



# Hadronic Shower Code Inter-Comparison and Verification<sup>1</sup>

N.V. Mokhov<sup>2</sup> and S.I. Striganov<sup>3</sup>

*Fermilab, Batavia, IL 60510, U.S.A.*

**Abstract.** To evaluate the quality of general purpose particle interaction and transport codes widely used in the high-energy physics community, express benchmarking is conducted. Seven tasks, important for high-energy physics applications, are chosen. For this first shot, they are limited to particle production on thin and thick targets and energy deposition in targets and calorimetric setups. Five code groups were asked to perform calculations in the identical conditions and provide results to the authors of this report. Summary of the code inter-comparison and verification against available experimental data is presented in this paper. Agreement is quite reasonable in many cases, but quite serious problems were revealed in the others.

**Keywords:** Hadrons, cascades, simulation, particle production, energy deposition

**PACS:** 13.85.-t, 24.10.Lx

## INTRODUCTION

Predictive power and reliability of hadron-nucleus event generators and general purpose particle interaction and transport codes are of a great importance in numerous detector, accelerator, shielding and cosmic ray applications. All code development groups do perform their code verifications and usually well document them. At the same time, several instances were discussed in the community over last few years, with a puzzling disagreement between simulations performed by the code users and data, and between different versions of the same code. Therefore, it was decided to conduct an express code benchmarking, limiting it for this first shot by the energy range and two values important primarily for neutrino experiments and calorimetry as well as for accelerator and shielding applications: particle production on thin and thick targets and energy deposition in targets and calorimetric setups.

Certainly, we realized that there are many other cases to consider. Some members of the Workshop Organizing Committee have proposed several important calorimetric tasks. Many things – such as neutronics, shielding, low energies, nuclide production, etc. – were intentionally left aside as not directly related to the workshop and rather time-consuming to be performed by the meeting. We have limited the list to the tasks which can easily be simulated by the code teams on a very short notice.

---

<sup>1</sup> Presented paper at the Hadronic Shower Simulation Workshop, September 6-8, 2006, Fermilab.

<sup>2</sup> Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

<sup>3</sup> On behalf of Benchmarking Working Group: M. Baznat, P. Folger, K. Gudima, H.-S. Lee, N. Matsuda, N. Mokhov, N. Nakao, K. Niita, P. Sala, T. Sanami, S. Striganov, L. Waters, D. Wright.

## TASKS FOR INTER-COMPARISON

Seven tasks were chosen to cover the workshop primary goals and be simple in modeling by all the codes involved, reliable and well documented on the experimental side. Five codes used worldwide in the above applications and discussed in detail at this workshop are involved in this analysis: FLUKA [1], GEANT4 [2], MARS [3], MCNPX [4], and PHITS [5]. In addition, two stand-alone event generators – LAQGSM03 [6] and DPMJET-III [7] – were involved in benchmarking for a particle production on thin targets. The principal developers of the codes were asked to submit results of their simulations to the authors of the report. This assured one that the latest versions of the codes were used and that the calculations are performed in the most “optimal” way.

The following tasks were proposed to be calculated by each of the code group:

1. HARP experiment (2006). 12.9 GeV/c  $p + Al \rightarrow \pi^+ + X$ : 1D and 2D inclusive production cross-sections.
2. NA49 experiment (2006). 158 GeV/c  $p + A \rightarrow \pi^+, \pi^- + X$ : 1D and 2D inclusive production cross-sections, for (a) proton and (b) carbon targets.
3. IHEP experiment (1980). 67 GeV/c protons on a thick aluminum target: double differential yields for  $p, \bar{p}, \pi^+, \pi^-, K^+, K^-$ .
4. PAL experiment (2004). Neutron spectra at several angles from a thick target irradiated by a 2-GeV electron beam.
5. KEK experiment (2004). 12 GeV protons on a thick target: energy deposition distribution in a surrounding cylindrical absorber.
6. CDHS-measured longitudinal profiles of hadronic showers for 10, 20, 50 and 100 GeV pion beams on an iron-scintillator calorimeter: longitudinal and lateral energy deposition profiles.
7. Energy deposition longitudinal profiles in a 10-cm thick tungsten target for proton beam energies of 1, 20 and 50 GeV.

