RESULTS FROM HARP
AND THEIR IMPLICATIONS FOR NEUTRINO PHYSICS

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Recent results from the HARP experiment on the measurements of the double-differential production cross-section of pions in proton interactions with beryllium, carbon and tantalum targets are presented. These results are relevant for a detailed understanding of neutrino flux in accelerator neutrino experiments MiniBooNE/SciBooNE, for a better prediction of atmospheric neutrino fluxes as well as for an optimization of a future neutrino factory design.

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 HARP experiment makes use of a large-acceptance spectrometer consisting of a forward and large-angle detection system. A detailed description of the experimental apparatus can be found in Ref. [2]. The forward spectrometer — based on large area drift chambers [7] and a dipole magnet complemented by a set of detectors for particle identification (PID): a time-of-flight wall [8] (TOFW), a large Cherenkov detector (CHE) and an electromagnetic calorimeter — covers polar angles up to 250 mrad which is well matched to the angular range of interest for the measurement of hadron production to calculate the properties of conventional neutrino beams. The large-angle spectrometer — based on a Time Projection Chamber (TPC) 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 of the pions accepted in the focusing system of a typical design. The neutrino beam of a neutrino factory originates from the decay of muons which are in turn the decay products of pions.

2 Results obtained with the HARP forward spectrometer

The first HARP physics publication [9] reported measurements of the π^+ production cross-section from an aluminum target at 12.9 GeV/c proton momentum. This corresponds to the energies of the KEK PS and the target material used by the K2K experiment. The results obtained in Ref. [9] 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 (see [9] and [4] for a detailed discussion) and thus an increased K2K sensitivity to the oscillation signal.

A detailed description of established experimental techniques for the data analysis in the HARP forward spectrometer can be found in Ref. [9,10]. Our next goal is to contribute to the understanding of the MiniBooNE and SciBooNE neutrino fluxes. 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. As was the case for the K2K beam, a fundamental input for the calculation of the resulting ν_μ flux is the measurement of the π^+ cross-sections from a thin 5% nuclear interaction length (λ_{I}) beryllium target at 8.9 GeV/c proton momentum, which is presented here and in the forthcoming HARP publication [11].

With respect to our first published physics paper [9], a number of improvements to the analysis techniques and detector simulation have been made. The most important improvements introduced in this analysis compared with the one presented in Ref. [9] are:

- An increase of the track reconstruction efficiency which is now constant over a much larger kinematic range and a better momentum resolution coming from improvements in the tracking algorithm;
- Better understanding of the momentum scale and resolution of the detector, based on data, which was then used to tune the simulation. This results in smaller systematic errors associated with the unsmearing corrections determined from Monte Carlo;
- New particle identification hit selection algorithms both in the TOFW and in the CHE resulting in much reduced background and negligible efficiency losses;
- Significant increases in Monte Carlo production have also reduced uncertainties from Monte Carlo statistics and allowed studies which have reduced certain systematics.

It is important to point out that an analysis incorporating these improvements yields results for the aluminum data fully consistent with those published in Ref. [9].

The absolutely normalized double-differential cross-section for the process $p + \mathrm{Be} \rightarrow \pi^+ + X$ can be expressed in bins of pion kinematic variables in the laboratory frame, (p_π, θ_π), as

$$\frac{d^2\sigma^{\pi^+}}{dpd\Omega}(p_\pi, \theta_\pi) = \frac{A}{N_{\mathrm{A}}\rho t} \cdot \frac{1}{\Delta p \Delta\Omega} \cdot \frac{1}{N_{\mathrm{pot}}} \cdot N^{\pi^+}(p_\pi, \theta_\pi) \ , \quad (1)$$

where:

- $\frac{d^2\sigma^{\pi^+}}{dpd\Omega}$ is the cross-section in $\mathrm{cm}^2/(\mathrm{GeV/c})/\mathrm{srad}$ for each (p_π, θ_π) bin covered in the analysis.
- $\frac{A}{N_{\mathrm{A}}\rho}$ is the reciprocal of the number density of target nuclei for Be ($1.2349 \cdot 10^{23}$ per cm^3).
- t is the thickness of the beryllium target along the beam direction. The thickness is measured to be 2.046 cm with a maximum variation of 0.002 cm.
- Δp and $\Delta\Omega$ are the bin sizes in momentum and solid angle, respectively.[a]

[a] $\Delta p = p_{max} - p_{min}$; $\Delta\Omega = 2\pi(cos(\theta_{min}) - cos(\theta_{max}))$

Table 1: Total number of events in the 8.9 GeV/c beryllium 5% λ_{I} target and empty target data sets, and the number of protons on target as calculated from the prescaled trigger count.

