national accelerator laboratory

NAL-THY-67

July 1972

Pion Production in High Energy Proton Anti-Proton Annihilation

M. JACOB* AND S. NUSSINOV**

National Accelerator Laboratory, Batavia, Illinois 60510

ABSTRACT

A simple annihilation model leads to a set of predictions for pion distributions with marked differences with those found in proton-proton collisions. In particular most pions should be produced with low (<2) center of mass rapidity and their mean multiplicity should increase proportionally to the center of mass energy.

*On leave of absence from CERN, Geneva, Switzerland

**On leave of absence from University of Tel Aviv, Ramat Aviv, Israel

I. INTRODUCTION

Proton anti-proton annihilation at rest has been extensively studied and detailed information is now available about various final states.[1] Many configurations do occur but a very striking fact is the relatively narrow distribution of the number of charged pions. Annihilations frequently yield two π^- but seldom one or three. As a result the π^- multiplicity is far from the Poisson distribution which is known to provide a reasonable approximation for meson production in πp or pp collisions at present machine energy.[2] The reported value for the quantity $f_2 = \langle n(n-1)\rangle - \langle n\rangle^2$, in low energy $\bar{p}p$ annihilation where n is the number of π^-, is slightly below -1 with an averaged multiplicity $\langle n\rangle$ of 1.5.[3] This is to be contrasted with a value of f_2 close to zero which is observed in pp collisions with a similar pion yield $\langle n\rangle$ (at 20 - 70 GeV).[4] In the latter case, the observed multiplicity distribution can be interpreted in terms of the excitation of particle clusters.[5] The width of the multiplicity distribution then results more from the relatively wide spectrum of hadronic states which can be excited from the initial particles at any given energy rather than from the distribution width proper expected from each cluster. The latter distribution is narrow on statistical grounds and indeed found to be so in annihilation at rest. The same mean multiplicity may be therefore associated with very different distributions whether it is observed in proton proton collisions or in proton anti-proton annihilation. With increasing incident energy both multiplicities increase[6] and it is interesting to see if the pion distribution in the two cases will stay different or converge to a similar behavior. Any phenomenological statement is of course relevant at low or medium energy only since the annihilation cross section decreases very fast. It is expected to do so in view of the decreasing difference between the pp and $\bar{p}p$ total cross sections. The annihilation cross section could however account for only part of this difference which apparently decreases as $s^{-1/2}$ and it could exhibit still a faster drop off. Nevertheless we may define trends with increasing energy.

The model which we present here leads us to expect very different behavior for pion distributions in pp collisions and $\bar{p}p$ annihilation respectively. The few qualitative remarks which we can make are specific enough to test the annihilation mechanism which we emphasize. They are the following:

i) The annihilation cross section decreases as s^{-1},

ii) The mean multiplicity increases proportionaly to the center of mass energy ($\sqrt{s}$), even though the model is far from presenting a globally statistical picture,

iii) All pions are predominantly produced with small center of mass momenta. The model does not account for low multiplicity (2, 3 pions) annihilation which gives obviously fast pions but with very small branching ratios. For multiplicities close to the mean multiplicity we expect however that fast center of mass pions should be found only rarely. In other words, the rapidity distribution for annihilation should be more narrow than the one observed in pp collision with the same energy available for production and should even not change appreciably with energy, whereas the width of the rapidity distribution for pp processes is expected to become broader in proportion to log s.

iv) In much the same way as in pp collisions, the K/π ratio should remain small,

v) With increasing energy f_2 should eventually rise and increase even much faster than expected in pp collisions.[5]

Even though separating out the annihilation reactions from other production processes is difficult, these few features are very striking and are worth some emphasis.

II. A MODEL FOR ANNIHILATION

An annihilation amplitude implies baryon exchange between the two incident particles. At high energy one may consider production amplitudes with multi-baryon exchange as shown on Fig. 1a. Nevertheless considering the annihilation process in such a "multiperipheral" way would neglect important effects. When considering the central part of the chain, where the rapidity difference between secondaries becomes on the average small, the annihilation amplitude at rest should better replace the baryon exchange approximation. On the other hand, when considering the upper and lower part of the graph, the clustering effects expected and found[5, 7, 8] in pp collisions should be included. One may therefore consider it a better approximation to look at the annihilation amplitude as a double pole term. This is shown on Fig. 1b. One may then calculate the pion distributions in a semi classical way combining the distribution observed at rest (central part) with those expected from the proton and antiproton when slowing down. Such a picture may seem a priori to be plagued with multi-counting problems. This difficulty is however circumvented by the very fast decrease of the annihilation cross section at low energy. We may neglect annihilation when the $p\bar{p}$ rapidity difference is larger than a certain limit y_0 and consider that it happens when it is smaller. This is a crude approximation but it is good enough to determine the relevant trend. We may therefore view annihilation as a two step process. The first step is a slowing down of <u>both</u> the proton and the antiproton through pion emission. The second step is their annihilation proper which practically occurs once their rapidity difference or center of mass energy is small enough. The first step should be very similar to what observed in pp collision when both final nucleons are slow in the center of mass (a relatively unlikely process at high energy). The second step should be similar to annihilation at rest. The observed pion distribution should combine the general features of both.

