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Pion Yield from 450 GeV/c Protons on Beryllium.

The SPY Collaboration

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Abstract

This paper reports on the charged pion production yields measured by the SPY/NA56 experiment for 450 GeV/c proton interactions on beryllium targets. The present data cover a secondary momentum range from 7 GeV/c to 135 GeV/c in the forward direction. An experimental accuracy ranging from 5 to 10%, depending on the beam momentum, has been achieved, limited mainly by the knowledge of the beam acceptance. These results will be relevant in the calculation of neutrino fluxes in present and future neutrino beams.

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1 Introduction

The SPY/NA56 (Secondary Particle Yield) experiment [1] has carried out a measurement of the production rates of charged pions and kaons from 450 GeV/c protons hitting beryllium targets of different lengths and shapes. Data were collected over a secondary particle momentum range from 7 GeV/c to 135 GeV/c and up to 600 MeV/c of transverse momentum. A previous paper already reported on the K/π production ratios and on the shape of the p_T distributions of π fluxes measured by the SPY/NA56 experiment [2]. The present paper reports on the total production yield of charged pions in the forward direction measured with a Be plate target 160 mm wide (horizontal plane), 2 mm high (vertical plane) and 100 mm long (in beam direction). No corrections for pion reabsorption or decays into pions of short lived particles within the target length, nor for the contribution from secondary interactions are applied. These effects, which might be of interest for deriving 'elementary' particle yields as they would be produced in an infinitesimally thin target, will be addressed in a future paper, where a comparative analysis of yields from targets of different length will be presented. For the extrapolation to targets of different length and shape the reader may also refer to [3].

Prior to this experiment, measurements of the pion and kaon production rates in the range 60 GeV/c $\leq p \leq$ 300 GeV/c at transverse momenta up to 500 MeV/c were performed by Atherton *et al.* [4] for 400 GeV/c protons incident on beryllium. Our data link up and extend the earlier particle production measurements to lower secondary momenta and comparisons will be made in the area of overlap.

Besides its general interest, the measurement of secondary particle fluxes was mainly motivated by and is of particular importance for the understanding and planning of neutrino oscillation experiments. The calculation of fluxes for neutrino experiments at accelerators is based on the knowledge of the pion and kaon yields produced by high energy protons incident on targets of materials of low atomic number. Below 60 GeV/c there has been no direct measurement of these particle production yields, and so extrapolations of the existing data [5] or Monte Carlo calculations had to be used to make flux predictions.

Therefore, flux predictions are most uncertain in the low energy region, particularly relevant in oscillation experiments. A solid knowledge of the available secondary meson yield and of its angular distribution at low momenta is of great value for the accurate estimation of the neutrino flux at the current West Area Neutrino Facility [6] of the Super Proton Synchrotron (SPS) at CERN, where a substantial fraction of the ν_μ flux (around 50%) is due to mesons with momentum lower than 60 GeV/c, and for the planning and design of future neutrino beams [7, 8, 9].

2 Experimental Apparatus

The SPY/NA56 experiment was performed using the NA52 spectrometer [10] in the H6 beam in the North area of the SPS at CERN. The beam is derived from a target station served by a primary proton beam of 450 GeV/c with typical intensities of 10^{12} protons per burst. The H6 beamline is basically a four-stage focusing spectrometer, of total length 524 m. The first and third stages encompass the principal, equal and opposite, vertical deflections, which provide momentum analysis and recombination. It can transport secondary particles in the momentum range $5 \leq p \leq 200$ GeV/c, within a maximum acceptance of $\Delta p/p \times \Delta\Omega = \pm 1.5\% \times 2.1\mu$sr. A set of Secondary Emission Monitors (SEM) around the target station was used to steer the primary protons onto the target and record throughout the experiment the spot size, the position and the intensity of the primary beam [11]. Three sets of motorized two-jaw collimators served to define the horizontal and vertical angular acceptance and the transmitted momentum bite of the secondary beam, respectively. In order to minimize systematic errors due to uncertainties in the field strengths of the quadrupoles, these collimators were installed as early as possible in the beamline. For the horizontal and vertical collimators, at 41 and 48 m from the target, this implied that only two quadrupoles were located upstream of the acceptance limitation - a significant improvement over the layout used by Atherton *et al.* [4]. For the momentum slit, located at 128 m from the target, a total of three relevant quadrupoles was involved.