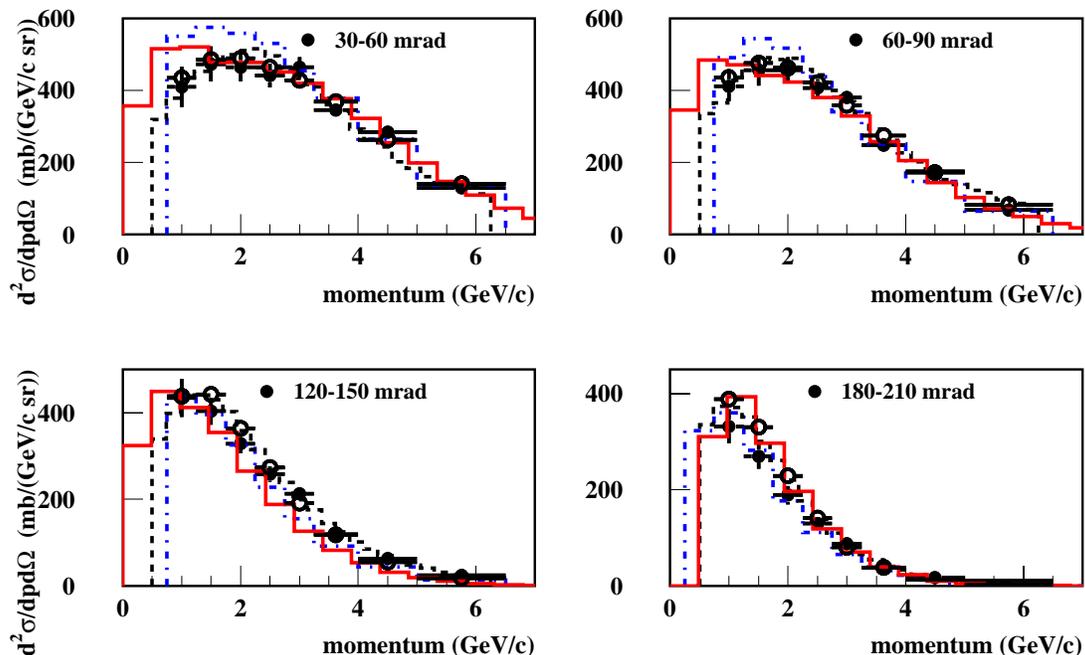
Five groups sent their results to S. Striganov at Fermilab by the beginning of the Workshop. Table 1 lists the codes and the contributor names. The QGSP physics list was used in GEANT4. MCNPX-2.40 was used for Tasks 4 and 5, while the newest version MCNPX-2.6b03 was used for Task 7. Stand-alone event generator results were additionally provided for Task 1 (LAQGSM03, K. Gudima) and Task 2 (LAQGSM03, K. Gudima and DPMJET-III, M. Baznat).

**TABLE 1.** Summary of main contributors.

Task	FLUKA-2005	GEANT4-8.1	MARS15	MCNPX	PHITS-2.13
1	P. Sala	-	S. Striganov	-	N. Matsuda
2	P. Sala	P. Folger	S. Striganov	-	N. Matsuda
3	-	D. Wright	S. Striganov	-	N. Matsuda
4	-	-	T. Sanami	T. Sanami	-
5	-	D. Wright	N. Mokhov	N. Matsuda	N. Matsuda
6	-	-	N. Nakao	-	N. Matsuda
7	P. Sala	D. Wright	N. Mokhov	L. Waters	N. Matsuda

## TASK 1

Recently, the HARP collaboration has published new data on double differential cross sections of a positive pion production in proton-aluminum interactions at 12.9 GeV/c [8]. A comparison of FLUKA-2005, LAQGSM03, MARS15 and PHITS results with the HARP data is presented in Fig. 1. The codes agree with the data at  $p > 2$  GeV/c, while at lower momenta and small angles, LAQGSM and MARS tend to overestimate experiment by up to 15%.



**FIGURE 1.** Comparison of HARP data (filled circles) with simulations: PHITS - opaque circles, LAQGSM - solid, FLUKA - dashed, MARS - dot-dashed lines.