Data Set	**8.9 GeV/c Be 5% λ_{I}**	**8.9 GeV/c Empty Target**
protons on target	13,074,880	1,990,400
total events processed	4,682,911	413,095
events with accepted beam proton	2,277,657	200,310
beam proton events with FTP trigger	1,518,683	91,690
total good tracks in fiducial volume	95,897	3,110

- N_{pot} is the number of protons on target after event selection cuts.
- $N^{\pi^+}(p_\pi, \theta_\pi)$ is the yield of positive pions in bins of true momentum and angle in the laboratory frame.

Eq. 1 can be generalized to give the inclusive cross-section for a particle of type α

$$\frac{d^2\sigma^\alpha}{dpd\Omega}(p,\theta) = \frac{A}{N_{\mathrm{A}}\rho t} \cdot \frac{1}{\Delta p \Delta\Omega} \cdot \frac{1}{N_{\mathrm{pot}}} \cdot M^{-1}_{p\theta\alpha p'\theta'\alpha'} \cdot N^{\alpha'}(p', \theta') \ , \tag{2}$$

where reconstructed quantities are marked with a prime and $M^{-1}_{p\theta\alpha p'\theta'\alpha'}$ is the inverse of a matrix which fully describes the migrations between bins of true and reconstructed quantities, namely: lab frame momentum, p, lab frame angle, θ, and particle type, α.

There is a background associated with beam protons interacting in materials other than the nuclear target (parts of the detector, air, etc.). These events are subtracted by using data collected without the nuclear target in place where one has been careful to normalize the sets to the same number of protons on target. This procedure is referred to as the 'empty target subtraction':

$$N^{\alpha'}(p', \theta') \rightarrow [N^{\alpha'}_{\mathrm{target}}(p', \theta') - N^{\alpha'}_{\mathrm{empty}}(p', \theta')] \ . \tag{3}$$

The event selection is performed in the following way: a good event is required to have a single, well reconstructed and identified beam particle impinging on the nuclear target. A downstream trigger in the forward trigger plane (FTP) is also required to record the event, necessitating an additional set of unbiased, pre-scaled triggers for absolute normalization of the cross-section. These pre-scale triggers (1/64 for the 8.9 GeV/c Be data set) are subject to exactly the same selection criteria for a 'good' beam particle as the event triggers allowing the efficiencies of the selection to cancel, thus adding no additional systematic uncertainty to the absolute normalization of the result. Secondary track selection criteria have been optimized to ensure the quality of the momentum reconstruction as well as a clean time-of-flight measurement while maintaining high reconstruction and particle identification efficiencies. The results of the event and track selection in the beryllium thin target data set are shown in Table 1.

The double-differential inelastic cross-section for the production of positive pions from collisions of 8.9 GeV/c protons with beryllium have been measured in the kinematic range from 0.75 GeV/c $\leq p_\pi \leq$ 6.5 GeV/c and 0.030 rad $\leq \theta_\pi \leq$ 0.210 rad, subdivided into 13 momentum and 6 angular bins. Systematic errors have been estimated. A full $(13 \times 6)^2 = 6048$ element covariance matrix has been generated to describe the correlation among bins. The data are presented graphically as a function of momentum in 30 mrad bins in Fig. 1. To characterize the uncertainties on this measurement we show the diagonal elements of the covariance matrix plotted on the data points in Fig. 1. A typical total uncertainty of 9.8% on the double-differential cross-section values and a 4.9% uncertainty on the total integrated cross-section are obtained.

