PROCEEDINGS OF SCIENCE

Cross-sections of hadron production by 3-15 GeV/c beams of protons and charged pions

Anastasia BOLSHAKOVA* **(for the HARP-CDP group†)**
Joint Institute for Nuclear Research
E-mail: nst@nusun.jinr.ru

Precise measurements of hadron production on nuclear targets are vital for the design of a future neutrino factory and important for the tuning of hadron generators such as Geant4. The hadron yield must be known as a function of the energy and the production angle of the secondary particles. We report on HARP-CDP measurements of double-differential inclusive cross-sections of pion, proton and deuteron production on beryllium, copper and tantalum targets, by beams of protons and charged pions in the momentum range between 3 and 15 GeV/c. Our studies show that cross-sections published by the "HARP Collaboration" are wrong by factors up to two.

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*Speaker.

†The members of the HARP-CDP group are: A. Bolshakova, I. Boyko, G. Chelkov, D. Dedovich, A. Elagin, M. Gostkin, S. Grishin, A. Guskov, Z. Kroumchtein, Yu. Nefedov, K. Nikolaev and A. Zhemchugov from the Joint Institute for Nuclear Research, Dubna, Russian Federation; F. Dydak and J. Wotschack from CERN, Geneva, Switzerland; A. De Min from the Politecnico di Milano and INFN, Sezione di Milano-Bicocca, Milan, Italy; V. Ammosov, V. Gapienko, V. Koreshev, A. Semak, Yu. Sviridov, E. Usenko and V. Zaets from the Institute of High Energy Physics, Protvino, Russian Federation.

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1. Detector characteristics and performance

The HARP detector was designed to carry out a programme of systematic and precise (at the few percent level) measurements of hadron production by protons and charged pions with momenta from 1.5 to 15 GeV/c. The detector combined a forward spectrometer with a large-angle spectrometer. The latter comprised a cylindrical Time Projection Chamber (TPC) around the target and an array of Resistive Plate Chambers (RPCs) that surrounded the TPC. The purpose of the TPC was track reconstruction and particle identification by dE/dx. The purpose of the RPCs was to complement the particle identification by time of flight. The main detector properties are summarised in Table 1. Our calibration work on the HARP RPCs and TPC is described in detail in Refs. [1] and [2], and in references cited therein.

TPC	RPCs
$\sigma(1/p_{\mathrm{T}}) \sim 0.20 - 0.25(\mathrm{GeV}/c)^{-1}$	Intrinsic efficiency 98%
$\sigma(\Theta) \sim 9$ mrad	$\sigma(\mathrm{TOF}) \sim 175$ ps
$\sigma(\mathrm{d}E/\mathrm{d}x) \sim 16\%$	

Table 1: Technical characteristics of the HARP large angle spectrometer; p_{T} is transverse momentum.

The work reported here is on the large-angle production (polar angle θ in the range $20^\circ < \Theta < 125^\circ$) of secondary protons and charged pions, and of deuterons, in the interactions with 5% λ_{abs} (absorbtion length) Be, Ta and Cu targets, of protons and charged pions with beam momenta between ± 3.0 and ± 15.0 GeV/c [3 – 6].

2. Double-differential inclusive cross-sections on Be, Ta and Cu targets

The double-differential inclusive cross-sections $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\Omega$ for various combinations of incoming beam particle (p, π^+, π^-) and secondary particle (p, π^+, π^-) on a beryllium target are shown in Fig. 1.

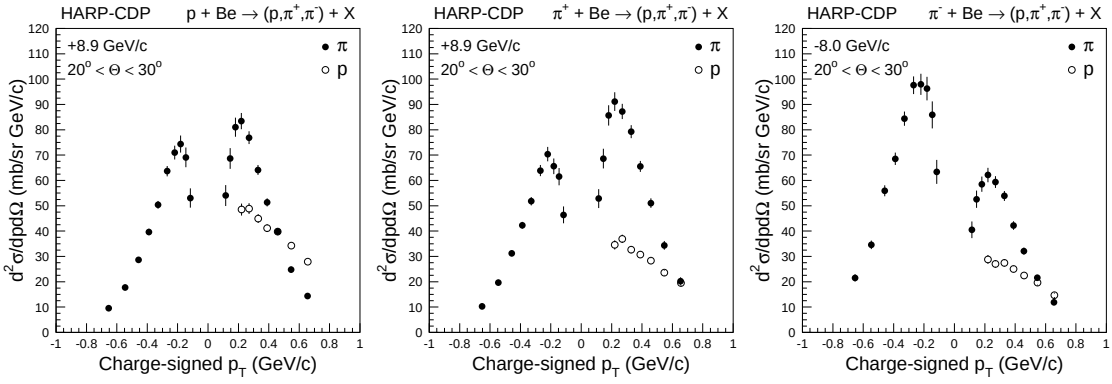

Figure 1: Inclusive cross-sections of the production of secondary protons (open circles), π^+'s, and π^-'s (black dots), by 8.9 GeV/c protons and π^+, and 8.0 GeV/c π^-, on beryllium nuclei, in the polar-angle range $20^\circ < \Theta < 30^\circ$, as a function of the charge-signed p_{T} of the secondaries; the shown errors are total errors.

