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HIERARCHY OF MEAN MULTIPLICITIES IN pn AND π^+n INTERACTIONS AT 195 GeV/c(*)

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Abstract

The dependence of the average charged multiplicity, $\langle n_X \rangle$, of the system X on $|t|$ and M_X^2 is studied for the reactions $p(\pi^+)n \to p_{fast}(\pi^+_{fast})+X$ and $p(\pi^+)n \to p_{slow}+X$ at 195 GeV/c. For a fixed M_X^2, $\langle n_X \rangle$ changes significantly among these reactions, yielding a systematic hierarchy of mean multiplicities. The results indicate that a proton emits on the average less charged particles than a pion and more than a neutron.

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The dependence of the average charged multiplicity $\langle n_X \rangle$ of the system X in inclusive hadronic reactions $a+b \to c+X$ on the square of the invariant mass of X, M_X^2, and on the square of the four-momentum transfer t between the incoming (a or b) and the outgoing particle c, has been previously studied both theoretically [1] and experimentally [2]. No specific predicition has been given for the $\langle n_X \rangle$ dependence on t. Experimentally, in some cases no dependence was found [3] and in others - a linear rise was indicated [2]. The M_X^2 dependence of $\langle n_X \rangle$, however, was predicted by various models and found experimentally in many reactions to have the form:
$\langle n_X \rangle = A + B \ln M_X^2$, where B is a universal slope of $\sim 1.3 - 1.4$. As predicted theoretically [1] this slope B was found [2] to be independent of t, s (total energy) and the type of incident particle, and identical to the slope of the linear increase with ln s of the average charged multiplicity $\langle n_c \rangle$ in reactions $a+b \to X$. On the other hand, contrary to prior works [4], the intercept A, namely the value of $\langle n_X \rangle$ for a fixed missing mass M_X^2 (or energy s), was recently found [2] to depend on the nature of the particle such that a pion fragments on the average into more charged particles than a proton (by about half a unit).

In this paper we present new results on the dependence of $\langle n_X \rangle$ on t and M_X^2 in a larger variety of inclusive reactions than before, by using a neutron target. The difference between the values of A reaches in the extreme case two units. Our results together with previous ones are interpreted in terms of a simple model [5], yielding a hierarchy of mean multiplicities in inclusive reactions.

The experiment was performed at Fermilab where the hybrid spectrometer consisting of the 30-inch deuterium bubble-chamber and proportional wire counters [6] was exposed to a mixed π^+/p beam of 195 GeV/c. The present analysis is based on ~110,000 pictures. Outgoing particles are defined to be π mesons, unless identified by ionization as protons (for $P_{lab} < 1.4$ GeV/c). Since fast particles with $x > 0.5$ ($x = 2P_L/\sqrt{s}$), when produced by a proton beam, are mostly protons, as found in a pp experiment [7], we define them to be protons. A pure sample of 3247 pn interactions and 1354 π^+n interactions was obtained by studying only odd prong events and even prong events with a backward visible spectator. Events that failed were remeasured yielding an overall track efficiency of almost 100%. With the forward PWC system, the accuracy in momentum of fast forward tracks is considerably improved over bare bubble chamber results.

We have studied the reactions:

(1) $p + n \to P_{fast} + X$ (1036 events)

(2) $p + n \to P_{slow} + X$ (652 events)

(3) $\pi^+ + n \to \pi^+_{fast} + X$ (345 events)

(4) $\pi^+ + n \to P_{slow} + X$ (278 events).

A cut $x > 0.5$ has been applied for the fast particle in (1) and (3), while slow protons are included in (2) and (4) when identified by ionization ($P_{lab} < 1.4$ GeV/c). A double scattering (D.S.) correction for secondary interactions of the produced particles with the other nucleon of the deuteron has been applied to reactions (1-4). Slow ("non-jet") particles in the primary interaction are assumed to move independently of each other

and to contribute incoherently to the secondary process, while fast ("jet") particles behave effectively as one entity (identical to the projectile) in the double scattering [8]. The overall D.S. effect is constrained to 14% [9]. A different correction is obtained for reactions (1)(3) and for reactions (2)(4) due to the different abundance of "non-jet" and "jet" particles in the system X. The effect of the D.S. correction on $\langle n_X \rangle$ is found to be not too big (~0.2).

