Vol. B8 (1977) ACTA PHYSICA POLONICA No 3

DOES BARYON EXCHANGE SHOW UP IN TRANSVERSE MOMENTUM OF PIONS?

By T. Hofmokl, J. Królikowski, A. Para and A. K. Wróblewski

Institute of Experimental Physics, Warsaw University*

(Received November 2, 1976)

The average transverse momentum of pions is studied as a function of the longitudinal proton momentum for πp interactions in the momentum range from 5 to 23 GeV/*c*. It is concluded that the effect of a possible baryon exchange on $\langle p_T \rangle$ of pions is much smaller than previously found by comparing events with backward and forward going protons.

1. Introduction

In a study of pp inelastic collisions it was found [1] that the average transverse momentum of pions produced in annihilation processes is significantly higher than that for non-annihilation reactions. Since high values of $\langle p_T \rangle$ suggest an interaction of short range, the difference has been attributed to baryon exchange in annihilation processes.

A baryon exchange mechanism in πp reactions is expected to give rise to protons emitted predominantly in the forward direction in the πp c. m. system. The forward direction is defined here as that of the primary pion in the c. m. system. For several reactions the average transverse momentum of pions in events with forward-going protons was indeed found to be larger than that of pions associated with backward-going protons [2, 3]. The difference was again interpreted as resulting from the baryon exchange mechanism.

In the present work the average transverse momentum of pions is studied as a function of the longitudinal proton momentum for πp interactions in the momentum range from 5 to 23 GeV/*c*. It is argued that the straightforward comparison of $\langle p_T \rangle$ values of pions associated with protons in the forward and backward hemispheres may lead to misleading conclusions. Thus, instead of comparing the hemispheres the following question is studied: is the $\langle p_T \rangle$ of pions equal or different in events in which the longitudinal momenta of protons differ only in sign buf not in the absolute value. It is shown that for many re-

* Address: Instytut Fizyki Doświadczalnej, Uniwersytet Warszawski, Hoża 69, 00-681 Warszawa, Poland.

actions studied the $\langle p_T \rangle$ of pions is equal within errors in the two classes of events. Thus any influence of baryon exchange in πp reactions of $\langle p_T \rangle$ of pions is negligible or at least much smaller than previously interpreted [3].

2. *Experimental data*

Table I contains a list of all reactions studied in the present work. The data at 8 and 16 GeV/*c* come from the ABBCCHW collaboration. In addition we used some data at 5 GeV/*c* [4], 11 GeV/*c* [5] and 23 GeV/*c* [6].

TABLE I

Data used for analysis

Reaction	Primary momentum GeV/*c*	Number of events	Average pion momentum MeV/*c* associated with proton going: backward $\langle p_T \rangle_F$	forward $\langle p_T \rangle_B$	$R = \frac{\langle p_T \rangle_F}{\langle p_T \rangle_B}$
$\pi^+ p \to p 2\pi^+ \pi^-$	8	5822	315 ± 2	465 ± 10	1.477 ± 0.032
	16	29229	327.8 ± 0.7	483 ± 10	1.474 ± 0.031
	23	5036	330 ± 2	445 ± 31	1.349 ± 0.094
$\pi^- p \to p \pi^- 2\pi^+$	16	5208	335 ± 2	439 ± 27	1.311 ± 0.081
$\pi^+ p \to p 3\pi^+ 2\pi^-$	5	1047	281 ± 3	300 ± 4	1.059 ± 0.018
	8	530	333 ± 4	383 ± 10	1.152 ± 0.033
	16	8745	350 ± 1	428 ± 4	1.220 ± 0.012
	23	776	354 ± 4	398 ± 15	1.124 ± 0.044
$\pi^- p \to p 2\pi^+ 3\pi^-$	11	917	331 ± 3	398 ± 9	1.202 ± 0.029
	16	1246	335 ± 3	462 ± 13	1.302 ± 0.038
$\pi^+ p \to p 4\pi^+ 3\pi^-$	16	1584	340 ± 3	374 ± 5	1.099 ± 0.018
$\pi^- p \to p 4\pi^- 3\pi^+$	16	303	340 ± 3	386 ± 14	1.136 ± 0.046
$\pi^+ p \to p 5\pi^+ 4\pi^-$	16	225	304 ± 1	320 ± 10	1.053 ± 0.050
$\pi^- p \to p 5\pi^- 4\pi^+$	16	30	299 ± 13	325 ± 22	1.087 ± 0.088