A schematic view of the H6 spectrometer, with the NA52 equipment used for this experiment is given in figure 1. A set of time of flight (TOF) hodoscopes, threshold (Č0-Č2) and differential (CEDAR) Cherenkov counters along the beamline and a hadron calorimeter at the end of the beamline provided redundant particle identification over a wide momentum range. Moreover, a set of proportional wire chambers (WnT, WmS) allowed particle tracking along the spectrometer. A more complete discussion of the particle separation capabilities of the experimental apparatus, with examples of the performance obtained during NA56/SPY was given in [2].

The trigger logic was based on two independent trigger signals formed 268 m (trigger A = TOF2·B1) and 505 m (trigger B = TOF4·B2) downstream of the target. In addition, the threshold Cherenkov counters were used in anti-coincidence to veto or prescale particles above threshold.

3 Data analysis

At each measured point ($p = \pm 7$, ± 10, ± 15, $+20$, $+30$, ± 40, ± 67.5 and $+135$ GeV/c[1)]) about 10^5 pion triggers were collected to ensure a statistical accuracy better than 1%. Data analysis was similar to the one described in ref. [2] for the measurement of the K/π ratios. At 7 and 10 GeV/c, trigger A alone was required in order to increase the detection efficiency for short lived particles. The pion flux was measured from the sample of data collected with the Č0-Č1 counters set to veto electrons and muons. In the analysis, particles were tracked up to B1, where the mass resolution of the TOF system already allowed for a clean pion selection. At higher momenta, we required a coincidence of both triggers (A·B). In data analysis, electrons and muons were rejected at the calorimeter by requiring an energy deposition and a shower development consistent with the expectation for hadrons. At 15 and 20 GeV/c, the TOF measurement and the information of the Cherenkov counters were then exploited to identify pions; while above 20 GeV/c, the pion identification was based solely on the Cherenkov detectors. At all the momenta, pions were selected with full efficiency and negligible background, as measured directly from the data by combining the information from the different detectors.

To extract pion production rates, data were corrected for trigger and data acquisition efficiencies, particle decays in flight and contributions to pion fluxes from interactions of the primary beam with the material around the target area and from strange particle decays (K^0_s, Λ, Σ, ...) outside the target. Moreover, the pion flux normalization required the knowledge of the primary proton beam intensity and of the spectrometer acceptance.

Corrections for acquisition livetime and trigger efficiency were derived with a precision of 0.1% from the counting rates registered in the various components of the trigger system. The pion background due to proton interactions in the material around the target was measured at each momentum in empty target runs and amounted to about 3–4% of the pion flux with the target. The corresponding correction had an uncertainty below 0.1%. The corrections for pion decays in flight and for contributions to pion fluxes from strange particle decays outside the target were already discussed in [2] and had an overall uncertainty of 1% or less.

The absolute proton intensity delivered to SPY/NA56 by the SPS was determined with an overall uncertainty of 1.7%, after the absolute calibration of the SEM monitors and the careful monitoring of their long term stability throughout the experiment [11]. An additional uncertainty of 1% was related to the estimate of the fraction of primary beam that struck the target (0.988 ± 0.007) and to its long term stability. This was derived from the comparison of the primary beam position and spot size to the transverse dimensions of the target.

The acceptance of the spectrometer can be represented as the product of a phase-space acceptance, defined through the collimator openings, and a transmission coefficient, which accounts for particle losses along the beamline. To ensure an acceptable trigger rate two sets of collimator openings were chosen at $p \leq 40$ GeV/c and $p > 40$ GeV/c. The resulting phase-space acceptance was estimated to (16.53 ± 0.54) $\times 10^{-3}$ μsr ($\Delta p/p$ %) and (3.22 ± 0.19) $\times 10^{-3}$ μsr ($\Delta p/p$ %), respectively. The accuracy of the phase-space acceptance relied on the knowledge of the gaps between the jaws of the collimators. The physical aperture of the three collimators for a given electronic reading was carefully calibrated in the laboratory prior to installation in the beam tunnel. Moreover, the opening scale of each collimator was tested at the beginning of the experiment in a number of dedicated runs at 135 GeV/c, in which the flux of secondary protons was measured as a function of one collimator opening, the other two remaining fixed. All the three collimators showed the expected linear behaviour. However, an important offset in the scale of one of the collimators was revealed by the analysis of these measurements: extrapolation to zero flux lead to negative collimator opening. This offset was later confirmed by a mechanical inspection of the collimator and is accounted for in the quoted acceptances and their errors.