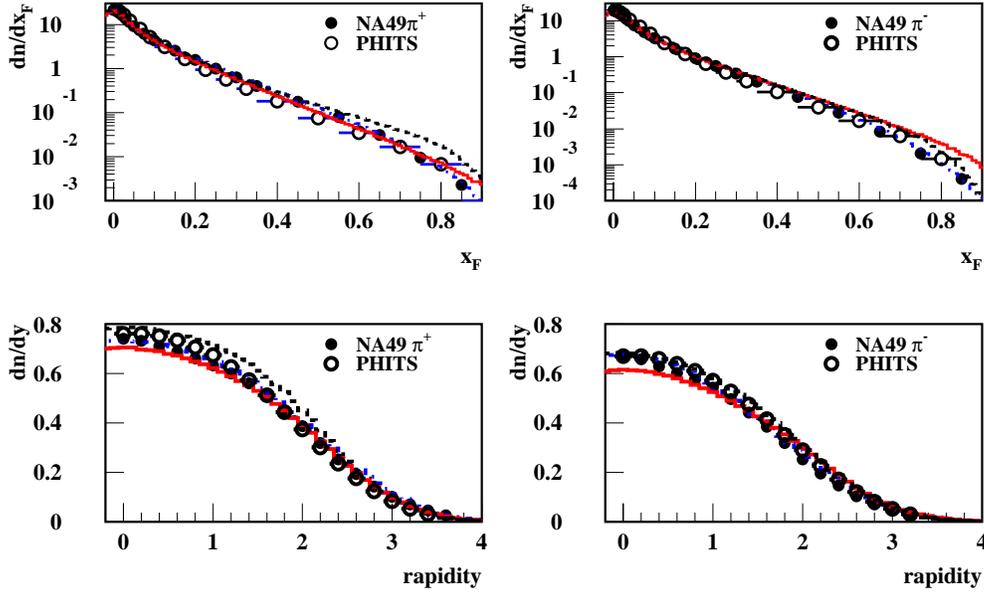
## TASK 2

The NA49 collaboration has measured transverse momentum distributions at fixed Feynman  $x_F$  values as well as integrated  $x_F$  and rapidity distributions for charged pion production in proton-proton and proton-carbon collisions at 158 GeV/c [9, 10].

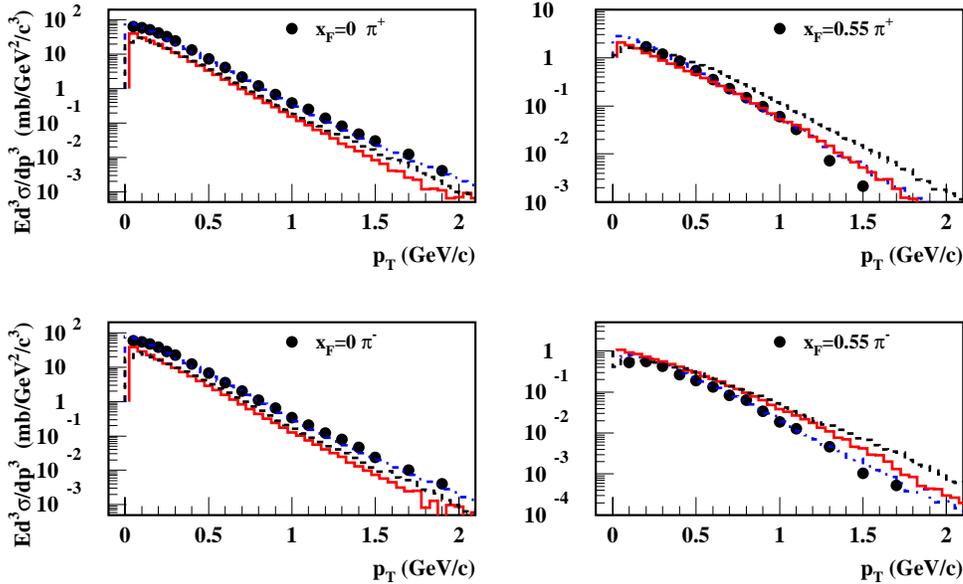
### Proton target

Results for comparison with data [9] are available from the DPMJET-III, LAQGSM03, MARS15, and PHITS groups. Integrated rapidity distributions are compared in Fig. 2. MARS and PHITS agree very well with measurements, DPMJET overestimates high-momentum and mid-rapidity positive pion yields, LAQGSM somewhat overestimates fast and underestimates central negative pion yields. The invariant

cross sections as a function of transverse momentum at two  $x_F$  are presented in Fig. 3 together with the three code results. A comparison of simulations with data for the other six  $x_F$  values can be found in Ref. [11]. MARS results agree quite well with data while both LAQGSM and DPMJET underestimate central pion production and overestimate it at high transverse momenta.



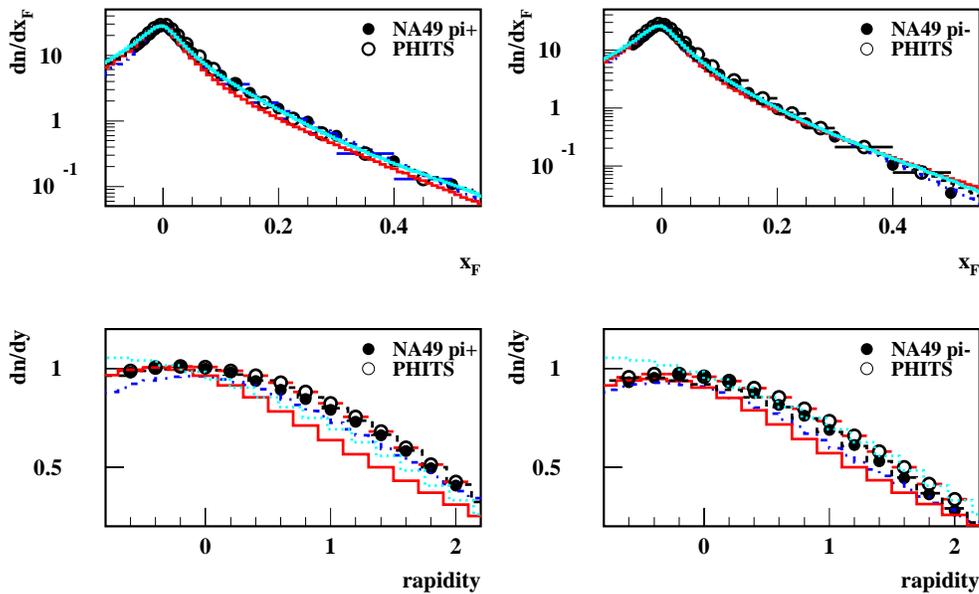
**FIGURE 2.** Comparison of NA49 pp-data (filled circles) with simulations: PHITS - open circles, LAQGSM - solid, DPMJET - dashed, MARS - dot-dashed lines.