We have analysed only four-constraint channels in order to avoid identification biases. In spite of the limited number of events with protons emitted in the forward direction the average transverse momenta of pions associated with forward and backward going protons differ significantly (see Table I) in agreement with previous results [2, 3]. The ratio $R = \langle p_T \rangle_F / \langle p_T \rangle_B$ of the average transverse momenta of pions in events with forward and backward protons is approximately 1.4 in the reaction $\pi p \to p 3\pi$ and decreases with multiplicity to about 1.0 for the reaction $\pi p \to p 9\pi$. The energy dependence of R for a given reaction is less clear but the data are consistent with R being constant.

We believe that a straightforward comparison of $\langle p_T \rangle_B$ and $\langle p_T \rangle_F$ values may lead to misleading conclusions about the influence of possible baryon exchange on the transverse momentum of pions. This is so because in averaging over the two hemispheres different regions of phase space may be involved. It is shown in the next section that the observed differences between $\langle p_T \rangle_B$ and $\langle p_T \rangle_F$ values can partly be explained by the shape of the longitudinal momentum distribution of protons.

3. *Influence of the distribution in x of protons on the average transverse momentum of pions*

It is a well known feature of high energy interactions that secondary protons are more and more peaked backwards when energy increases and/or multiplicity decreases. In the following it is shown that the increase of the pion mean transverse momentum with the increase in $x_p = p_L/p_L^{max}$ for protons can be partly explained as a reflection of the shape of x distribution of protons.

Let as assume for a moment that secondary pions in πp interactions are emitted according to the available phase space, whereas protons follow an experimental distribution. It is obvious that no dynamical correlation between $\langle p_T \rangle$ of pions and x_p should exist.

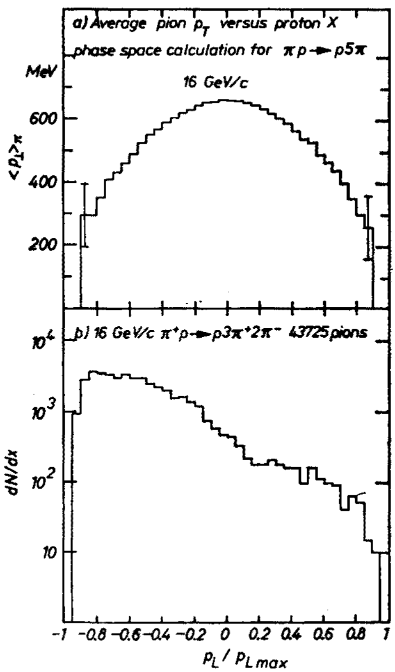

Fig. 1a. Phase space predictions for average pion transverse momentum as a function of proton x_p for $\pi p \to p(5\pi)$ reaction at 16 GeV/c. b. Experimental distribution of proton x_p for $\pi^+p \to p\pi^+\pi^+\pi^+\pi^-\pi^-$ reaction at 16 GeV/c

However one can show that the mean transverse momentum of pions associated with forward protons can be significantly higher than that of the remaining pions if the proton x_p distribution is peaked backward. This kinematical effect can be easily understood by comparing phase space prediction for $\langle p_T \rangle$ vs x_p using the experimental x_p distribution.