Figure 2 (left) shows a comparison of secondary π^+ and π^- inclusive cross-sections produced in the interactions of 8.0 (8.9) GeV/c protons with Ta, Cu and Be targets. One can see that cross-sections of heavy tantalum ($A = 181$) nuclei are 10 times higher with respect to beryllium ($A = 9$) nuclei, and twice higher with respect to copper ($A = 64$) nuclei.

Figure 2 (right) demonstrates the rather striking differences in the production of secondary particles in the interactions of protons with beryllium ($A = 9$) and tantalum ($A = 181$) nuclei. One can see that π^+ and proton production is quite different for light and heavy nuclei. Reinteractions of secondaries in the nuclear matter of the heavy tantalum nucleus lead to a stark increase of the production of protons, deuterons, and even tritons, with respect to the beryllium nucleus.

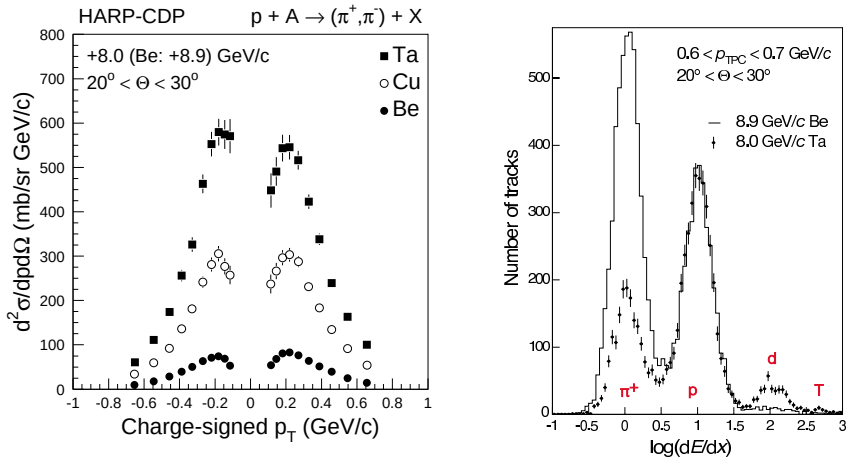

Figure 2: Left figure: cross-sections of π^+'s and π^-'s produced in the interaction of 8.0 (8.9) GeV/c protons with Ta, Cu and Be targets, in the polar-angle range $20^\circ < \Theta < 30^\circ$, as a function of the charge-signed p_{T} of the secondaries; the shown errors are total errors. Right figure: comparison of pion, proton, deuteron (**d**) and triton (**T**) production by protons between beryllium (histogram) and tantalum (black dots) target nuclei; the beryllium data are normalized such that the number of protons on beryllium and on tantalum agree; the momentum refers to particle momentum in the TPC.

3. Comparison with the results from other experiments

Experiment E802 [7] at Brookhaven National Laboratory (BNL) measured secondary π^+'s in the polar-angle range $5^\circ < \Theta < 58^\circ$ from the interactions of $+14.6$ GeV/c protons with beryllium nuclei. Figure 3 (left) shows their published Lorentz-invariant cross-sections of π^+'s and π^-'s production by $+14.6$ GeV/c protons, in the rapidity range $1.2 < y < 1.4$, as a function of $m_{\mathrm{T}} - m_\pi$, where m_{T} denotes the pion transverse momentum.Their data are compared with our cross-sections from the interactions of $+15.0$ GeV/c protons with beryllium nuclei, expressed in the same unit as used by E802. The E802 $\pi^\pm$ cross-sections are in good agreement with our cross-sections measured nearly at the same proton beam momentum, taking into account the normalization uncertainty of (10–15)% quoted by E802. We draw attention to the good agreement of the slopes of the cross-sections over two orders of magnitude.