**FIGURE 3.** Comparison of NA49 pp-data (filled circles) with simulations: LAQGSM - solid, DPMJET - dashed, MARS - dot-dashed lines.

## Carbon target

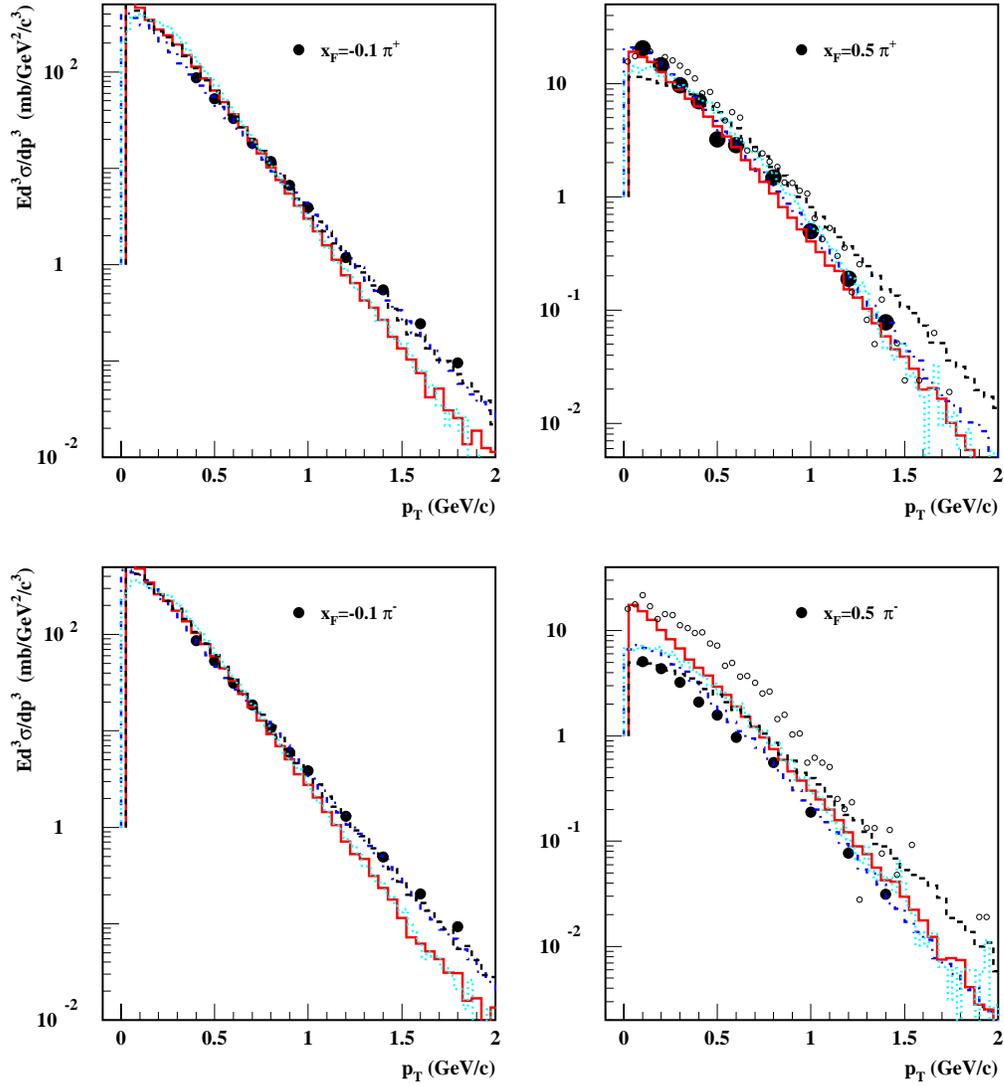
Figs. 4-5 show comparisons of results from six codes with data [10] for charged pion production in proton-carbon collisions. All the codes agree quite well with data for  $x_F$  distributions (there are no measurements at  $x_F > 0.5$  for carbon target where DPMJET and LAQGSM overestimate data for a proton target). The codes reproduce well measured rapidity distributions except for LAQGSM at mid-rapidities. Transverse momentum distributions in central ( $x_F = -0.1$ ) and fragmentation ( $x_F = 0.5$ ) regions are compared in Fig. 5. Additional comparisons for intermediate values of  $x_F$  can be found in [11]. MARS and FLUKA are very close to the data. LAQGSM and DMPJET underestimate high- $p_{\perp}$  central pion production. LAQGSM overestimates a negative pion yield at low- $p_{\perp}$  for  $x_F = 0.5$ . GEANT4 agrees well with data for positive pions but overestimates a negative pion yield in the fragmentation region.



