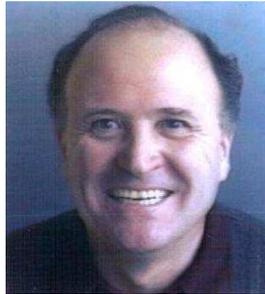# HARP COLLABORATION RESULTS ON THE PROTON-NUCLEI INTERACTIONS AT FEW GEV ENERGIES

Roumen Tsenov

Department of Atomic Physics, Faculty of Physics,
St. Kliment Ohridski University of Sofia, Sofia, Bulgaria
(on behalf of the HARP Collaboration)

Recent results obtained by the HARP collaboration on the measurements of the double-differential production cross-section of positive and negative pions in proton interactions with nuclear targets from Beryllium to Lead are presented. They cover production at small angles (30-210 mrad) and relatively large momenta up to 8 GeV/c as well as large angles (0.35 - 2.15 rad) and small momenta (0.1 - 0.8 GeV/c). These results are relevant for a detailed understanding of neutrino fluxes in accelerator neutrino experiments, better prediction of atmospheric neutrino fluxes, optimization of a future neutrino factory design and for improvement of hadronic generators widely used by the HEP community in the simulation of hadronic interactions.

1 The HARP experiment

The HARP experiment [1,2] at the CERN PS was designed to make measurements of hadron yields from a large range of nuclear targets and for incident particle momenta from 1.5 GeV/c to 15 GeV/c. The main motivations are the measurement of pion yields for a quantitative design of the proton driver of a future neutrino factory, a substantial improvement in the calculation of the atmospheric neutrino flux and the measurement of particle yields as input for the flux calculation of accelerator neutrino experiments, such as K2K [3,4], MiniBooNE [5] and SciBooNE [6].