Particle losses along the beamline were calculated by means of an updated version of the TURTLE Monte Carlo simulation of beam transport [12], with the inclusion of multiple scattering and nuclear

[1)] The sign of the momentum indicates the charge of the particle.

collisions in the detector and beamline material (about 20% of a nuclear collision length in total). In addition, the particle transmission in the second part of the spectrometer (downstream of B1) was also measured at different momenta and collimator settings with special "proton runs", in which trigger A alone was required with the Č0-Č1 counters set to veto particles lighter than protons.

The TURTLE simulation was reliable in the first part of the beamline (up to B1), where a good agreement was obtained at all the momenta between the beam profiles predicted by TURTLE and the ones observed in the wire chambers. Moreover, according to the simulation, for $p \geq 15$ GeV/c the transmission upstream of B1 was never limited by the physical apertures of the beam magnets. The beam profiles observed at TOF2 (see fig. 2), where the beam had maximum beam size in the first part of the apparatus, were well within the transverse dimensions of all the beamline elements and corroborated this prediction. The calculation of the transmission up to B1 was checked for systematic contributions by changing various parameters of the simulation. In particular, the field strengths of all the quadrupoles in the first part of the beamline were allowed to vary according to the uncertainty in the supplied current. This resulted in a rather important uncertainty in the transmission at low momenta, ranging from about 8% at 7 GeV/c and about 4% at 15 GeV/c to 1.5% at 40 GeV/c.

Contrary to the upstream part, the transmissions measured in proton runs in the second part of the beamline were always lower than the expectations for protons, with a discrepancy ranging from about 2% at $p \geq 40$ GeV/c to about 8% at 15 GeV/c[2)] (see fig. 3). This discrepancy was most striking in the last part of the beamline (downstream of TOF3), where broader beam profiles were also observed in data than in Monte Carlo. In that region and in particular at low momenta, the transmission was limited by the physical aperture of the magnets along the beamline and the calculation of the particle loss might critically depend on magnet misalignments and on the exact treatment of edge effects in the fields of the magnets. Several proton runs were repeated during the experiment and the measured transmissions were found to be reproducible. Therefore, the transmissions predicted for pions from B1 to the end of the spectrometer were scaled according to the observed data/Monte Carlo discrepancy for protons. A systematic error of the order of 1% was attributed to this procedure to account for the uncertainty in the measurement of the proton transmission. An additional systematic error equal to the observed discrepancy between TURTLE and the measurements was added in quadrature, reflecting a very conservative choice in the estimate of the error on the beamline acceptance.

In summary, the acceptance of the spectrometer was determined with an accuracy ranging from 5% to 10% depending on the beam momentum. This was limited by the uncertainty on the phase-space acceptance at high momenta and on the beamline transmission at low momenta.

4 Results

Pion production yields in the forward direction as a function of the best estimate of the secondary beam momentum are listed in table 1. The units are particles per incident proton per sr($\Delta p/p$ %). For momenta up to 40 GeV/c the estimate of the momentum was derived in each run using the TOF system to measure the speeds of particles of different mass. At 67.5 and 135 GeV/c the momentum estimate from the beam magnet strengths was more accurate. The accuracy of the momentum estimate was better than 0.1% up to 20 GeV/c and of a few tens of a percent at higher momenta. This translates into a negligible error on the pion production yields.

The table gives both the pion yields corrected for strange particle decays outside the target and the yields prior to such correction (in parentheses). The latter might be of use for the calculation of neutrino fluxes in beamline configurations in which the distance between the target and the first magnetic element is of the same order as in our setup (about 1.35 m).