**FIGURE 4.** Comparison of NA49 pC-data (filled circles) with simulations: PHITS - open circles, LAQGSM - solid, DPMJET - dashed, MARS - dot-dashed, FLUKA - dotted histograms.

## TASK 3

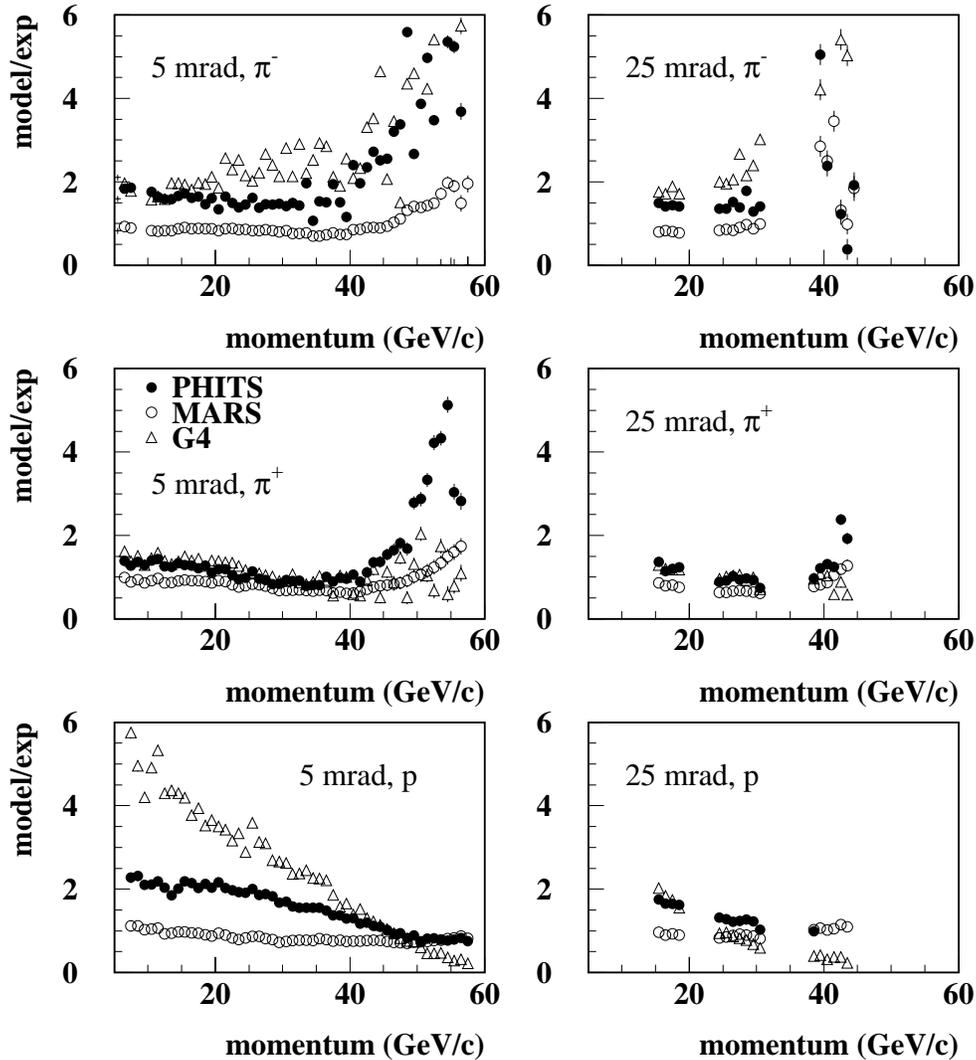
Double-differential cross sections of charged pions and kaons, protons and antiprotons in 67 GeV/c proton interactions with  $Al$  and  $Al_2O_3$  thick targets were measured for neutrino experiments at IHEP [12]. Ratios of calculated results for particle yields from an aluminum target ( $L=60$  cm,  $R=3$  cm) to the data are presented in Fig. 6 for  $p$ ,  $\pi^+$ ,  $\pi^-$  and two angles of 5 and 25 mrad. Results for other particles and angles can be found in Ref. [11]. MARS15 agrees with data within a factor of two. The disagreement of both GEANT4 and PHITS results with data is quite substantial except for positive pions at 5 mrad.



**FIGURE 5.** Comparison of NA49 pC-data (filled circles) with simulations: G4 - open symbols, LAQGSM - solid, DPMJET - dashed, MARS - dot-dashed, FLUKA - dotted histograms.

