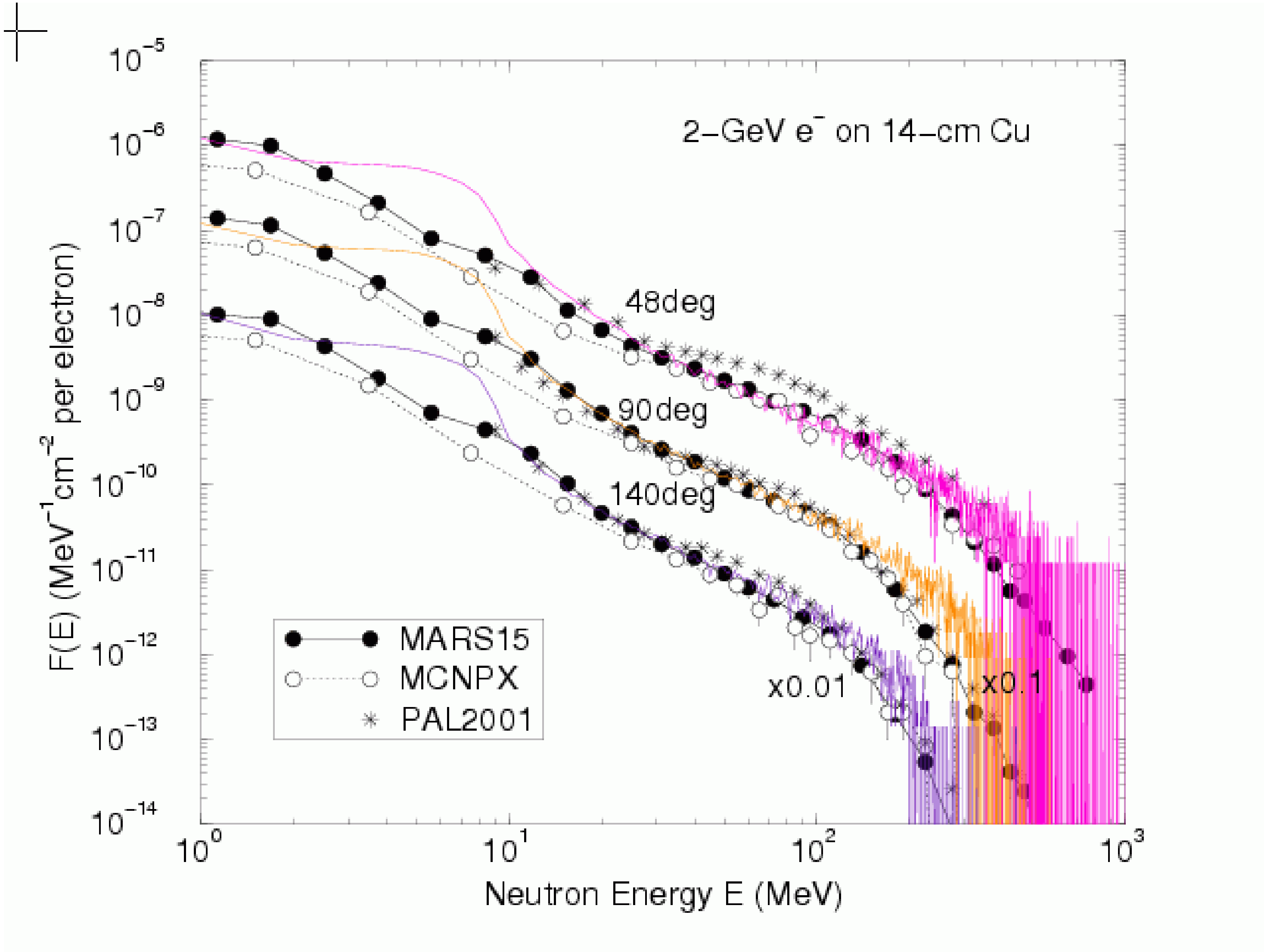
Task 3: K^+, K^- from 67 GeV/c p on Al



Task 4: 2 GeV e on Cu (PAL)