A typical experimental x_p distribution of protons (lower curve) is plotted in Fig. 1 together with the phase space prediction for mean pion transverse momentum as a function of x_p (upper curve). The experimental proton x_p distribution is peaked backwards. The phase space curve is symmetric and shows a broad maximum around $x_p = 0$. It can easily be understood that a sampling of events according to the experimental x_p distribution results in different $\langle p_T \rangle$ values of pions in events with forward and backward protons. The events with backward protons are concentrated near $x_p = -1$ which corresponds to low values of the pion $\langle p_T \rangle$ in these events. For events with forward protons higher values of $\langle p_T \rangle$ of pions are predicted by phase space since these events are concentrated near $x_p = 0$. This then produces the discussed difference in the $\langle p_T \rangle$ of pions in the two classes of events.

This purely kinematical effect was studied in detail for different energies using the $F(t)$ model [7]. In this model the transition matrix element depends only on the four-momentum transfer to the proton. The t dependence of the matrix element was derived from the experiment and approximated by $K(e^{At} + Be^{Ct} + De^{Et} + P)$. The results of the calculation are shown in Table II.

TABLE II

$F(t)$ model predictions for the ratio R of the average transverse momentum of pions associated with forward-going proton to that of pions associated with backward-going one

Reaction	Primary momentum GeV/c	$R = \dfrac{\langle p_T(\pi) \rangle_F}{\langle p_T(\pi) \rangle_B}$
$\pi p \to p5\pi$	5	1.041 ± 0.004
$\pi p \to p3\pi$	8	1.081 ± 0.005
$\pi p \to p5\pi$	8	1.087 ± 0.004
$\pi p \to p5\pi$	16	1.203 ± 0.004

The statistical errors were calculated from the number of FOWL generated events.

It is seen from Table II that the difference between the results for the forward and backward hemispheres increases with the increasing energy.

The above example shows that averaging over large x intervals may be misleading. In particular any averaging of the transverse momentum of pions over the two hemispheres may involve different regions of phase space depending on the actual shape of the x distribution of protons.

Thus instead of comparing the $\langle p_T \rangle$ of pions in the two hemispheres we studied the following question: Is the $\langle p_T \rangle$ of pions equal or different in events in which the longitudinal momenta of protons differ only in sign but not in absolute value?

In the limiting case the comparison can be made event by event by comparing each event with a forward proton with a corresponding event with the closest absolute value of $-x_p$ in the backward hemisphere. This comparison showed that for most reactions studied the difference in $\langle p_T \rangle$ of pions in the backward and forward hemispheres is negligible. However, in such an approach one does not use the full sample of events from the backward hemisphere and therefore the statistical significance of the result is decreased.

The next step is to compare the $\langle p_T \rangle$ of pions in narrow bins of $|x_p|$ in the forward and backward hemispheres. Such a comparison is shown in Fig. 2 for four π^+p reactions at 16 GeV/c for which we have the largest number of events. The experimental x_p distributions is also shown. One may see that for the ten-body and eight-body reactions the values

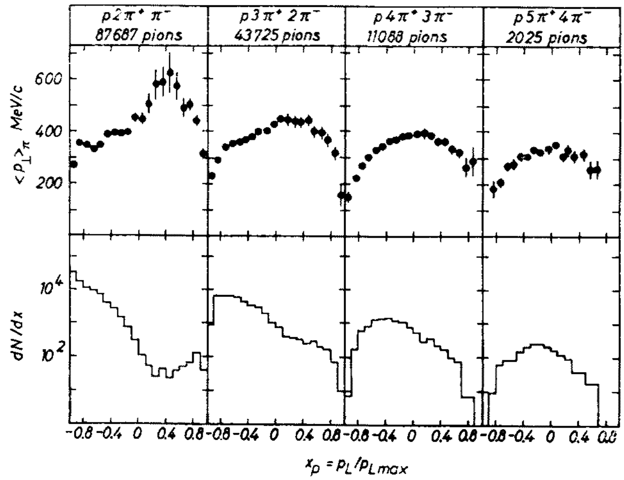

Fig. 2. The average pion transverse momentum as a function of x_p and the distribution of x_p for four π^+p reactions at 16 GeV/c

of $\langle p_T \rangle$ in the corresponding intervals of $|x_p|$ are equal within errors, whereas for the six-body and four-body reactions a certain forward-backward asymmetry is observed.