The experiment makes use of a large-acceptance spectrometer consisting of a forward and large-angle detection systems. A detailed description of the experimental apparatus can be found in Ref. [2]. The forward spectrometer – based on large area drift chambers and a dipole magnet complemented by a set of detectors for particle identification [8]: a time-of-flight wall, a large Cherenkov detector and an electromagnetic calorimeter – covers polar angles up to 250 mrad which is well matched to the angular range of interest for the conventional neutrino beams. The large-angle spectrometer – based on a Time Projection Chamber (TPC) and Resistive Plate Chambers (RPCs), located inside a solenoidal magnet – has a large acceptance in the momentum and angular range for the pions relevant to the production of the muons in a neutrino factory. It covers the large majority ($\sim 70\%$) of the pions accepted in the focusing system of a typical design.
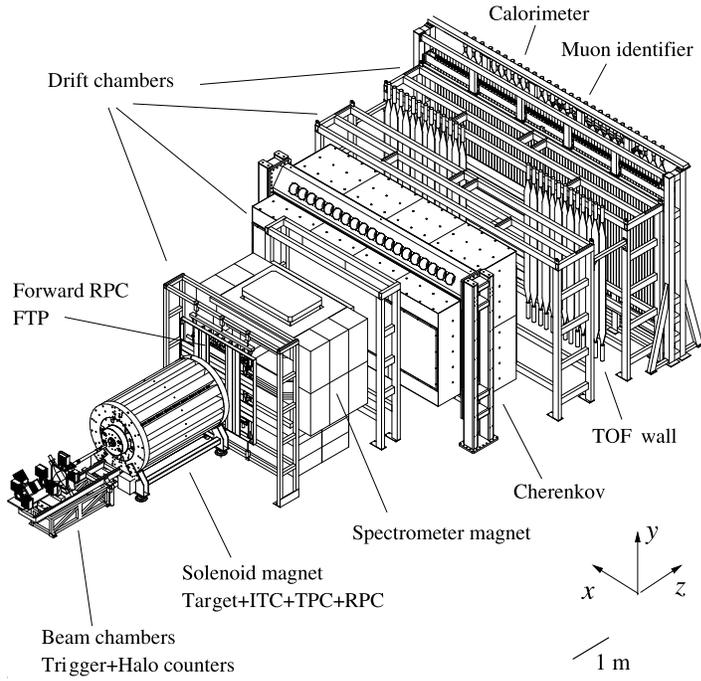
Figure 1: Overall mechanical layout of the HARP detector. The different sub-detectors are shown. The target is inserted inside the TPC.
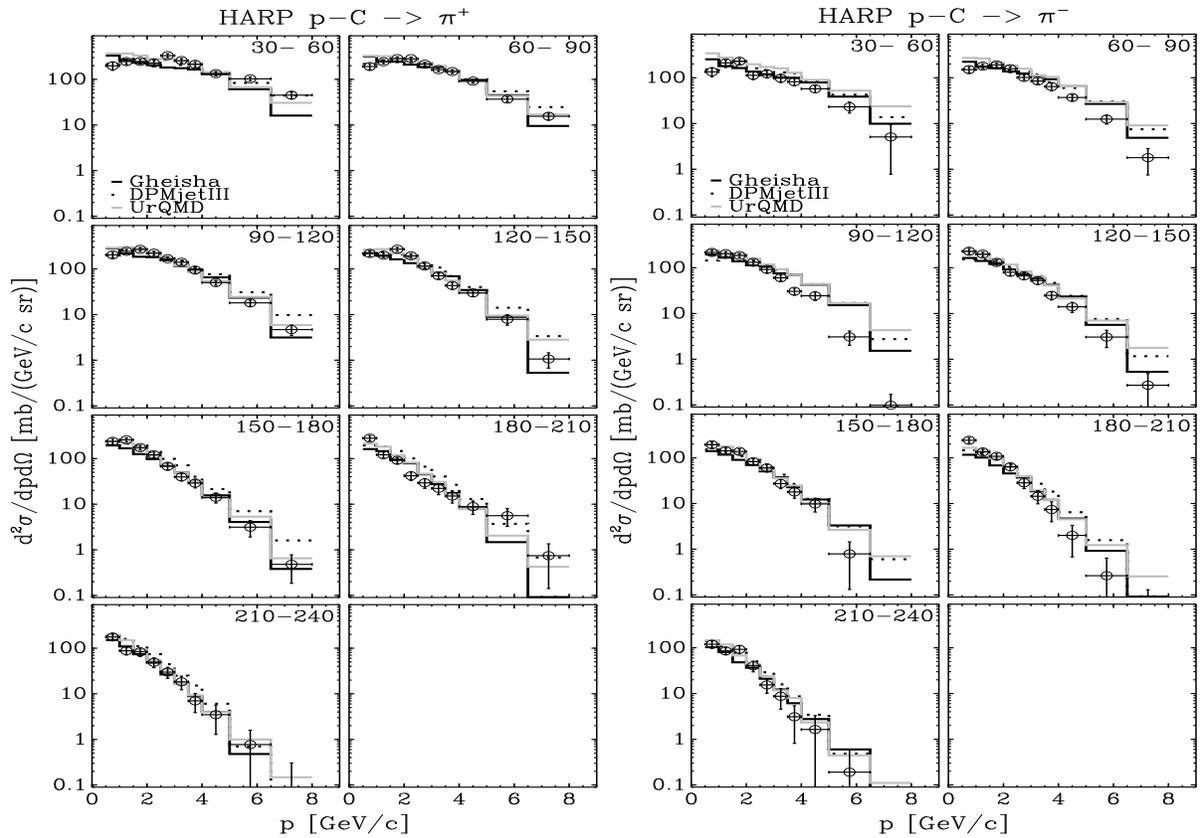