The corrected pion yields are shown in figure 4, together with the results from Atherton *et al.* [4]. Since the primary beam in our experiment (450 GeV/c) had a higher momentum than in Atherton *et al.* (400 GeV/c), their measurements at 60 and 120 GeV/c, corresponding to the same x_F as our measurements at 67.5 and 135 GeV/c are shown in the figure at $p = 67.5$ and 135 GeV/c. Moreover, the pion yields measured by Atherton *et al.* were rescaled by $(450/400)^2$ to account for the relation between the invariant cross-section and the yields given in the figure. The results of the two experiments agree within the experimental accuracy.

Kaon production rates in the forward direction as well as pion and kaon production rates as a

[2)] Note that in the measurement of the particle fluxes at 7 and 10 GeV/c, particles were not tracked downstream of B1.

function of the transverse momentum can be derived by combining the results quoted in this letter to the results on the K/π production ratios and on the shape of the p_T distributions already reported in [2]. Since the errors in the pion fluxes are largely dominated by the acceptance calculation and by the knowledge of the primary beam intensity, the errors quoted in this and in the previous letter can be safely treated as fully uncorrelated.

5 Conclusions

The present paper has reported on the NA56/SPY measurement of the pion production rates from 450 GeV/c protons hitting a beryllium target. An experimental accuracy better than 10% has been achieved, which is comparable to the one obtained in a previous experiment at higher momenta. The present data cover a secondary momentum range from 7 GeV/c to 135 GeV/c and provide the first measurement of these yields below 60 GeV/c. This low momentum region is of particular interest for the calculation of neutrino fluxes in neutrino experiments at accelerators.

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p (GeV/c)	π^+ production yield	
7.17	0.319 ± 0.031	(0.335 ± 0.033)
10.11	0.497 ± 0.041	(0.519 ± 0.043)
15.18	0.860 ± 0.086	(0.892 ± 0.089)
20.14	1.27 ± 0.10	(1.32 ± 0.11)
30.16	2.16 ± 0.13	(2.21 ± 0.14)
40.30	3.02 ± 0.15	(3.08 ± 0.16)
67.5	5.31 ± 0.35	(5.38 ± 0.36)
135.0	11.88 ± 0.79	(12.02 ± 0.80)

p (GeV/c)	π^- production yield	
6.97	0.236 ± 0.024	(0.259 ± 0.026)
10.00	0.313 ± 0.027	(0.341 ± 0.028)
15.07	0.702 ± 0.071	(0.751 ± 0.075)
40.40	2.41 ± 0.12	(2.47 ± 0.12)
67.5	3.09 ± 0.21	(3.13 ± 0.21)

Table 1: Pion production yields with the 100 mm Be target in the forward direction as a function of the pion momentum. The units are particles per incident proton per sr($\Delta p/p$ %). Values in parentheses are not corrected for the contribution to the pion flux coming from strange particle decays.

NA52 spectrometer (H6 beamline)