In a naive picture of hadronic interactions baryon exchange is likely to occur in central collisions in which many pions are produced. It is known, for example, that the F/B ratio for protons increases to unity with the increase in the number of pions (see Fig. 2). Therefore if baryon exchange is expected to produce predominantly forward going protons, its relative contribution and possible influence on the transverse momenta of pions should be larger in higher multiplicities.

The results presented in Fig. 2 do not support such an expectation.

4. *Weighting procedure and results*

In order to obtain a quantitative measure of the difference between $\langle p_T \rangle_F$ and $\langle p_T \rangle_B$ free from the influence of the x_p distribution we have introduced appropriate weights to symmetrize the x_p distributions in the forward and backward hemispheres. For each reaction the events with backward going proton were weighted by the x_p distribution in the forward hemisphere. Each event with a forward going proton determined the limits of a narrow bin in such a way that no other event was to be found there. The bin limits were set in the middle between the values of x_p of two neighbouring events. If an event had no neighbour on the side of large x_p the upper bin limit was set at the same distance from x_p as the lower bin limit. Exactly the same pattern of bins was reflected in the backward hemisphere (see Fig. 3). Backward events attributed to a particular forward event were

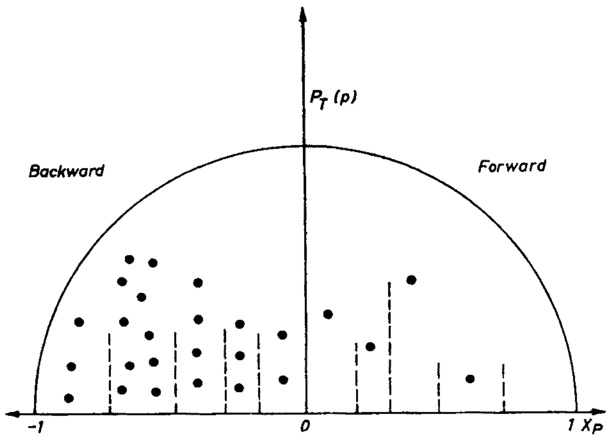

Fig. 3. The sketch explaining the choice of bins used in the weighting procedure

then so weighted that the sum of their weights equals that of the forward event. In some cases there remained backward-proton events (with x_p close to -1) not attributed to any forward event in which case their weights were set to zero.

The x_p distributions for forward proton events and weighted backward proton events were therefore set to be identical in shape. Also the total number of events in each of the two hemispheres was set to be equal through the weighting procedure.

Then we have calculated for each reaction the ratio, R_w, of the $\langle p_T \rangle_F$ to the $\langle p_T \rangle_B$ for weighted events. The results are presented in Table III. It is seen that R_w is considerably smaller than R (the ratio without weighting) which means that a significant part of the difference in the $\langle p_T \rangle$ of pions in the two hemispheres results from the asymmetry in x_p.

The results presented in Table III show that for most individual reactions the values of R_w are consistent with unity within two standard deviations[1]. However in π^+ induced reactions R_w is in several cases significantly greater than 1. Assuming duality diagrams [8] for many-body multiperipheral processes one may expect stronger contribution of baryon exchange for π^+p than in π^-p reactions which could explain the observed differences in R_w in the two cases. One should, however, keep in mind that the available statistics of π^-p events is much smaller than that of π^+p events and the statistical significance of results is not large.