## TASK 4

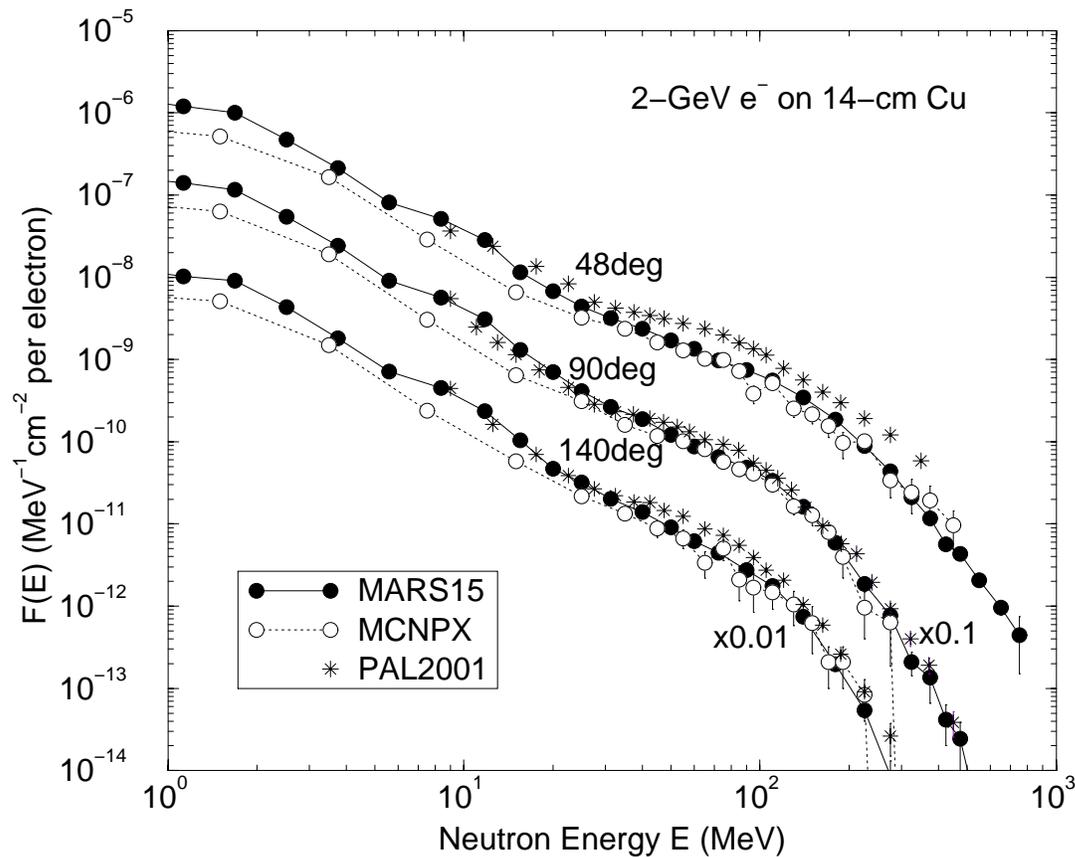
Double-differential neutron yields from thick targets irradiated by a 2-GeV electron beam were measured in the PAL experiment [13]. The copper target was 14-cm long with a radius of 2.5 cm. MARS15 and MCNPX-calculated results are presented in Fig. 7 together with this data. MARS results nicely agree with data at  $9 \leq E \leq 40$  MeV for all angles, and underestimate the data at higher energies by up to a factor of two. MCNPX results practically coincide with the MARS's ones at  $E > 25$  MeV but are lower by about a factor of two at  $E < 15$  MeV.



**FIGURE 6.** Ratio of calculated and measured cross sections of particle production in proton collisions with a thick aluminum target at 67 GeV/c.