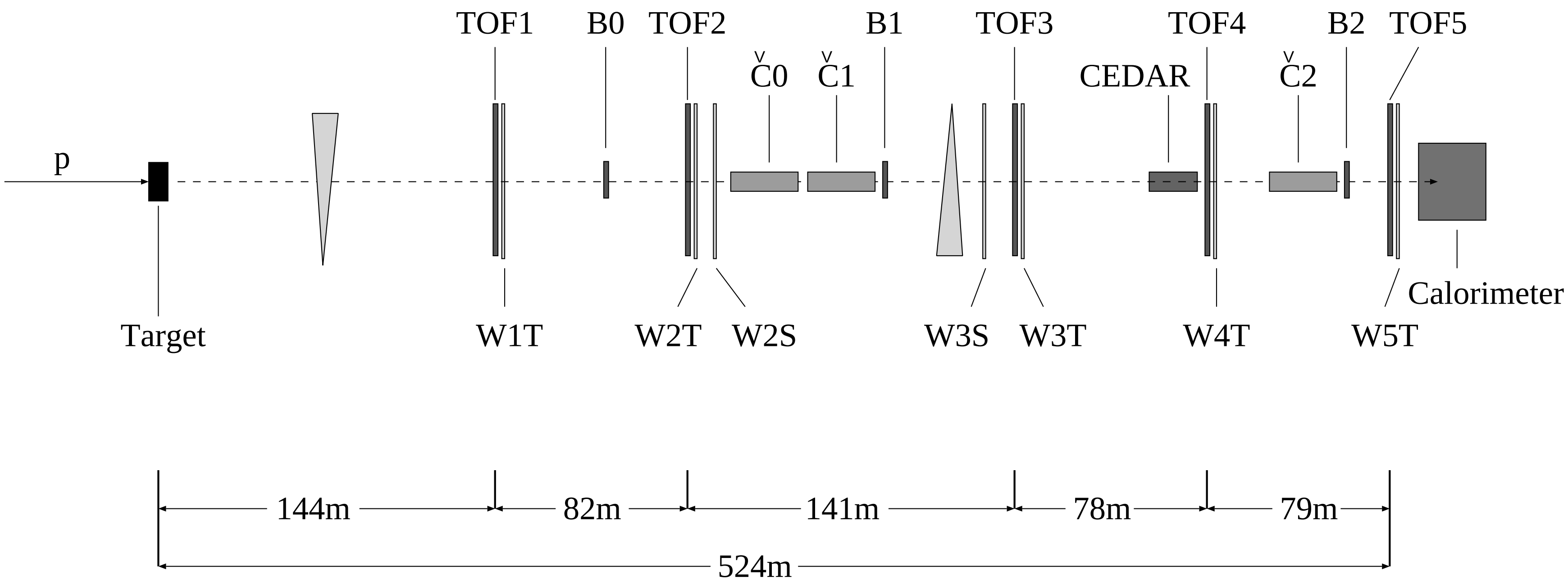

Figure 1: The SPY/NA56 experimental set-up.

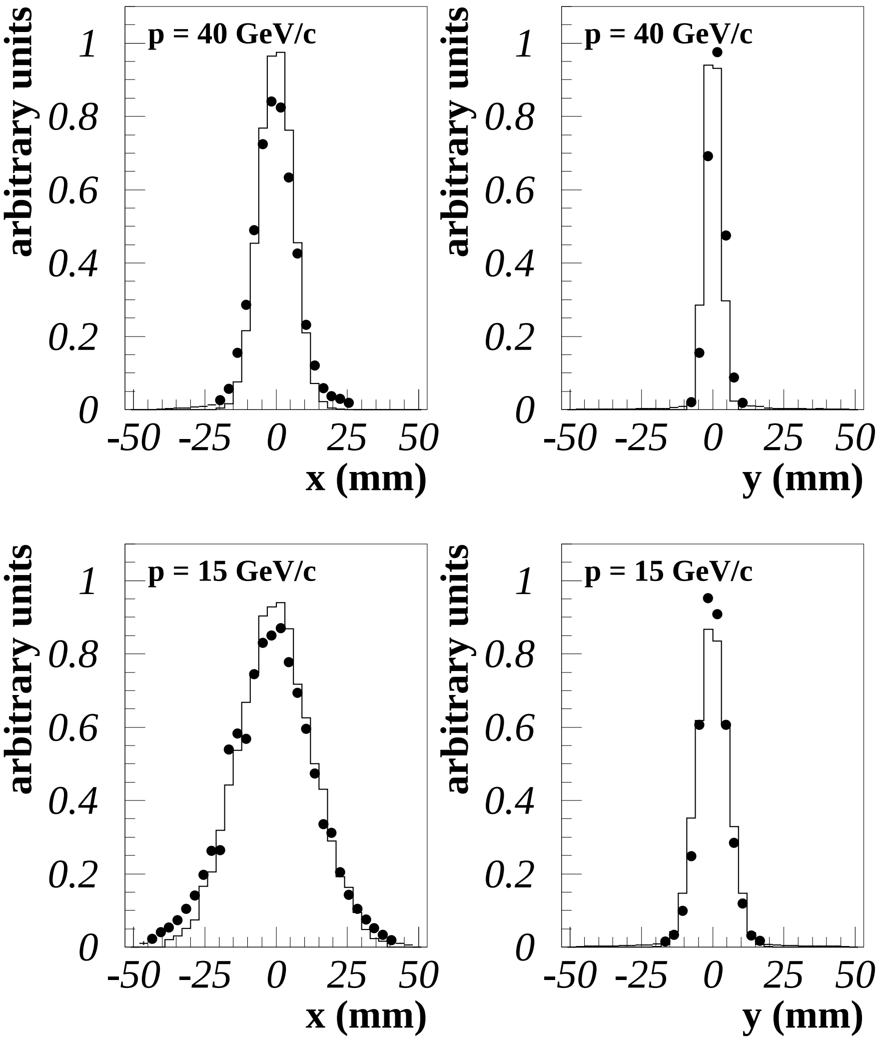

Figure 2: Beam profiles at TOF2 in data (full dots) and Monte Carlo (line) for 40 and 15 GeV/c protons. These beam profiles were recorded with the wire chamber W2T, located in a position where the beam had maximum (almost maximum) beam size in the x (y) coordinate upstream of B1.