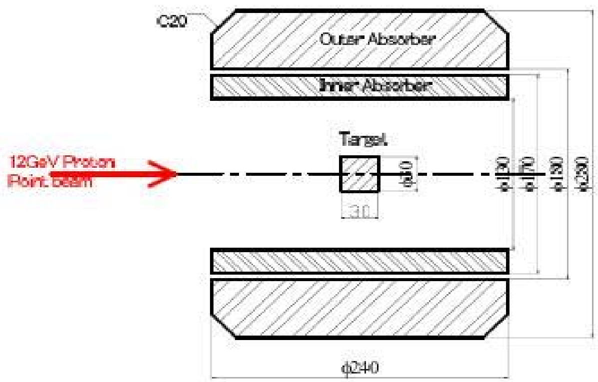
Task4: PAL with Geant4 prediction

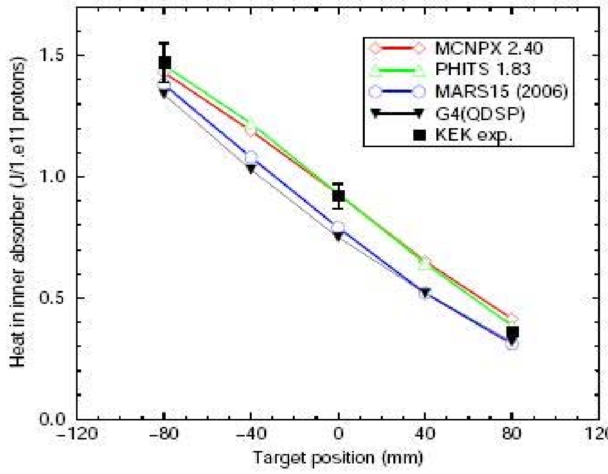


Task 5: Total Energy in a Cu Absorber

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。

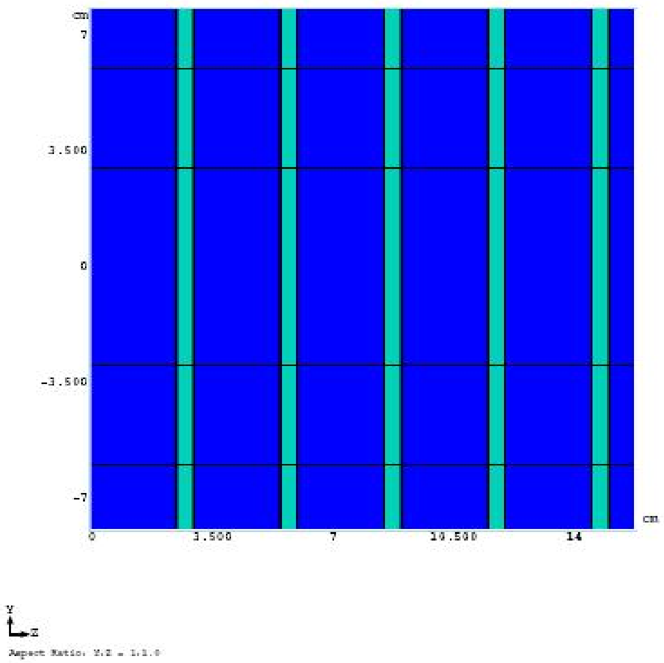
63Cu -6.19 $69.1 % density of 63Cu in natural copper