Figure 2: Double-differential production cross-section of π^+ and π^- in p–C reactions at 12 GeV/c (points with error bars) and comparison with model predictions.
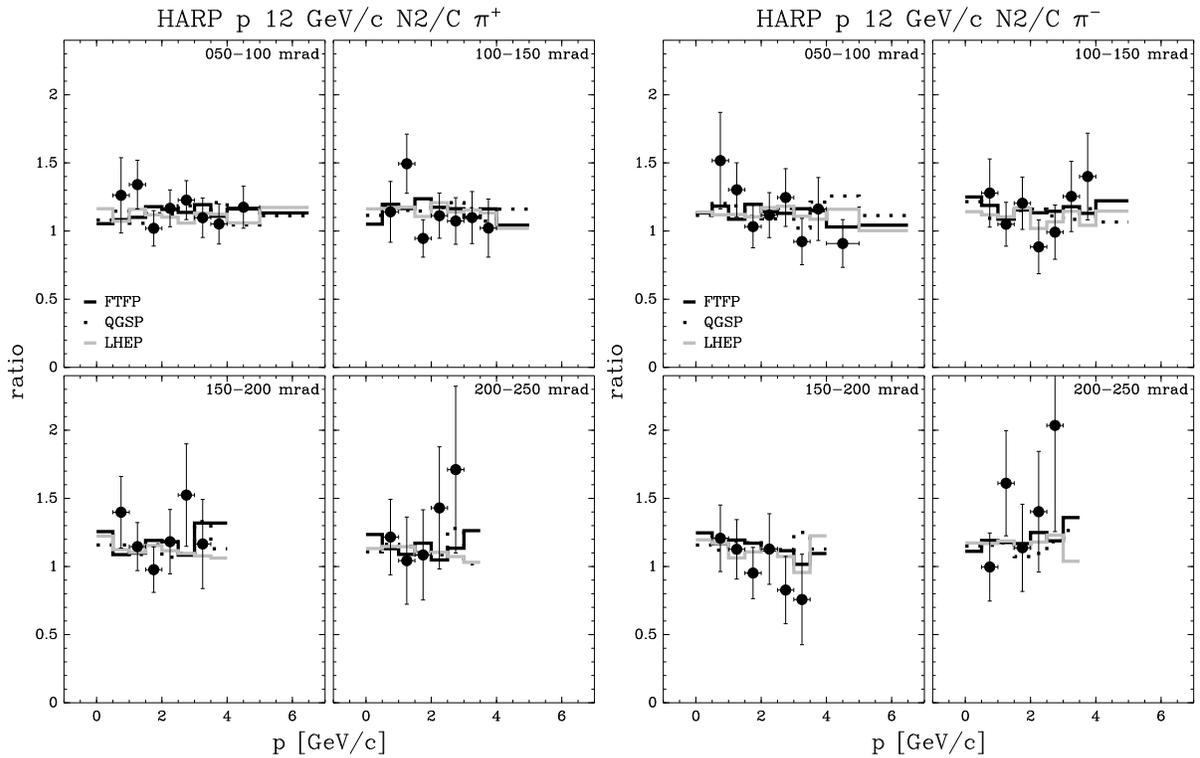
Figure 3: p–N_2 to p–C production ratio for π^+ and π^- at 12 GeV/c, compared with GEANT4 simulation predictions using different models. Only statistical errors are displayed, since most systematic ones cancel.

2 Results obtained with the HARP forward spectrometer

The first HARP physics publication [7] reported measurements of the π^+ production cross-section from an aluminum target at 12.9 GeV/c proton momentum for the K2K experiment at KEK PS. The results were subsequently applied to the final neutrino oscillation analysis of K2K [4], allowing a significant reduction of the dominant systematic error associated with the calculation of the so-called far-to-near ratio. Our next result [9] was the measurement of the π^+ cross-sections from a thin 5% λ_I beryllium target at 8.9 GeV/c proton momentum. It contributed to the understanding of the MiniBooNE and SciBooNE neutrino fluxes [10]. They are both produced by the Booster Neutrino Beam at Fermilab which originates from protons accelerated to 8.9 GeV/c by the booster before being collided against a beryllium target.

Further, measurements of the double-differential production cross-section of $\pi^\pm$ in the collision of 12 GeV/c protons and $\pi^\pm$ with thin 5% λ_I carbon target and liquid N_2 and O_2 targets were performed . These measurements are important for a precise calculation of the atmospheric neutrino flux and for a prediction of the development of extended air showers. The results for the pion production on the carbon target, the ratio N_2/Carbon, and comparison with models typically used in air shower simulations [11] are shown in Figs. 2 and 3 [12]. The conclusion of comparing the predictions of the models to the measured data is that they do predict the ratio of cross-sections and often fail in predicting the absolute rates, especially in certain regions of the phase space.