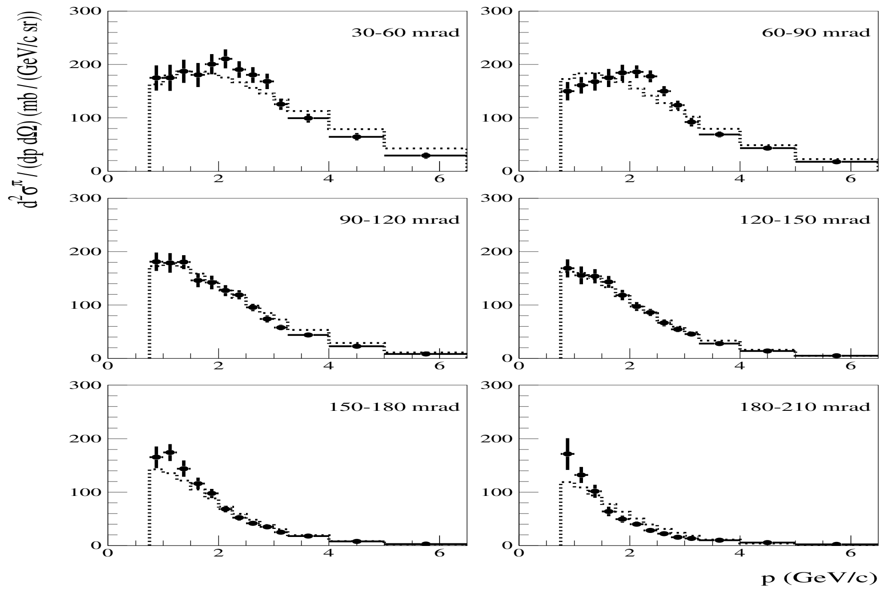

Figure 1: HARP measurements of the double-differential production cross-section of positive pions, $d^2\sigma^{\pi^+}/dpd\Omega$, from 8.9 GeV/c protons on 5% $\lambda_{\rm I}$ beryllium target as a function of pion momentum, p, in bins of pion angle, θ, in the laboratory frame. The error bars shown include statistical errors and all (diagonal) systematic errors. The dotted histograms show the Sanford-Wang parametrization that best fits the HARP data.

Table 2: Sanford-Wang parameters and errors obtained by fitting the dataset. The errors refer to the 68.27% confidence level for seven parameters ($\Delta\chi^2 = 8.18$).

Parameter	c_1	c_2	c_3	$c_4 = c_5$	c_6	c_7	c_8
Value	(82.2 ± 19.8)	(6.47 ± 1.62)	(90.6 ± 20.3)	$(7.44 \pm 2.30) \times 10^{-2}$	(5.09 ± 0.49)	(0.187 ± 0.053)	(42.8 ± 13.6)

Sanford and Wang [12] have developed an empirical parametrization for describing the production cross-sections of mesons in proton-nucleus interactions. This parametrization has the functional form:

$$\frac{d^2\sigma(\mathrm{p{+}A} \rightarrow \pi^+ + X)}{dpd\Omega}(p,\theta) = \exp[c_1 - c_3\frac{p^{c_4}}{p_{\rm beam}^{c_5}} - c_6\theta(p - c_7 p_{\rm beam}\cos^{c_8}\theta)]p^{c_2}(1 - \frac{p}{p_{\rm beam}})\ , \quad (4)$$

where X denotes any system of other particles in the final state, $p_{\rm beam}$ is the proton beam momentum in GeV/c, p and θ are the π^+ momentum and angle in units of GeV/c and radians, respectively, $d^2\sigma/(dpd\Omega)$ is expressed in units of mb/(GeV/c sr), $d\Omega \equiv 2\pi\ d(\cos\theta)$, and the parameters $c_1, \ldots, c_8$ are obtained from fits to meson production data.

The π^+ production data reported here have been fitted to this empirical formula (Eq. 4). In the χ^2 minimization, the full error matrix was used. The best-fit values of the Sanford-Wang parameters are reported in Table 2, together with their errors.