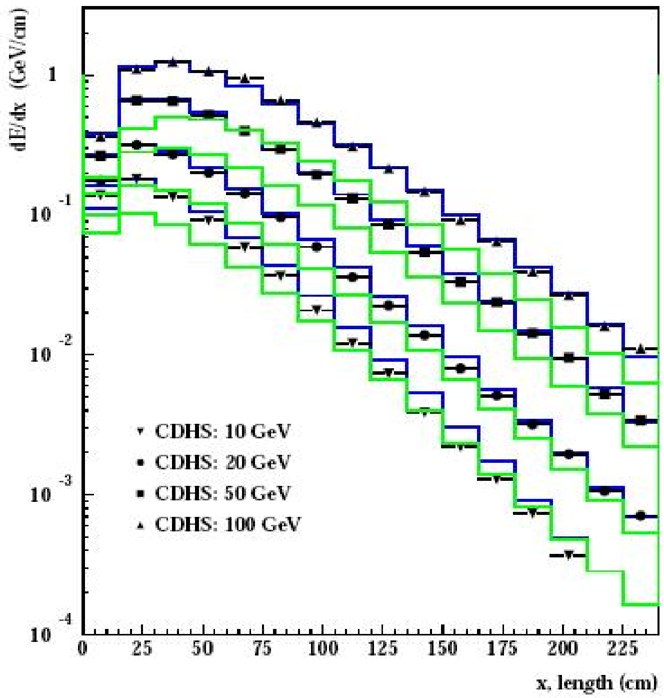
65Cu -2.77 $30.9 % density of 65Cu in natural copper

入熱分布を計算する。

Task6: π^- in Fe-Scint Calorimeter

TASK 6

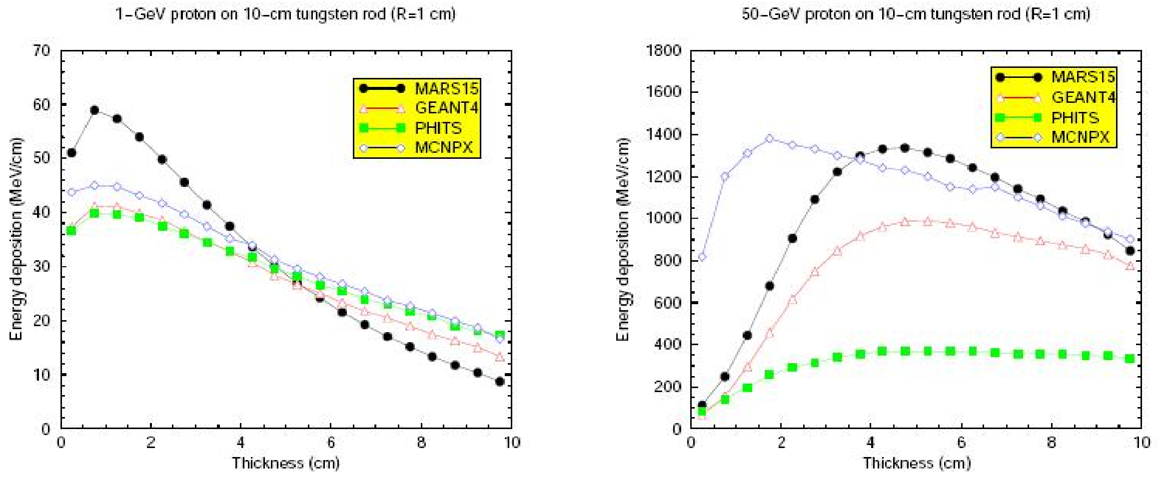




Black symbols - CDHS data, green line - PHITS, blue line - MARS

Task 7: Energy Deposited in W Rod

TASK 7



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

(2) MARS15 results from an unofficial developer version.

The crucial elements of hadronic shower simulations (2)

The electromagnetic shower component

Characteristics affecting calorimeter performance in crucial ways

Let f_{em} (= E_{em}/E_{tot}) be the *em shower fraction*

Characteristic	*Consequence for calorimetry*
• $<f_{em}>$ increases with energy	Hadronic signal non-linearity
• Fluctuations in f_{em} non-Poissonian	Non-Gaussian response function Deviations from $E^{-1/2}$ scaling
• Differences between *p* and π	Differences in response Differences in response function
• Em component distributed over entire shower development	No "characteristic" profiles

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 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.