In pp collisions low multiplicity events can be considered as due to cluster formation, the initial proton (s) getting excited into hadronic states which decay through a flare of pions.[7,8] The average momentum (rapidity) of the final proton is related to the mass of the excited hadronic state (Nova). We have

$$y = \mathrm{Log}\,\frac{q_L + \omega}{M} \qquad (1)$$

where y, q_LW and M respectively stand for the proton (nova) rapidity, the longitudinal, center of mass energy and mass of the nova. We have neglected the transverse momentum compared to the nova mass. We have assumed a statistical distribution in the cluster rest frame, with proton and pions produced with the same average rapidity. We keep the same picture for large multiplicities where all secondaries are slow in the center of mass. A similar mechanism should apply to $p\bar{p}$ collisions and in a certain fraction of the cases the two particles should slow down through pion emission. This provides for an efficient annihilation mechanism since the slow moving baryon anti-baryon system has a very large annihilation cross section. This picture for annihilation does not of course conflict with the multi-baryon exchange process of Fig. 1a. It merely corresponds to a more direct though approximate way for calculating the corresponding cross section. When Fig. 1a would however *a priori* lead to a somewhat uniform rapidity distribution, the distribution which we now get is strongly concentrated around zero center of mass rapidity. The annihilation pions proper come from a slow moving system and will therefore be produced (on the average) with a small rapidity. The "slowing down" pions on the other hand have to originate from relatively heavy clusters which only can give a baryon and an anti-baryon with small enough center of mass energy. As it follows from (1) they will have therefore small rapidity also.

Since in our picture annihilation occurs only when the proton and antiproton rapidities are small enough, we expect the rapidity distribution of the produced pions not to change appreciably with energy in contradistinction with what occurs in proton-proton collisions.

One may estimate the critical rapidity value y_o under which annihilation is assumed to occur. To this end we may take the center of mass energy squared to be below 5 GeV^2 ($q = 0.65$ GeV/c). This corresponds to an annihilation cross section of 60 mb which is of the same size as the $\bar{p}p$ total cross section.[9] This gives $y_o = 0.7$ and we may assume that annihilation takes place when both the proton and antiproton are within a rapidity interval ± 0.7 out of a total rapidity interval of ± 1.25 at 6 GeV/c, a typical high energy $\bar{p}$ momentum as available on present machine.

The invariant momentum distribution[10] observed in pp inelastic collisions is relatively flat. Using this for $\bar{p}p$ collisions one may thus estimate that the probability for both the baryon and the anti-baryon to be slow enough in the "intermediate" state is of the order of 0.3 at 6 GeV/c. With a total $\bar{p}p$ cross section of 63 mb, we obtain an estimate of about 20 mb for the annihilation cross section, in agreement with the experimental value.

The probability for the nucleon (anti-nucleon) to reach a center of mass momentum lower than a certain limit through pion emission will decrease inversely proportionally to the center of mass momentum as long as their inclusive distribution remains flat. Imposing that both particles slow down we obtain an annihilation cross section decreasing as s^{-1}. The proton distribution eventually dips at $x \approx 0$ at very high energies and the annihilation cross section thus calculated eventually decreases faster. It appears very unlikely that total annihilation cross section could be separated at these energies. The s^{-1} behavior is therefore to be tested against low or medium energy and Fig. 2 shows how available $s\sigma_A$ compares to a constant value. This is not excluded at all by present experiment and a constant value for $\sqrt{p_L}\,\sigma_A$, which would correspond to a usual Regge behavior, is at least not better supported by data.

It is worthwhile to mention that a multi-baryon exchange model for $\bar{p}p$ annihilation also suggests that

$$\sigma_A(s) \approx s^{-a}\left(\sigma_{\bar{p}p}^{tot}(s) - \sigma_{pp}^{tot}(s)\right) \qquad (2)$$

with $a > 0$ but not in general equal to 1/2 as obtained here. The reason is the following. The difference between the two total cross sections is assumed to result from the ω contribution with strong coupling to mesonic ($\rho\pi$) as well as baryonic $B\bar{B}$ t-channel states. The annihilation cross section however gets contribution from the $B\bar{B}$ t-channel only. One thus expects a weaker coupling and a lower effective intercept.