## TASK 5

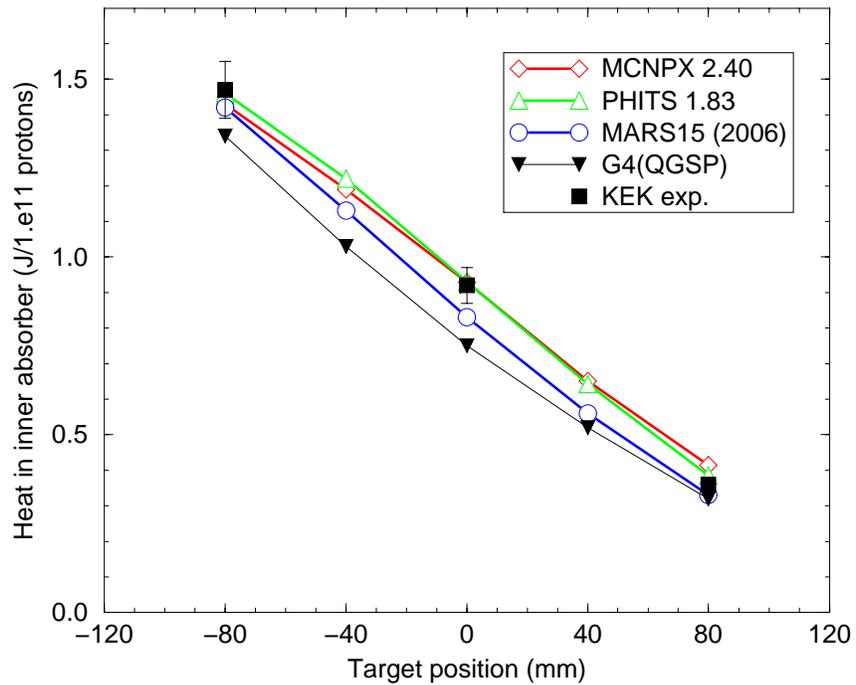
Energy deposition in a cylindrical copper absorber ( $L=24$  cm,  $R_{in}=6.5$  cm,  $R_{out}=8.5$  cm) around a copper target ( $L=3$  cm,  $R=1.5$  cm) irradiated by a 12-GeV proton beam was measured at KEK [14]. Experimental data versus the target longitudinal position with respect to the absorber center are shown in Fig. 8 along with four sets of calculation results. GEANT4 predictions here are almost identical for different physics lists, therefore only QGSP simulations are shown. MARS15, MCNPX and PHITS are very close to the measurements, except for the middle point where MARS15 underestimates data by 5%. GEANT4 underestimates data by about 10% for two points but it is closer to data than MCNPX and PHITS for the last point.



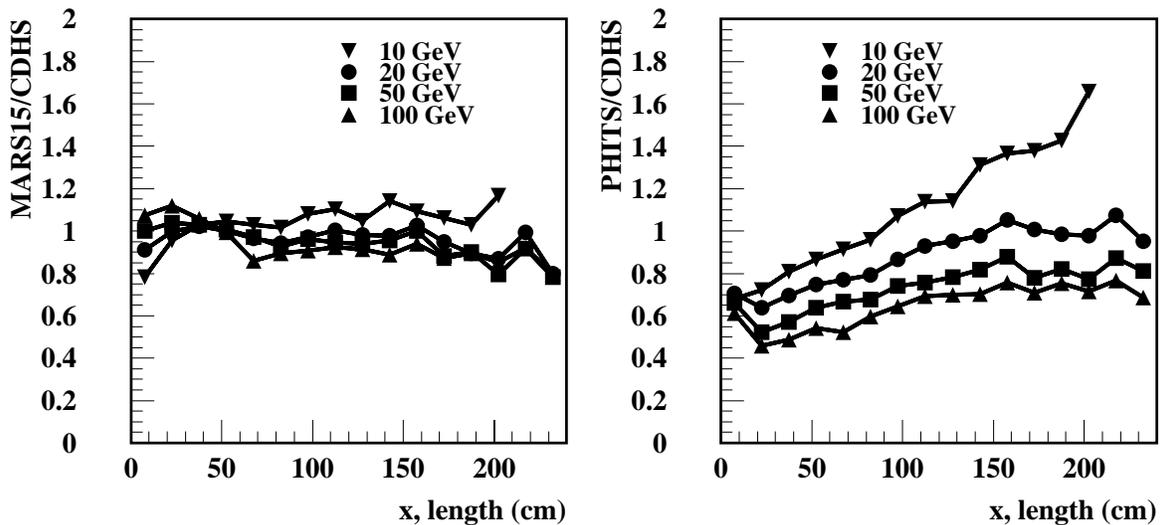
**FIGURE 7.** Neutron spectra calculated with MARS15 and MCNPX at three angles for a 2-GeV electrons on a thick copper target vs data [13].

## TASK 6

The CERN-Dortmund-Heidelberg-Saclay-Warsaw (CDHS) collaboration measured longitudinal profiles of hadronic showers in iron-scintillator calorimeters for 10 to 100 GeV pion beams at the CERN SPS [15]. The ratios of lateral integrated energy deposition calculated with MARS15 and PHITS to this data are presented in Fig. 9. MARS15 results agree with the experiment within about 15%. PHITS does not transport photons with energy  $E > 1$  GeV just ignoring them [16]. This explains a growing with a primary energy underestimation by PHITS. Note that the 10-GeV PHITS's results behave quite differently compared to other energies.