Another BNL experiment, E910 [8], measured secondary charged pions in the momentum range 0.1 – 6 GeV/c from the interactions of +12.3 GeV/c protons with copper nuclei. This experiment used a TPC for the measurement of secondaries, with a comfortably large track length of $\sim$1.5 m. This feature, together with a magnetic field strength of 0.5 T, is of particular significance, since it permits considerably better charge identification and proton-pion separation by dE/dx than is possible in the HARP detector. Figure 3 (right) shows their published cross-section $\mathrm{d}^2\sigma/\mathrm{d}p\mathrm{d}\Omega$ of $\pi^{\pm}$ production by +12.3 GeV/c protons, in the polar-angle range $0.8 < \cos\Theta < 0.9$. Since E910 quoted only statistical errors, our data in Figure 3 (right) from the interactions of +12.0 GeV/c protons with copper are also shown with their statistical errors. The normalization uncertainty quoted by E910 is $\leq$5%. Also here, the E910 data are shown as published, and our data are expressed in the same unit as used by E910. We draw attention to the good agreement between our and E910 cross-sections.

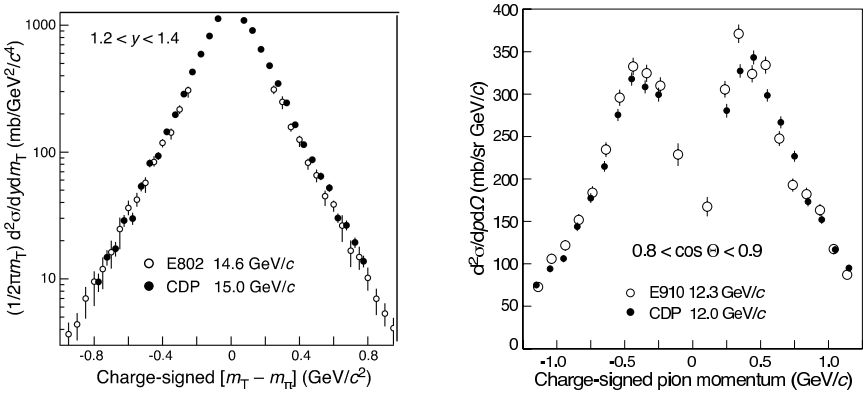

Figure 3: Left figure: comparison of our cross-sections (black circles) of $\pi^{\pm}$ production by +15.0 GeV/c protons off beryllium nuclei, with the cross-sections published by the E802 Collaboration for the proton beam momentum of +14.6 GeV/c (open circles); all errors are statistical only. Right figure: comparison of our cross-sections of $\pi^{\pm}$ production by +12.0 GeV/c protons off copper nuclei, with the cross-sections published by the E910 Collaboration for the proton beam momentum of +12.3 GeV/c (open circles); all errors are statistical only.

Figure 4 shows the comparison of our cross-sections of pion production by +12.0 GeV/c protons off beryllium (Figure 4a), copper (Figure 4b) and tantalum (Figure 4c) nuclei with the ones published by the HARP Collaboration [9], in the polar-angle range $0.35 < \Theta < 0.55$ rad. The latter cross-sections are plotted as published, while we expressed our cross-sections in the unit used by the HARP Collaboration. The discrepancy between our results and those published by the HARP Collaboration is evident. We note the difference especially of the π^+ cross-section, and the difference in the reported momentum range. The discrepancy is even more serious as the same data set has been analysed by both groups. We hold that the discrepancy is caused by problems in the HARP Collaboration's data analysis. They result primarily, but not exclusively, from a lack of understanding TPC track distortions and RPC timing signals. These problems, together with others that affect the HARP Collaboration's data analysis, are discussed in detail in Refs.[10 – 12].

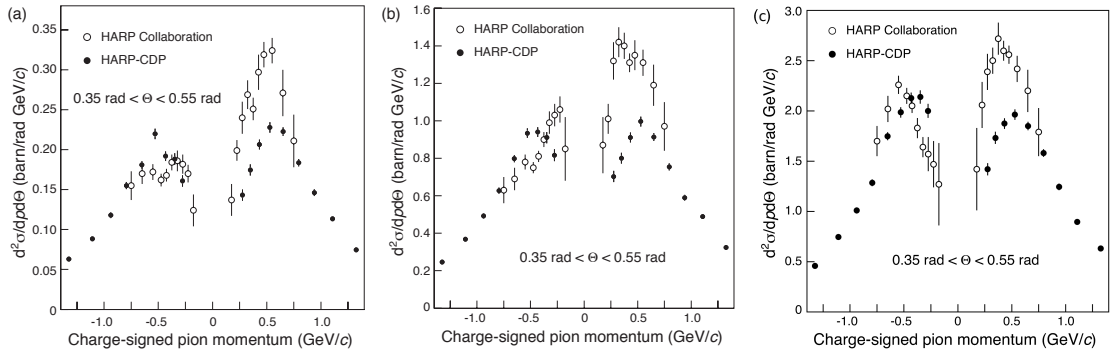

Figure 4: Comparison of our cross-sections (black circles) of $\pi^{\pm}$ productions by $+12.0$ GeV/c protons off beryllium (a), copper (b) and tantalum (c) nuclei with the cross-sections published by the HARP Collaboration (open circles).

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