In practice production targets are not thin and cascade calculations or dedicated measurements with 'replica targets' are needed. HARP has taken, albeit with somewhat lower statistics, and analyzed p+A data at different beam momenta with 100% λ_I targets. They can be used for parametrizations or tuning of models. Preliminary spectra are available for p + Be, C, Al, Cu, Sn, Ta, Pb interactions at $3 - 12$ GeV/c. The measurements are on the tapes and can be analyzed on demand.
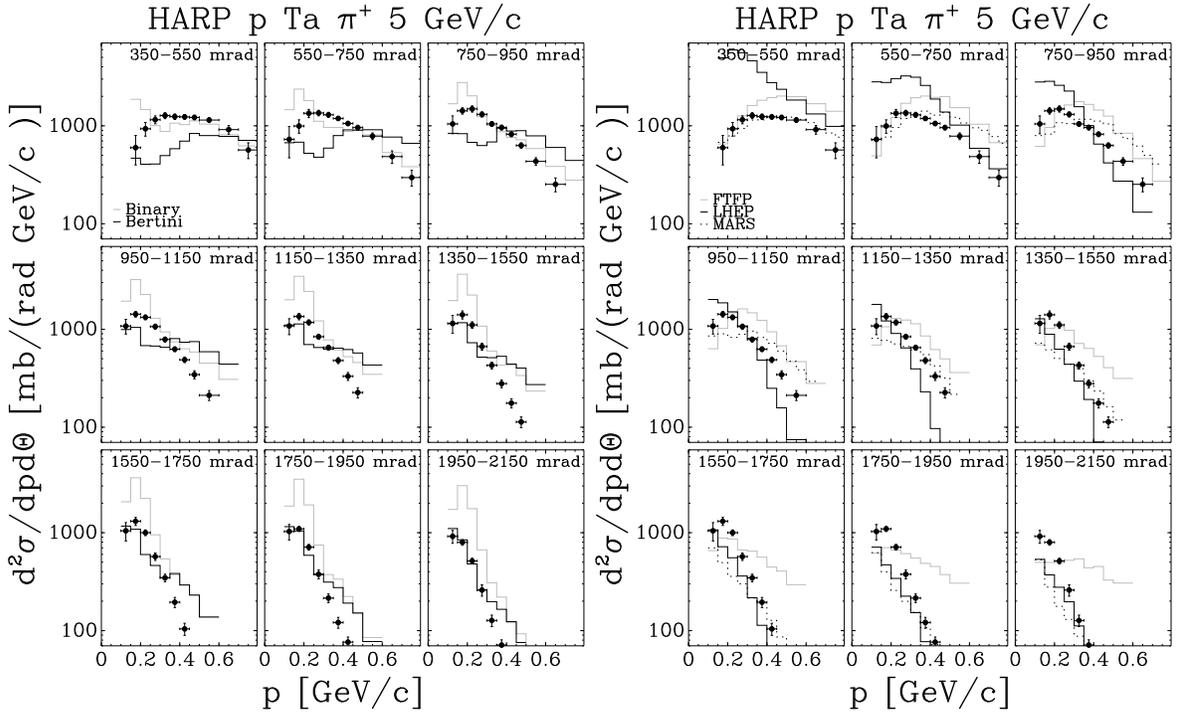
Figure 4: Double-differential π^+ production cross sections for p–Ta at 5 GeV/c and comparison with GEANT4 and MARS MC predictions, using several generator models.

3 Results obtained with the HARP large-angle spectrometer

The HARP TPC is the key detector for the analysis of tracks emerging from the target at large angles with respect to the incoming beam direction. It suffered from a number of shortcomings that were discovered during and after the data taking [2]. A description of the measures taken to correct for the effects of them is given in [2,15,16]. Wide range of experimental cross-checks has been employed to assess the momentum scale and momentum resolution in the HARP TPC, summarized in our recent paper [16].