In figure 1, $\langle n_X \rangle$ is presented as a function of M_X^2 for reactions (1-4). Fitting the data to $\langle n_X \rangle = A + B \ln M_X^2$ (solid lines), we confirm the linear behavior predicted and found before [1,2]. When similar fits are performed on sub-samples of the data in various $|t|$ slices, the slopes B are found to be independent of $|t|$ within the uncertainties. Although the values of B, as indicated in fig.1 are somewhat high, the distributions are consistent with the universal slope B = 1.4 (dashed lines). In fig.2, the dependence of $\langle n_X \rangle$ on $|t|$ is shown for the same reactions. A significant increase is observed for all reactions, when all events with $M_X^2 > 30$ GeV^2 are included. The overall data and those for various M_X^2 slices are consistent with a linear dependence $\langle n_X \rangle = A'' + C|t|$ (straight lines), where, within errors, C for each reaction is independent of M_X^2.

A two-dimensional fit has been performed with the data of reactions (1-4) to the expression $\langle n_X \rangle = a + b \ln M_X^2 + c|t|$. The best fit values and χ^2-probabilities are given in table 1 together with previous results [2] on the reactions

(5) $\pi^- + p \to P_{slow} + X$

(6) $\pi^- + p \to \pi^-_{fast} + X$

at 147 GeV/c. The results show that: a) b is consistent within errors with the universal slope B of the one-dimensionsal fits described above. b) c is small and consistent with zero within errors for the P_{slow} reactions (2) and (4), in agreement with previous results [2,3]. The rise of $\langle n \rangle$ with $|t|$ in fig.2 for these reactions is probably due to the rise with M_X^2, since high $|t|$ values are correlated with high M_X^2 values. c) c is positive and differs significantly from zero for the reactions (1) and (3) where a fast particle is involved, in agreement with [2].

A comparison between $\langle n_X \rangle$ of different reactions at fixed M_X^2 shows (fig.1) that a universal value for this quantity [4] is clearly ruled out. In particular, there is a surprisingly big difference of 2 units in the average multiplicities of reactions (3) and (4), which originate from one initial state in the same experiment; thus it is improbable that it be caused by systematic biases or normalization problems. In order to study this effect in a systematic way, we have fitted the data of reactions (1-4) in this experiment, reactions (5-6) at 147 GeV/c [2] and reactions (5) and (7)

$$(7)\quad p + p \rightarrow P_{slow} + X$$

at 205 GeV/c [4b] to the expression

$$(8)\quad \langle n_X \rangle = A' + 1.4 \ln (M_X^2/100) ,$$

where M_X^2 is given in units of GeV^2 and a universal slope of B = 1.4 is used. A' is the fitted value of $\langle n_X \rangle$ at $M_X^2 = 100\ GeV^2$. The results shown in table 1 reveal a hierarchy of values for A' for the various reactions extending from 4.6 up to 6.6.

Trying to explain this hierarchy we have parametrized $\langle n_X \rangle$ in the

inclusive reactions $a+b \rightarrow c+X$, where c is produced in the fragmentation region of a, by [2,5]

$$(9)\quad \langle n_X \rangle = n_{Eac} + B \ln(M_X^2/M_o^2) + n_b .$$

n_b, n_{Eac} are average multiplicities associated with the fragmentation regions of the real particle b and the virtual exchanged object coupled to particles a and c, E_{ac}, respectively, and M_o^2 is a constant scaling factor. The part of $\langle n_X \rangle$ due to the central region is $B \ln(M_X^2/M_o^2)$, and since B is universal, this term cancels out when differences of average multiplicities at fixed M_X^2 are calculated. The non-central contributions to $\langle n_X \rangle$ in (9) are given for reactions (1-7) in table 1. Taking differences between various pairs of reactions, we obtain the following results: $n_{Enp}-n_{Epp} = 0.27\pm0.25$(4-5), 0.21 ± 0.17 (2-7); $n_\pi - n_p = 0.59\pm0.10$(5-7), 0.65 ± 0.28(4-2); $n_{Epp}-n_{E\pi\pi} = 0.46\pm0.14$ (7-6), 0.51 ± 0.22(1-3); $n_p - n_n = 0.63\pm0.14$(7-1), 0.68 ± 0.22 (6-3), where the reaction numbers appear in brackets. Each quantity is calculated independently from two pairs of reactions and the results are internally consistent in all cases. For $n_\pi - n_p$, the results are also consistent with the difference in average multiplicities between the "on-mass shell" reactions, $\pi p \rightarrow X$ and $pp \rightarrow X$, as given in [2]. On the other hand, $n_p - n_n$ can also be obtained from the difference $\langle n \rangle_{bp\rightarrow X} - \langle n \rangle_{bn\rightarrow X}$ for any beam particle b. Experimentally [9,10] this energy independent quantity (∿0.3) is lower by about 2.5 standard deviations from the values of $n_p - n_n$ obtained in our reactions.