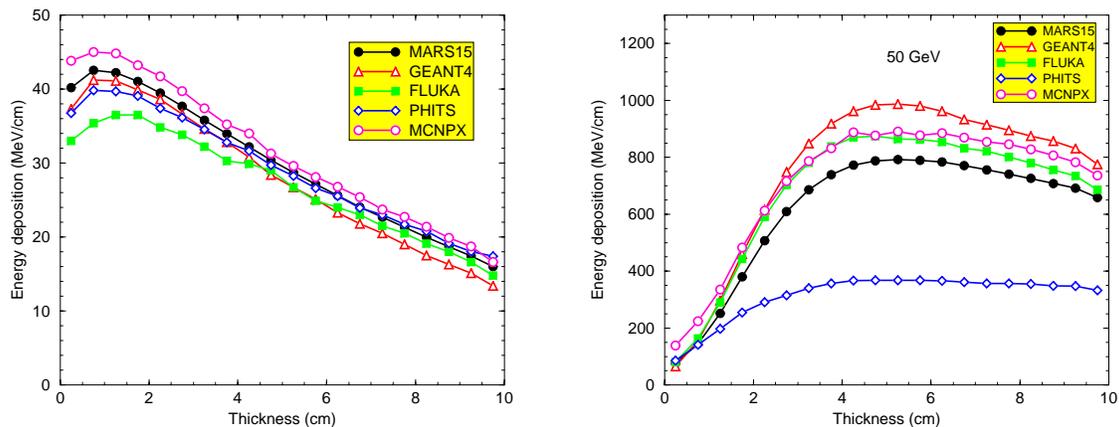
**FIGURE 8.** Energy deposition in a cylindrical absorber surrounding a copper target irradiated by a 12-GeV proton beam.



**FIGURE 9.** Ratio of calculated with MARS15 and PHITS to measured by CDHS laterally integrated energy deposition in the iron-scintillator calorimeter for four energies of a pion beam.

## TASK 7

Longitudinal profiles of energy deposition in a cylindrical tungsten target ( $L=10$  cm,  $R=1$  cm) irradiated by pencil proton beams of 1, 20 and 50 GeV were calculated by all the participated code groups. Fig. 10 shows results of this inter-comparison for proton energies of 1 and 50 GeV. The 20-GeV results are very similar in shape to the 50-GeV case and therefore are not shown here. Before the workshop, MCNPX version 2.6b03 was used in the mode where electrons are not tracked; their energies are deposited locally when created, which results in a pileup near the front of the shower, but greatly decreased tracking times. Corresponding energy deposition results at 20 and 50 GeV for this task were substantially off compared to the other codes. Therefore, MCNPX was recently re-run for 50 GeV in a mode where all particles are fully tracked. As one can see from Fig. 10, all the codes predict rather similar (within 10%) energy deposition for the 1-GeV protons, with some pileup at the beginning for MCNPX. At high energies, FLUKA, GEANT4, MARS15, and MCNPX agree again within 10%, while PHITS shows a substantial flaw. The reason is that PHITS does not simulate showers induced by high-energy photons from  $\pi^0 \rightarrow 2\gamma$  decays. Their energy at  $E > 1$  GeV is not included into energy deposition that explains a substantial underestimation in PHITS predictions at high primary energies.



**FIGURE 10.** Energy deposition in a cylindrical tungsten target irradiated by 1 and 50 GeV protons as calculated with five codes.

## CONCLUSION

Seven tasks, important for high-energy physics, accelerator, shielding, and space applications, were studied for the inter-comparison and verification against experimental data by the five major hadronic shower simulation code groups. As a result of this benchmarking, it was found that agreement between the codes and data is quite reasonable in many cases, but quite serious problems were revealed in the others. Obviously, much more verification is needed, especially for calorimetry-specific applications.

## REFERENCES

1. A. Fasso et al, *CERN-2005-10, SLAC-R-773* (2005); A. Fasso et al, *CHEP2003, hep-ph/0306267* (2003); <http://www.fluka.org>.
2. J. Allison et al, *IEEE Trans. Nucl. Sci.* **530**, 270–278 (2006); <http://geant4.web.cern.ch>
3. N.V. Mokhov, *Fermilab-FN-628* (1995); N.V. Mokhov et al, *Rad. Prot. Dosimetry*, **116**, 99 (2005); N.V. Mokhov et al, *Proc. Int. Conf. on Nucl. Data Sci. Technology*, **AIP Conf. Proc. 769**, 1618 (2005); <http://www-ap.fnal.gov/MARS/>.
4. J.S. Hendricks et al, *LA-UR-05-2675* (2005); <http://mcnpx.lanl.gov>.
5. H. Iwase et al, *J. Nucl. Sci. Technol.* **39**, 1142 (2002).
6. K. K. Gudima et al, *LA-UR-01-6804* (2001).
7. <http://sroesler.home.cern.ch/sroesler/dpmjet3.html>
8. M. G. Catanesi et al, *Nucl. Phys.* **B732**, 1–45 (2006).
9. C. Alt et al, *Eur. Phys. Jour.* **C45**, 343–381 (2006).
10. C. Alt et al, *hep-ex/06106028*.
11. <http://conferences.fnal.gov/hss06/>
12. N. I. Bozhko et al, *Sov. Jour. Nucl. Phys* **31**, 644 (1980).
13. H.-S. Lee et al, *Rad. Prot. Dosimetry*, **116**, 653–657 (2005).
14. H. Matsuda, private communication.
15. E. Huges, *Proc. I Int. Conf. on Calor. in HEP*, 525, FANL, Batavia (1990).
16. K. Niita, private communication.