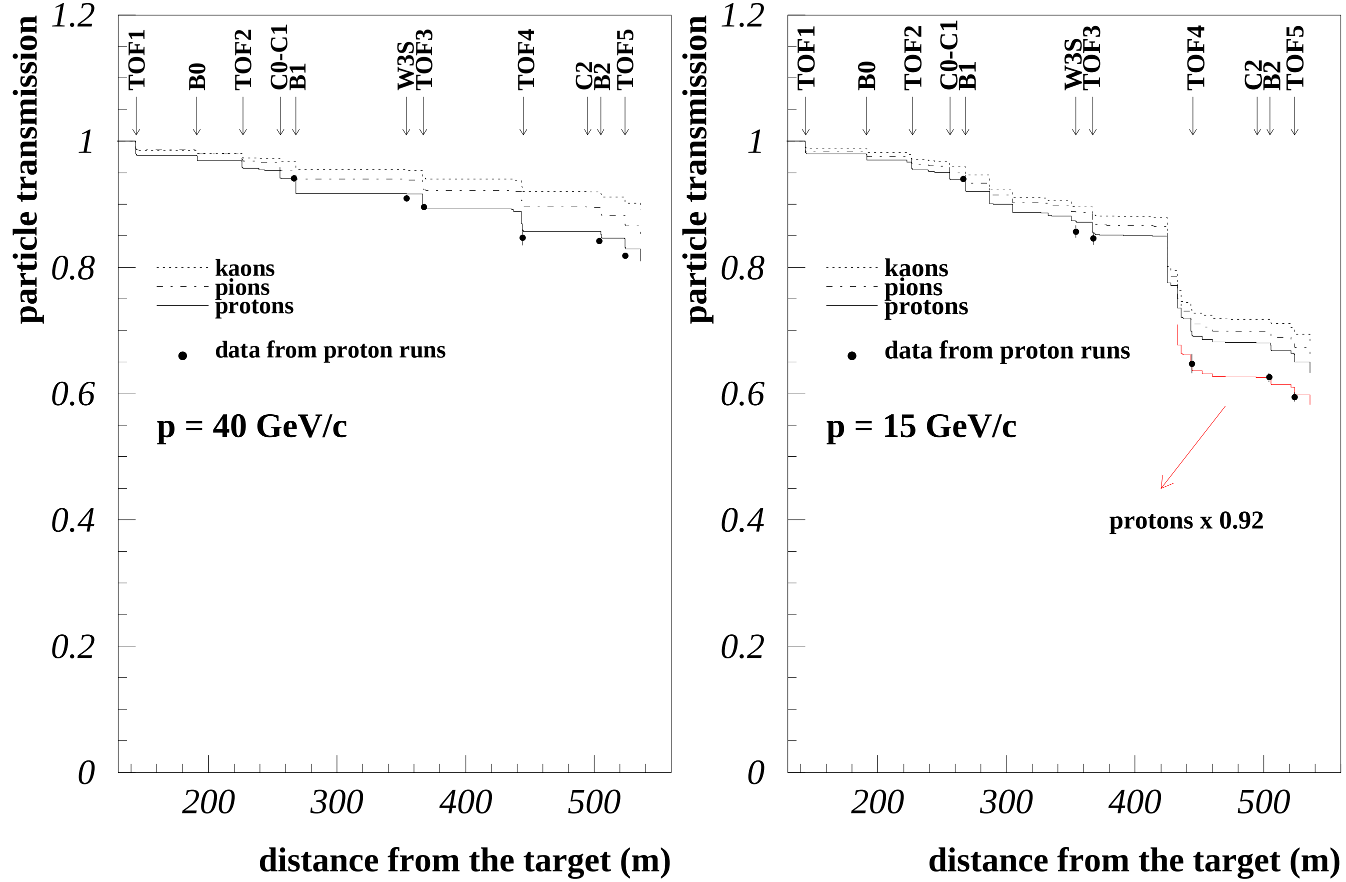

Figure 3: Particle losses downstream of the collimator which defines the momentum bite. The transmission measured in dedicated proton runs at 40 GeV/c (left) and 15 GeV/c (right) is compared to the results of the TURTLE simulation. The transmission is particle dependent due to the different interaction probabilities of protons, pions and kaons in the beamline material. At $p = 15$ GeV/c a rescaled TURTLE curve which fits the data in the final 150 m