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 special role of neutrons in calorimetry

In calorimeters with hydrogenous active material, neutrons lose a major fraction of their kinetic energy through elastic *n-p* scattering in that material.

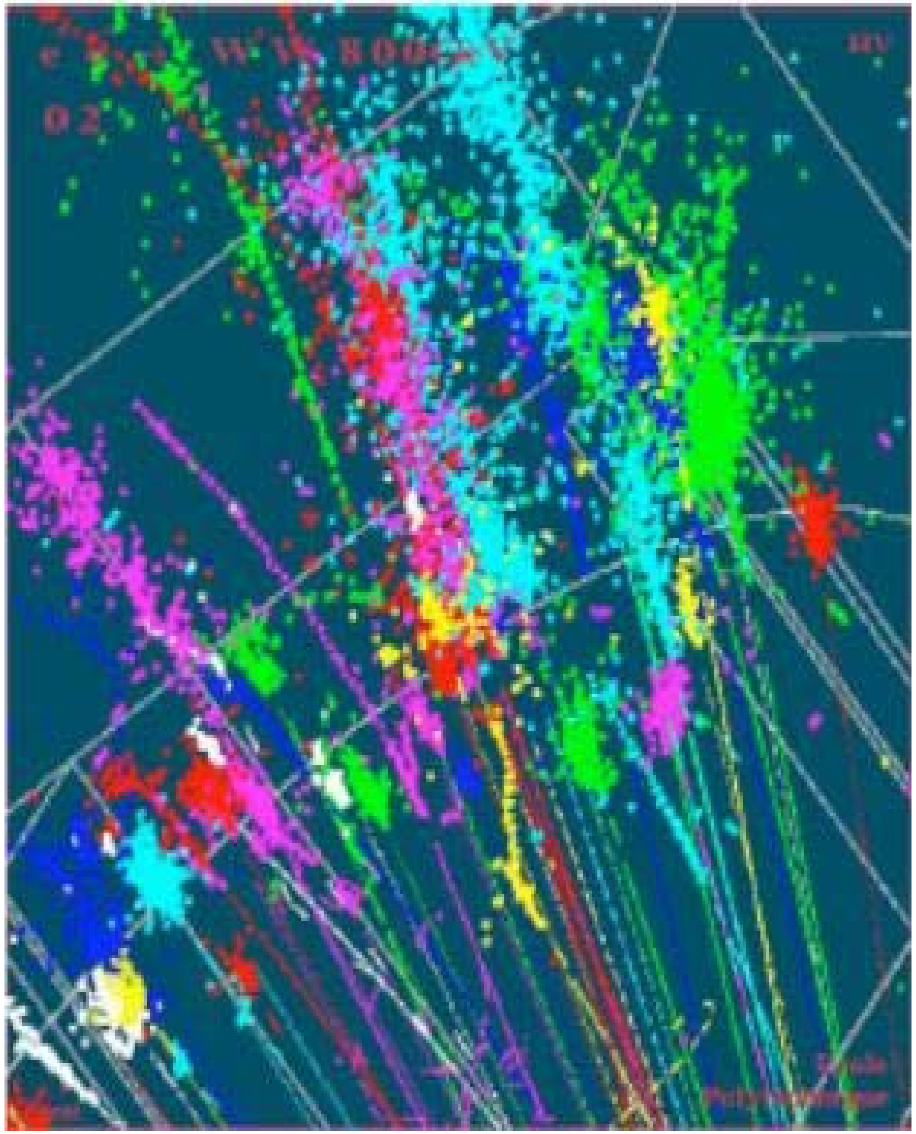
The recoil protons may contribute to the signals.