[1] The errors of R_w quoted in Table III are statistical only and do not include uncertainties in the shape of the forward x_p distribution. For reactions in which the number of forward-proton events is smaller than 100 this uncertainty has been taken into account and statistical errors increased. The increased errors, marked by an asterisk in Table III have been estimated by considering differences in subsamples of forward-proton events in the reaction $\pi^+ p \to p 2\pi^+\pi^-$ with the largest number of events available.

TABLE III

The results of the weighting procedure

Reaction	Primary Momentum GeV/c	Number of forward events	$R = \frac{\langle p_T \rangle_F}{\langle p_T \rangle_B}$	$\langle p_T \rangle_F$	Weighted	
					$\langle p_T \rangle_B$	$R_w = \frac{\langle p_T \rangle_F}{\langle p_T \rangle_B}$
$\pi^+p \to p2\pi^+\pi^-$	8	231	1.477 ± 0.032	465 ± 10	373 ± 2	1.245 ± 0.028
	16	234	1.474 ± 0.031	483 ± 10	374 ± 0.8	1.292 ± 0.027
	23	20	1.349 ± 0.094	445 ± 31	390 ± 2	1.141 ± 0.091*
$\pi^-p \to p\pi^-2\pi^+$	16	130	1.311 ± 0.081	439 ± 27	474 ± 3	0.926 ± 0.074
$\pi^+p \to p3\pi^+2\pi^-$	5	353	1.059 ± 0.018	300 ± 4	295 ± 3	1.011 ± 0.017
	8	106	1.152 ± 0.033	383 ± 10	377 ± 4	1.018 ± 0.029
	16	674	1.220 ± 0.012	428 ± 4	398 ± 1	1.073 ± 0.011
	23	46	1.124 ± 0.044	398 ± 15	424 ± 5	0.939 ± 0.075*
$\pi^-p \to p2\pi^+3\pi^-$	11	111	1.202 ± 0.029	398 ± 9	387 ± 4	1.030 ± 0.025
	16	67	1.302 ± 0.038	462 ± 13	391 ± 3	1.182 ± 0.094*
$\pi^+p \to p4\pi^+3\pi^-$	16	273	1.099 ± 0.018	374 ± 5	362 ± 3	1.032 ± 0.016
$\pi^-p \to p3\pi^+4\pi^-$	16	36	1.136 ± 0.046	386 ± 14	369 ± 4	1.045 ± 0.083*
$\pi^+p \to p5\pi^+4\pi^-$	16	61	1.053 ± 0.050	320 ± 10	316 ± 11	1.012 ± 0.089*
$\pi^-p \to d4\pi^+5\pi^-$	16	11	1.087 ± 0.088	325 ± 22	361 ± 22	0.900 ± 0.082*

We have also checked the conjecture that the resonance production increases the R_w value. It was done by repeating the described analysis for two samples of events: *i*) for those where there was neither ϱ^0 nor Δ^{++} and *ii*) for those where at least one combination of $\pi^+\pi^-$ or $p\pi^+$ was in the appropriate mass limit (620–920 MeV for ϱ^0 and 1120–1340 MeV for Δ^{++}).

The average transverse momentum of pions for "no resonances" events is higher than for the resonance case whereas the ratio R_w is smaller for "no resonance" events than for the remaining sample. Table IV shows the results for four reactions with significant statistics.

For the first and third reaction production of ϱ^0 and Δ^{++} is sufficient to explain the observed effect. The situation is more complex for the reaction $\pi^+p \to p2\pi^+\pi^-$ at 16 GeV/c

TABLE IV

R_w for "resonances" and "no resonances" samples

Reaction	P_{LAB} GeV/c	"No resonances"	"Resonances"
$\pi^+p \to p2\pi^+\pi^-$	8	1.036 ± 0.042	1.239 ± 0.033
	16	1.154 ± 0.033	1.281 ± 0.038
$\pi^+p \to p3\pi^+2\pi^-$	16	1.005 ± 0.080	1.072 ± 0.010
$\pi^-p \to p2\pi^-\pi^+$	16	0.826 ± 0.076	1.109 ± 0.114

where $R_w > 1$ for both "resonance" and "no resonance" events. It was shown [9] that for the second reaction only about 4% of the events cannot be attributed to resonance production. Inspection of these untagged events reveals that the average pion transverse momentum in forward-proton events is lower than for those where a proton is emitted backwards. It follows that in this particular reaction the observed effect can be explained by resonance production.