A group of people formerly belonging to the HARP collaboration and subsequently detached themselves from it have been criticizing our methods of TPC and RPCs calibration [13]. Our arguments against this criticism and for the correctness of our results are presented in [14,16].

A first set of results on the production of pions at large angles have been published by the HARP collaboration in the papers [15,18], based on the analysis of the data in the beginning of each accelerator spill. Track recognition, momentum determination and particle identification were all performed based on the measurements made with the TPC. The reduction of the data set was necessary to avoid problems in the chamber responsible for dynamic distortions to the image of the particle trajectories as the ion charge was building up during each spill. Corrections for such distortions that allow the use of the full statistics have been developed [16] and applied in the analysis. The results exploiting the full spill data have been obtained recently [17]. They are fully compatible with the previous ones and cover pion production by proton beams in a momentum range from 3 GeV/c to 12 GeV/c hitting Be, C, Al, Cu, Sn, Ta and Pb targets with a thickness of 5% λ_{I} in the angular and momentum phase space 100 MeV/$c \leq p < 800$ MeV/c and 0.35 rad $\leq \theta < 2.15$ rad in the laboratory frame.

As an example we show in Fig. 4 the results for the double-differential cross-sections $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\theta$ at 5 GeV/c incident proton beam momentum and Ta target compared to the respective predictions of several different generator models used in GEANT4 and MARS simulation packages. The comparison between data and models is reasonable, but some discrepancies are evident for
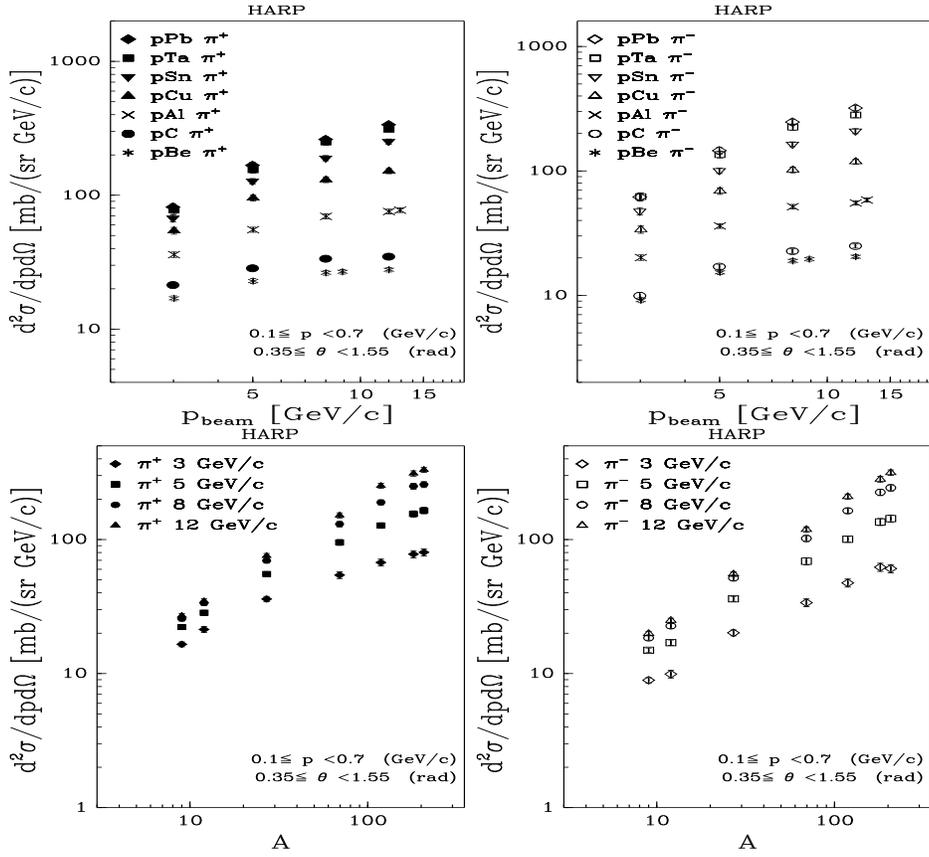
Figure 5: The dependence on the beam momentum and on the atomic number A of the π^- (right) and π^+ (left) production yields in p–Be, p–C, p–Al, p–Cu, p–Sn, p–Ta, p–Pb interactions averaged over the forward angular region (0.350 rad $\leq \theta <$ 1.550 rad) and momentum region 100 MeV/$c \leq p <$ 700 MeV/c. The results are given in arbitrary units, with a consistent scale for all panels.
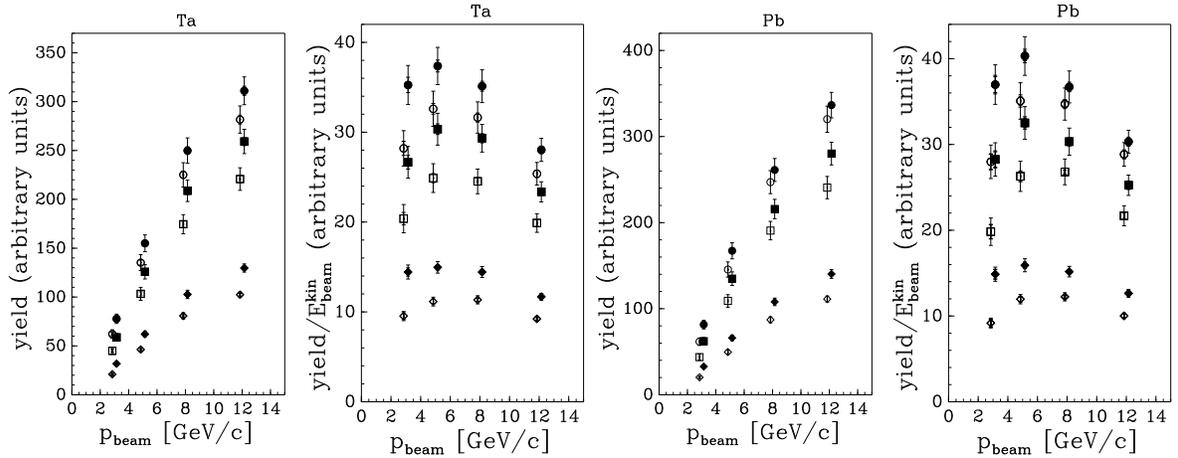