The MiniBooNE neutrino beam is produced from the decay of π and K mesons which are produced in collisions of 8.9 GeV/c protons from the Fermilab Booster on a 71 cm beryllium target. The neutrino flux prediction is generated using a Monte Carlo simulation. In this simulation the primary meson production rates are taken from a fit of existing data with a Sanford-Wang empirical parametrization in the relevant region. The results presented here, being for protons at exactly the booster beam energy, are then a critical addition to these global fits. The kinematic region of the measurements presented here contains 80.8% of the pions contributing to the neutrino flux in the MiniBooNE detector.

A similar analysis has been performed using the HARP forward spectrometer for the measurement of the double-differential production cross-section of $\pi^{\pm}$ in the collision of 12 GeV/c

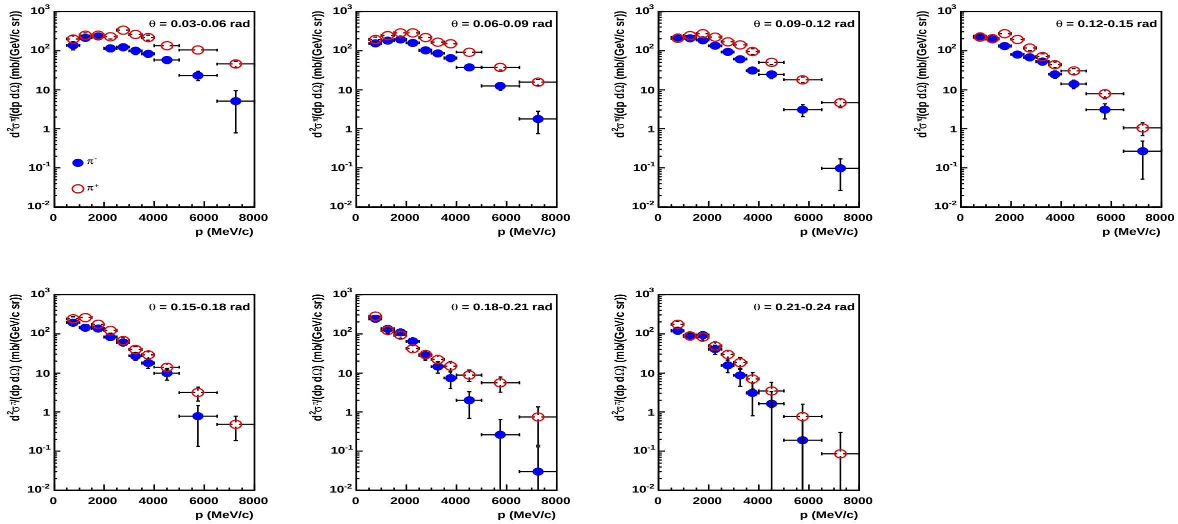

Figure 2: Measurements of the double-differential production cross-sections of π^+ (open circles) and π^- (closed circles) from 12 GeV/c protons on 5% λ_I carbon target as a function of pion momentum, p, in bins of pion angle, θ, in the laboratory frame. The error bars shown include statistical errors and all (diagonal) systematic errors.

protons with a thin 5% λ_I carbon target. The results are shown in Fig. 2. These measurements are important for a precise calculation of the atmospheric neutrino flux and for a prediction of the development of extended air showers.

3 Results obtained with the HARP large-angle spectrometer

First results on the measurements of the double-differential cross-section for the production of charged pions in proton–tantalum collisions emitted at large angles from the incoming beam direction have been obtained recently[13]. The pions were produced by proton beams in a momentum range from 3 GeV/c to 12 GeV/c hitting a tantalum target with a thickness of 5% λ_I. The angular and momentum range covered by the experiment (100 MeV/c $\leq p <$ 800 MeV/c and 0.35 rad $\leq \theta <$ 2.15 rad) is of particular importance for the design of a neutrino factory. Track recognition, momentum determination and particle identification were all performed based on the measurements made with the TPC. Results for the double-differential cross-sections $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\theta$ at four incident proton beam momenta (3 GeV/c, 5 GeV/c, 8 GeV/c and 12 GeV/c) are shown in Fig. 3.