The emerging hierarchy in A''s (table 1) yields the following inequalities: $n_\pi > n_p > n_n$, $n_{Enp} > n_{Epp} > n_{E\pi\pi}$, which indicate that a pion (real or virtual) tends to emit on the average more charged particles in its fragmentation region than non-pions. (Note that E_{np} is dominantly due to π-exchange [11], E_{pp} may consist partly of a pion, and in $E_{\pi\pi}$ pion exchange is forbidden by G-parity). The big difference of 2 units in the average multiplicities of reactions (3) and (4) is due to the fact that for the first (last) reaction, the contributions to $\langle n_X \rangle$ (table 1) are obtained from the lower (higher) parts of the inequalities.

In summary, we have presented the dependence of the average charged multiplicity $\langle n_X \rangle$ for reactions (1-4) on $|t|$ and M_X^2. We find that $\langle n_X \rangle$ rises with $|t|$ for reactions (1) and (3), and is consistent with being constant with $|t|$ for reactions (2) and (4), in agreement with previous results [2,3]. Our results are consistent with the universal linear rise of $\langle n_X \rangle$ with $\ln M_X^2$ ($B \sim 1.4$). We interpret the difference in the $\langle n_X \rangle$ values of various reactions at fixed M_X^2 in terms of non-central contributions to $\langle n_X \rangle$ due to the fragmentation regions of the incoming (real or virtual) particles. We find a systematic hierarchy of mean multiplicities which explains the big difference of two units in the average multiplicities of reactions (3) and (4), originating from the $\pi^+ n$ initial state of this experiment. The results are internally consistent in all cases, except for the difference in the values of $n_p - n_n$ between "on-shell" (~ 0.3) and "off-shell" (~ 0.65) reactions. It should be emphasized that these results are presented only for a restricted energy region ($30 \leq M_X^2 \leq 200$ GeV^2). Indeed, interpreting the πp and pp multiplicity differences in terms of absorption [12], a cross-over is predicted such that above FNAL energies, the p multiplicities will be higher than the pion ones. It will be interesting to study the energy-dependence of the hierarchy in $\langle n_X \rangle$ and to extend it to other virtual and real particles, such as K mesons.

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TABLE CAPTION

Table 1: Results of two-dimensional fits to $\langle n_X \rangle$ data for reactions (1-4) in this experiment and for reactions (5-6) at 147 GeV/c. The right-most columns present the values of A' obtained by fitting expression (8) to the $\langle n_X \rangle$ data for reactions (1-7) and the non-central contributions to $\langle n_X \rangle$ for these reactions according to expression (9).

FIGURE CAPTIONS

Figure 1: The average charged multiplicity $\langle n_X \rangle$ for reactions (1-4) as a function of M_X^2. Full lines are 2-parameter fits to $\langle n_X \rangle = A + B \ln M_X^2$; the values of B are indicated. Dashed lines are 1-parameter fits with B = 1.4. All fits yield acceptable χ^2-probabilities.

Figure 2: The average charged multiplicity $\langle n_X \rangle$ for reactions (1-4) as a function of $|t|$ for $M_X^2 > 30$ GeV^2. The straight lines are fits to $\langle n_X \rangle = A'' + C|t|$; the values of C are indicated.