Therefore, the *neutron component may be very efficiently sampled* in such calorimeters. The sampling fraction may be much larger than for the other shower particles .
This is the key element of *compensation.*

- 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)

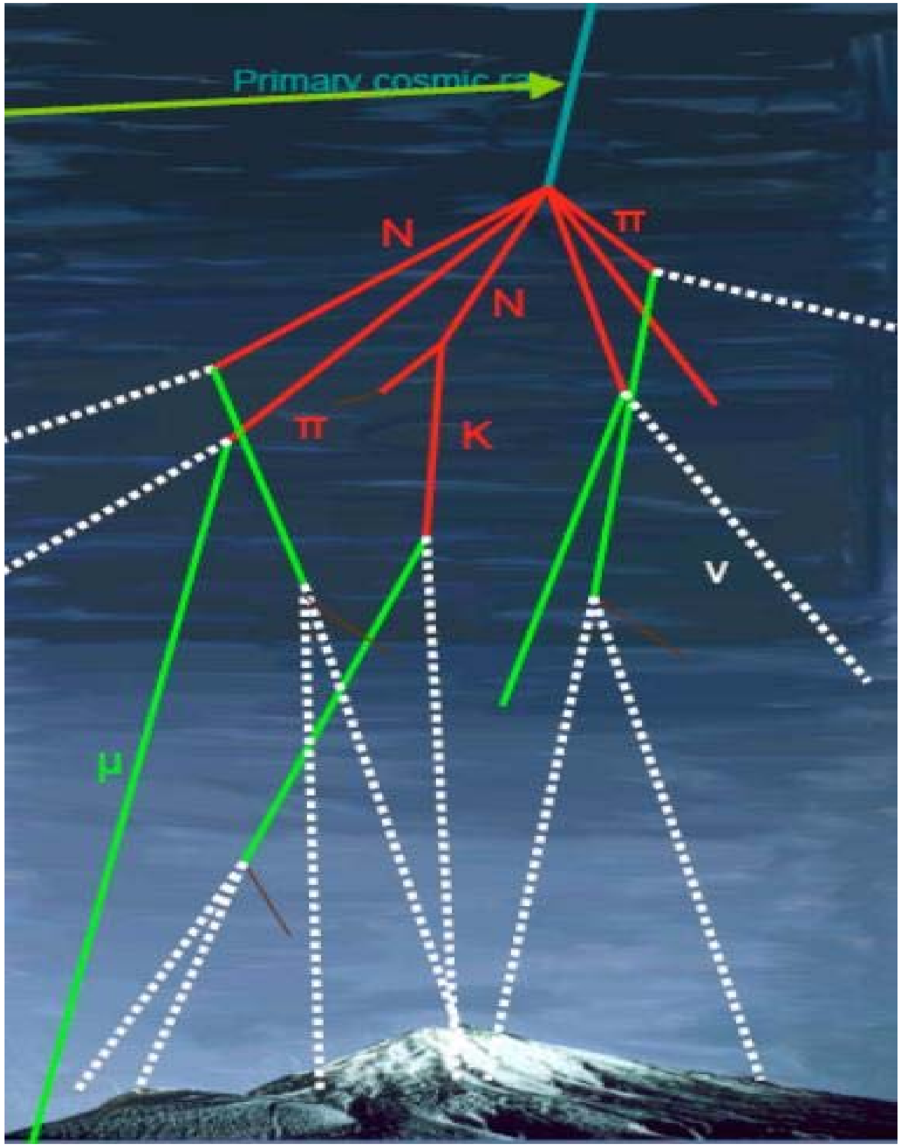
ILC Calorimetry

- 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
  - energy-flow calorimetry depends on good energy and baryon conservation



