Results from the HARP Experiment

Emilio Radicioni
Istituto Nazionale di Fisica Nucleare - Bari - Italy
E-mail: emilio.radicioni@cern.ch

Abstract. Hadron production is a key ingredient for precise prediction of atmospheric $\nu$ fluxes, characterization of accelerator $\nu$ beams, and quantification of $\pi$ production and capture for $\nu$-factory designs. HARP at the CERN PS was the first hadron production experiment designed on purpose to match all these requirements. We briefly describe here its most recent results.

1. Introduction and motivations
Hadron production data are relevant in several branches of $\nu$ physics. The study of atmospheric $\nu$s had shown strong evidence for $\nu$ oscillations[1, 2]; at the same time, to quantitatively understand this phenomenon, several accelerator-based $\nu$ experiments are being built, and new types of $\nu$ beams are being designed. In either cases, detailed knowledge of the hadron cross sections at the relevant energies is now considered a must.

2. HARP
HARP at the CERN PS [3][4] was the first hadron production experiment designed on purpose, combining a full phase space acceptance with low systematic errors and large statistics. HARP performed extensive measurements of hadron production cross sections and secondary particle yields in the energy range 3-15 GeV over the full solid angle, using a large set of cryogenic and solid (thin and thick) targets. A forward spectrometer covers polar angles up to 250 mrad, well matched to the angular range of interest to calculate the properties of conventional neutrino beams, like those of K2K and MiniBooNE: a dipole magnet and large planar drift chambers for particle tracking, and the particle identification is performed with a combination of time-of-flight, Cherenkov, and calorimeter information . In the large-angle region a TPC positioned in a solenoidal magnet is used for tracking; particle identification is performed by dE/dx in the TPC and by time-of-flight measurements with RPCs. The large-angle spectrometer acceptance is optimized for the measurement of pions relevant to the production of muons beams in future neutrino factories.

3. $\pi$ production relevant for K2K and MiniBoone
The K2K experiment is most sensitive to uncertainties in the predicted $\nu$ spectrum in the energy range between 0.5 and 1 GeV. The distortion of the spectrum measured with the far detector is predicted to be maximal in this range according to the $\nu$ oscillation parameters measured in atmospheric $\nu$ experiments. The transmission properties of the beam line in the K2K experiment match very well the HARP forward spectrometer acceptance. The measurement of $\pi$ production
for the K2K experiment using a 5% λ Al target and incident protons of 12.9 GeV/c momentum was published [5]. In Fig. 1 a ratio is shown between the ν flux measured at the near and at the far detector as a function of the ν energy. A comparison of the errors on the near/far ratio before and after the inclusion of the HARP results shows a reduction by a factor of two. The neutrino flux calculation for final disappearance analysis of K2K [6] is based on the HARP pion production data.

The case for the MiniBooNE measurement is equally compelling. Here too the ν flux comes predominantly from the π decay into μ + ν. Again in this case the HARP experiment covers the relevant range, 0.75-6.5 GeV/c in energy and 30-210 mrad in angle (more than 80% of the phase space). The cross section results published in [7] have a direct impact on the prediction of ν fluxes at Miniboone. Results recently presented by Miniboone [8] are based on a parametrization of the HARP π± cross sections.

4. Atmospheric neutrino fluxes and extended air showers

The first relevant HARP measurement in this field is the double-differential production cross-section of π± in the collision of 12 GeV/c protons with a thin 5% λ Carbon target. A systematic error analysis has also been done yielding integral errors (statistical + systematic) of 6.1% and 7.0% for π+ and π- in p–C interactions, 10.2% and 8.5% for π+ and π- in π+C interactions, 6.5% and 8.2% for π+ and π- in π–C interactions, and an overall normalization error of 2% for the proton beam and 3% for the pion beams. The results are final and a paper is in preparation. In addition, preliminary results using N2 and O2 cryogenic targets are now available.

5. Results obtained with the HARP Large Angle spectrometer

One of the main motivations of the HARP experiment is the measurement of the yields of positive and negative πs for a quantitative design of a proton driver and a target station in a future ν-factory. The variables affecting the π production are incident proton beam energy, target material and target geometry (diameter and length). In order to achieve the highest number of potentially collected πs of both charge signs per unit of energy a π production measurement should give the information necessary to optimize both proton beam energy and target material.

In most of the cases high-Z materials are proposed as targets; for this reason it was decided to first analyze a series of settings taken with a range of different beam momenta (from 3 to 12 GeV/c) incident on a Tantalum (5% λint) target [9]. Produced πs are best measured in the

![Figure 1. Near to far ratio in the K2K experiments measured by the K2K Monte-Carlo (boxes) and results from the Harp experiment (errored points).](image-url)
large-angle spectrometer, covering the full momentum range of interest for production angles above 0.35 rad.

Figure 2. Prediction of the $\pi^+$ (closed symbols) and $\pi^-$ (open symbols) yield from a tantalum target as a function of incident proton beam momentum for different designs of the neutrino factory focusing stage. Shown are the integrated yields (left) and the integrated yields normalized to the kinetic energy (right). The circles indicate the integral over the full HARP acceptance, the squares are integrated over $0.35 \text{rad} < \theta < 0.95 \text{rad}$, while the diamonds are calculated for the restricted angular range and $250 \text{MeV}/c < p < 500 \text{MeV}/c$.

The results are shown in Fig. 2. It is shown that the pion yield increases nearly linearly with momentum and that in our kinematic coverage the optimum yield is between 5 GeV/c and 8 GeV/c.

6. Systematic studies
Systematic studies over global characteristics of hadron production cross sections can now be performed. As an example, production off Be, C, Al, Cu, Sn and Pb targets using the same detector [10, 11] have been analysed. They allow, for example, to study the integrated pion yield as a function of beam momentum, its A-dependence, the $\pi^-/\pi^+$ ratio and all other relevant behaviours with a reduced systematic uncertainty. The fact that these data are taken with the same apparatus and analysed using the same methods improves the precision of the relative comparisons. Papers listing cross section data for all target materials at all available energies are in course of preparation.

7. Conclusions
The HARP experiment, combining almost full phase space acceptance with low systematic errors and high statistics, provide the required reference samples for simulation, and the needed information to characterize the present and future $\nu$ beams, and to help a quantitative description of the air showers development.

8. References
[1] Fukuda Y et al. Phys. Rev. Lett. 81 (1998) 1562.
[2] Fukuda Y et al. Phys. Rev. Lett. 82 (1999) 2644.
[3] Catanesi M G et al. CERN-SPSC-99-35.
[4] Catanesi M G et al. Nucl. Instr. Meth. A571 (2007) 527.
[5] Catanesi M G et al. Nucl. Phys. B732 (2006) 1-45.
[6] Aguilar A A et al. Phys. Rev. Lett. 98 (2007) 231801.
[7] Catanesi M G et al. E.P.J. C51 (2007) 787.
[8] Catanesi M G et al. E.P.J. C52 (2007) 29.