of the beamline is shown to indicate the magnitude of the data/Monte Carlo discrepancy.

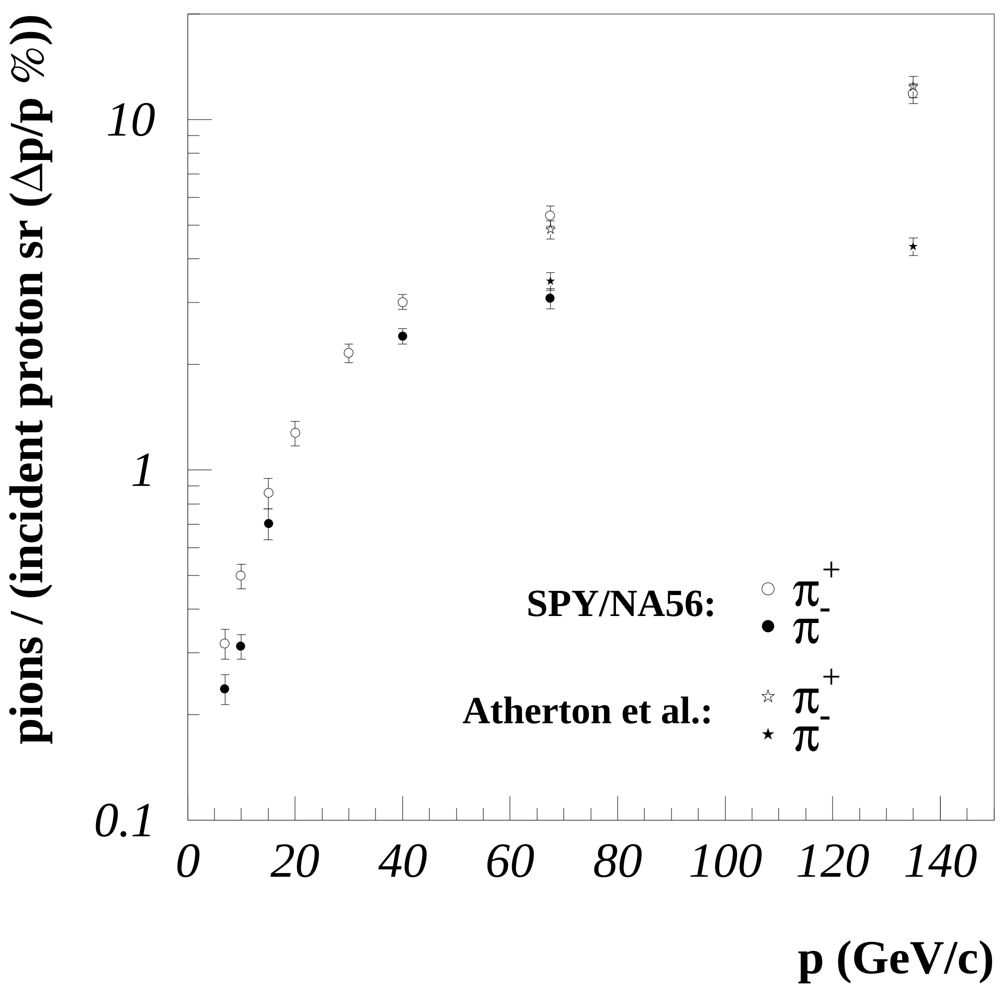

Figure 4: Pion production yields in the forward direction as a function of the pion momentum. Open (full) dots refer to positive (negative) particles. The SPY/NA56 data are corrected for the contribution of strange particle decays. The measurements of Atherton *et al.* have been rescaled to account for the lower primary beam momentum in their experiment (see text).