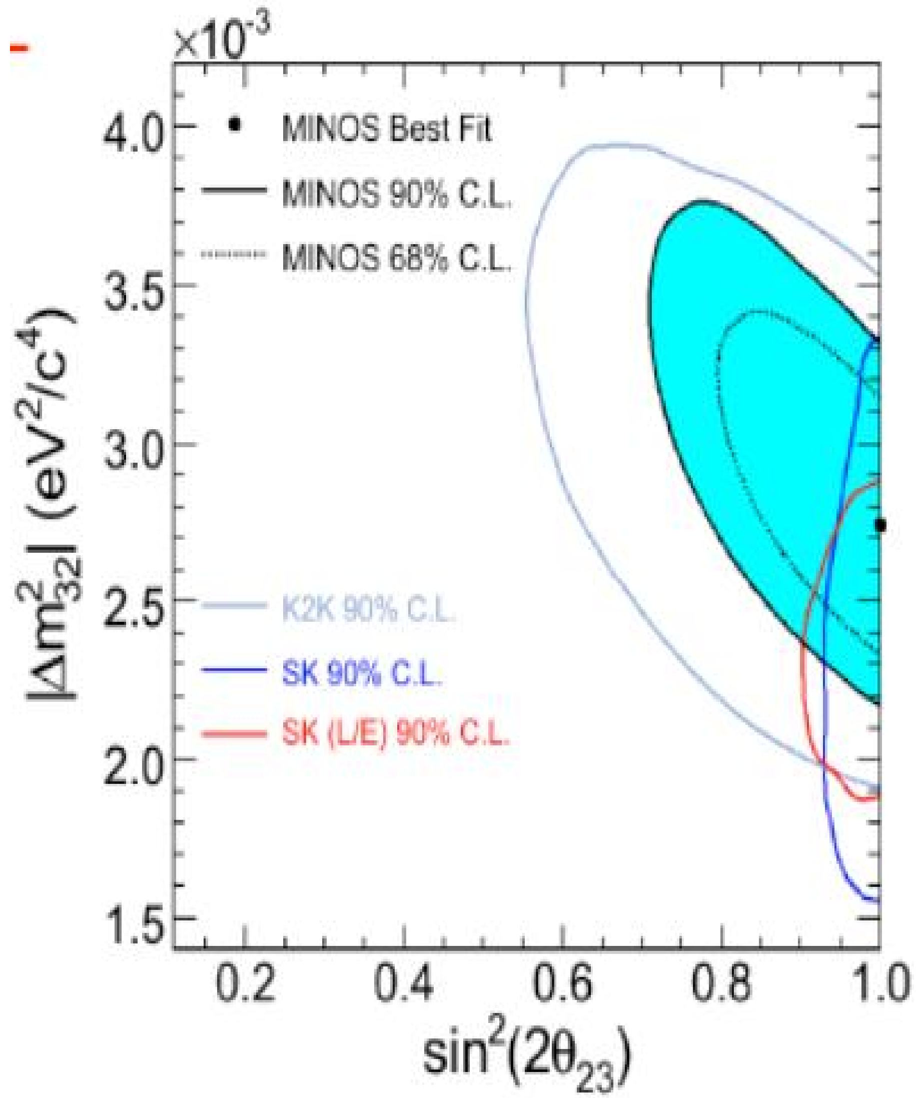
Air Shower Studies

- Infer A, E of primary from muon component near or on the ground
- A-A collision -> N, π
  - $\pi \rightarrow \mu\, \nu$
- very sensitive to hadronic interactions
  - largest uncertainty in neutrino flux calculations
  - nucleus-nucleus models very important



Neutrino Oscillations

- Neutrino beam flux calculations are a large uncertainty
  - Minos: 70% of systematic error is associated with uncertainties in hadronic interactions
- Two main reasons:
  - charged pion production
  - particle transport in thick production targets



Conclusions

- For LHC test beams Geant4 does reasonably well
  - some problems remain
  - not a good test of detailed models
- Grand validation: most hadronic codes do not compare well with data
  - and they often don't agree with each other
  - we've got a long way to go
- Contrary to popular opinion, details of low energy particle modeling are important to calorimetry
  - π^0 production, protons at ~100 MeV, neutron production and transport
- Hadronic shower simulations are even more important for:
  - ILC calorimeters, neutrino beams, cosmic rays