Similar analyses are being performed for the Be, C, Cu, Sn and Pb targets using the same detector, which will allow a study of A-dependence of the pion yields with a reduced systematic uncertainty to be performed.

4 Conclusions

Measurements of the double-differential production cross-section of positive pions in the collision of 8.9 GeV/c protons with a beryllium target have been presented. The data have been reported in bins of pion momentum and angle in the kinematic range from 0.75 GeV/c $\leq p_\pi \leq$ 6.5 GeV/c and 0.030 rad $\leq \theta_\pi \leq$ 0.210 rad. A systematic error analysis has been performed yielding an average point-to-point error of 9.8% (statistical + systematic) and an overall normalization error of 2%. The data have been fitted to the empirical parameterization of Sanford and Wang and the resulting parameters provided. These production data have direct relevance for the prediction of a ν_μ flux for MiniBooNE and SciBooNE experiments.

Preliminary results for the measurement of the double-differential production cross-section of $\pi^\pm$ in the collision of 12 GeV/c protons with a carbon target have been presented.

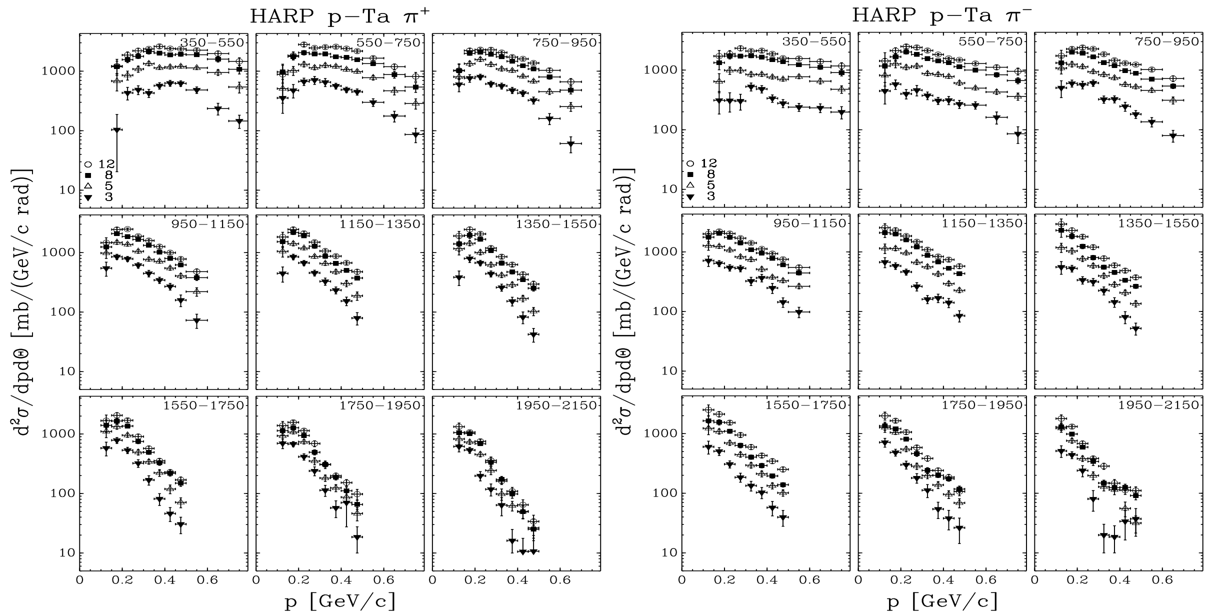

Figure 3: Double-differential cross-sections for π^+ (left) and π^- (right) production in p–Ta interactions as a function of momentum displayed in different angular bins (shown in mrad in the panels). The results are given for all incident beam momenta (filled triangles: 3 GeV/c; open triangles: 5 GeV/c; filled rectangles: 8 GeV/c; open circles: 12 GeV/c). The error bars take into account the correlations of the systematic uncertainties.

First results on the production of pions at large angles with respect to the beam direction for protons of 3 GeV/c, 5 GeV/c, 8 GeV/c and 12 GeV/c impinging on a thin tantalum target have been described. These data can be used to make predictions for the fluxes of pions to enable an optimized design of a future neutrino factory.

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