Figure 6: Predictions of the π^+ (closed symbols) and π^- (open symbols) yields for different designs of the neutrino factory focusing stage. Integrated yields and the integrated yields normalized to the kinetic energy of the proton for p–Ta and p–Pb interactions. The circles indicate the integral over the full HARP acceptance (100 MeV/$c <$ $p <$ 700 MeV/c and 0.35 rad $< \theta <$ 1.55 rad), the squares are integrated over 0.35 rad $< \theta <$ 0.95 rad, while the diamonds are calculated for the smaller angular range and 250 MeV/$c < p <$ 500 MeV/c. Although the units are indicated as "arbitrary", for the largest region the yield is expressed as $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\Omega$ in mb/(GeV/c sr). For the other regions the same normalization is chosen, but now scaled with the relative bin size to show visually the correct ratio of number of pions produced in these kinematic regions.

some models. Discrepancies up to a factor of three are seen. For details see the full paper [17]. The dependence on the beam momentum and on the atomic number A of integrated yields are presented in Fig. 5. Predictions of the π^+ and π^- integrated yields relevant for the design of the neutrino factory focusing stage are given in Fig. 6.

4 Conclusions

The full set of HARP data is in process of publishing now, It covers the pion production by protons and pions on nuclear targets spanning the full periodic table of elements and large solid angle and momentum range in the difficult energy region between 3 and 15 GeV/c of incident momentum. HARP results fill in an essential gap in the available experimental information for soft hadron production and help in the understanding of neutrino fluxes in accelerator neutrino experiments, prediction of atmospheric neutrino fluxes, optimization of a future neutrino factory design and may be used for improvements of the event generators for simulation of hadronic interactions.

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