In [10] it was established that the sample of πp events with $u > -1$ to the proton has features similar to $\bar{p}$p annihilation events. In particular, the average multiplicity $\langle n \rangle$ of produced pions and the correlation coefficient $f_2 = D^2 - \langle u \rangle$ are similar to those found in annihilation reactions and different from those for πp reactions with $t > -1$.

We have therefore repeated the analysis of $\langle p_T \rangle$ of pions in two samples of events

i) events with $u > -1$,

ii) events with $t > -1$.

The ratio R of the $\langle p_T \rangle$ pions in the two samples is shown in Fig. 4 for four π^+p reactions at 16 GeV/c. It is seen that again R is close to 1 and differs significantly from unity only

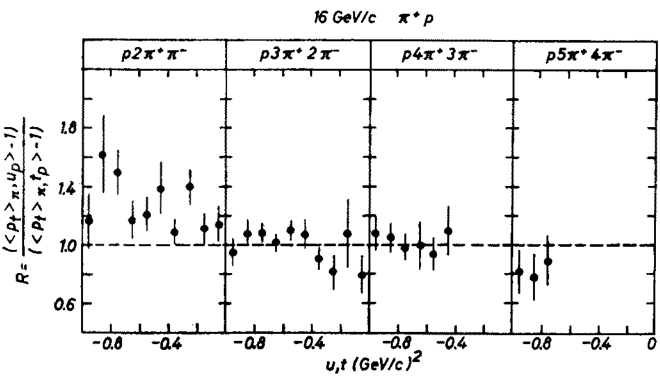

Fig. 4. The ratio R' of average pion transverse momenta of the events with $u_p > -1$ to those with $t_p > -1$ for four π^+p reactions at 16 GeV/c

in $\pi^+ p \to p\,\pi^- 2\pi^+$. It is in agreement with our previous conclusion that the $\langle p_T \rangle$ of pions in possible baryon exchange processes is not too different from the $\langle p_T \rangle$ in other πp events.

5. *Conclusions*

It was shown that the straightforward comparison of $\langle p_T \rangle$ of pions in πp events with forward and backward protons may result in misleading conclusions about the influence of baryon exchange process on transverse momenta of produced pions. The effect of a possible baryon exchange on pions is much smaller, if any, than previously believed.

We would like to thank ABBCCHW collaboration for permission to use 8 and 16 GeV/c πp data. We express our gratitude to P. Daronian, R. Lestienne and K. Lai for supplying us with the data of their collaborations used in this work.

REFERENCES

[1] P. S. Gregory et al., *Phys. Lett.* **43B**, 228 (1973).

[2] D. Bastien et al., *Phys. Rev.* **D9**, 1393 (1974).

[3] R. Lestienne et al., *Nucl. Phys.* **B67**, 348 (1973).

[4] Data of the Bonn–Durham–Nijmegen–Paris (E. P)–Torino Collaboration, privately communicated by R. Lestienne.

[5] Saclay data, privately communicated by P. Daronian.

[6] CERN–BNL–Wisconsin Collaboration.

[7] G. Białkowski, R. Sosnowski, *Phys. Lett.* **25B**, 529 (1969); A. Ziemiński, *Nucl. Phys.* **B14**, 75 (1969).

[8] G. Bozoki, E. Gombosi, T. Hofmokl, *Lettere Nuovo Cimento* **1**, 1099 (1971).

[9] ABBCCHLVW Collaboration, privately communicated by J. Stieve and *Nucl. Phys.* **B99**, 397 (1975).

[10] ABBCCHLVW Collaboration, to be published.