Table 1

Reaction No.	Reaction	P_{lab} GeV/c	$\langle n_X \rangle = a + b \ln M_X^2 + c\|t\|$: a	b	c	χ^2 Prob.	A' in (8)	Non-central Contribution to $\langle n_X \rangle$
4	$\pi^+ n \to p_s + X$	195	0.19 ± 2.57	1.28 ± 0.57	0.73 ± 0.69	0.37	6.60 ± 0.24	$n_{Enp} + n_\pi$
5	$\pi^- p \to p_s + X$	205					6.33 ± 0.06	$n_{Epp} + n_\pi$
		147		1.47 ± 0.15			6.14 ± 0.07	
2	$pn \to p_s + X$	195	-2.26 ± 0.70	1.75 ± 0.16	0.26 ± 0.26	0.96	5.95 ± 0.15	$n_{Enp} + n_p$
7	$pp \to p_s + X$	205					5.74 ± 0.08	$n_{Epp} + n_p$
6	$\pi^- p \to \pi^-_f + X$	147	-1.77 ± 0.61	1.43 ± 0.15	1.06 ± 0.19	0.26	5.28 ± 0.11	$n_{E\pi\pi} + n_p$
1	$pn \to p_f + X$	195	-0.49 ± 1.38	1.04 ± 0.31	1.51 ± 0.34	0.12	5.11 ± 0.12	$n_{Epp} + n_n$
3	$\pi^+ n \to \pi^+_f X$	195	-2.07 ± 1.82	1.23 ± 0.40	1.70 ± 0.36	0.09	4.60 ± 0.19	$n_{E\pi\pi} + n_n$

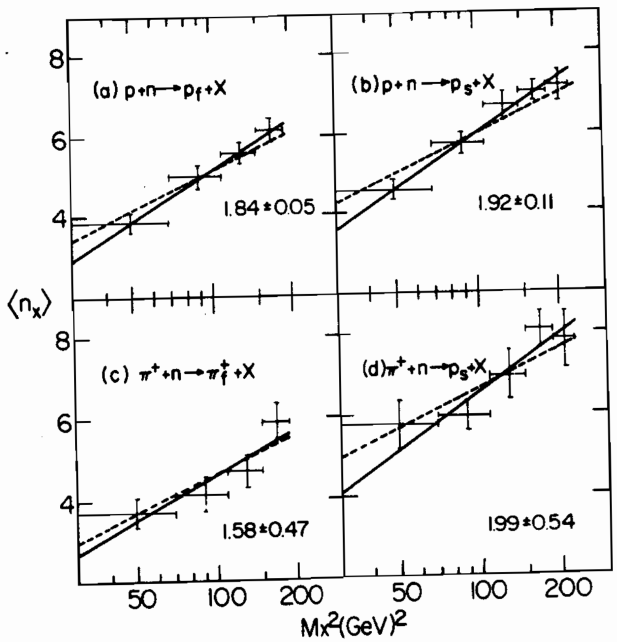

Figure 1

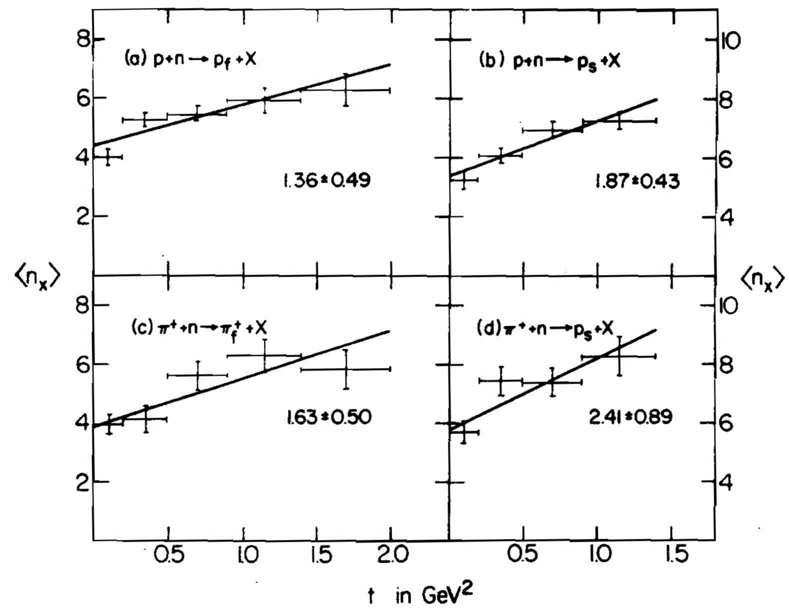

Figure 2