In our model secondaries originate from two separate sources. They come from annihilation at rest or low momentum which provides a mean multiplicity $\langle N_o \rangle$ of 5.5 (1.6 π^-) and they are also produced when both proton and anti-proton slow down. In both cases it is well known that the K/π ratio is small. We may then try to estimate the number of pions obtained during the slowing down process. Reducing the rapidity to 0.7 implies an excitation mass of $\sqrt{s/4}$ for large s. Both proton and anti-proton should be excited into heavy novae and we get

$$\langle n \rangle = \langle N_o \rangle + \frac{K}{\sigma_A} \int_{\sqrt{s}/4}^{\sqrt{s}-M_2} \rho(M_1) \int_{\sqrt{s}/4}^{3\sqrt{s}/4} \rho(M_2)\,(M_1+M_2)\, dM_1\, dM_2 \quad (2)$$

where $\rho(M)$ is the proton (anti-proton) excitation spectrum. The multiplicity is taken proportional to the excitation mass KM with $K \approx 2\ \mathrm{GeV}^{-1}$. With such an approximation, a logarithmic increase of the multiplicity in pp reaction imposes $\rho(M) \approx M^{-2}$ and it then follows that $\langle n \rangle$ increases proportionally to the center of mass energy: $\sqrt{s}$. Therefore the mean multiplicity increases much faster than the one measured in pp collisions. The reason is that in this model, annihilation requires very heavy excitation mass and hence relatively large multiplicities in order to happen at all. At the same time $< n(n-1)>$ should eventually increase proportionally to s.

We thus obtain a multiplicity increasing as the available energy in much the same way as we would expect from resonance formation and decay. It occurs however in a very different way. The relative invariance of the width of the rapidity distribution increasing quickly from the value observed at rest to its limit is however the strongest prediction of the model.

We also predict a rapid increase of the cross section or branching ratio for large multiplicities ($4\pi^+ 4\pi^-$ say) which are very small at low energy and which should quickly reach values charasteristic of the much more frequent (at rest) $3\pi^+ 3\pi^-$ annihilation mode as an extra $\pi^+\pi^-$ pair is obtained in the slowing down process.

The hypercharge exchange reaction $K\text{-}p \to \Lambda(\Sigma) + n\pi$ with a slow center of mass hyperon and large pion multiplicity could also use the same mechanism. Rapidity distributions in this particular case would also be very interesting.

REFERENCES

[1] R. Armenteros and B. French, High Energy Physics, Vol. N, 237, edited by E.H.S. Burhop, Academic Press (1969).

[2] D. Horn, Physics Reports, to be published.

[3] T. Field, Y. Oren, D.S. Rhines and T. Whitemore, ANL/HEP 7223 (1972).

[4] D. B. Smith, UCRL-20632 (1971); R. Panvini et. al., Brookhaven preprint 1972. Soviet French Collaboration preprint 1972.

[5] E. Berger, et. al., Correlations in High Energy Production Processes, Phys. Rev., to be published.

[6] E. Flamino, J.D. Hansen, D.R.O. Morrison and N. Tovey, CERN/HERA 70-3; G. Alexander, et.al., Nuclear Phys. B 23, 557 (1970).

[7] M. Jacob and R. Slansky, Phys. Letters 37B, 408 (1971), Phys. Rev. D5, 1847 (1972).

[8] W. Burdett, et.al., Vanderbilt. Brookhaven preprint 1972.

[9] We assume that the high energy total cross section reflects an interaction radius and we simply impose that the annihilation cross section, annihilation being considered as a final state effect, should be larger than this geometrical limit.

[10] L.G. Ratner, et.al., Phys. Rev. Letters 27, 68 (1971).

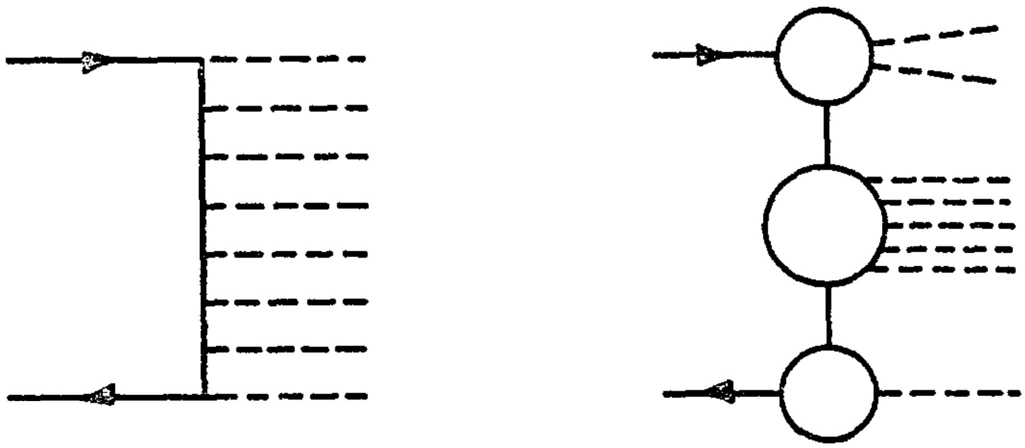
FIGURE CAPTIONS

Figure 1: Annihilation amplitude

1.a Multi-baryon exchange graph

1.b Grouping of secondaries according to low energy annihilation and slowing down processes.

Figure 2: $s\sigma_A$ and $\sqrt{s}\sigma_A$ as a function of energy. Data are from Ref. 6.



(a) (b)

Fig. 1

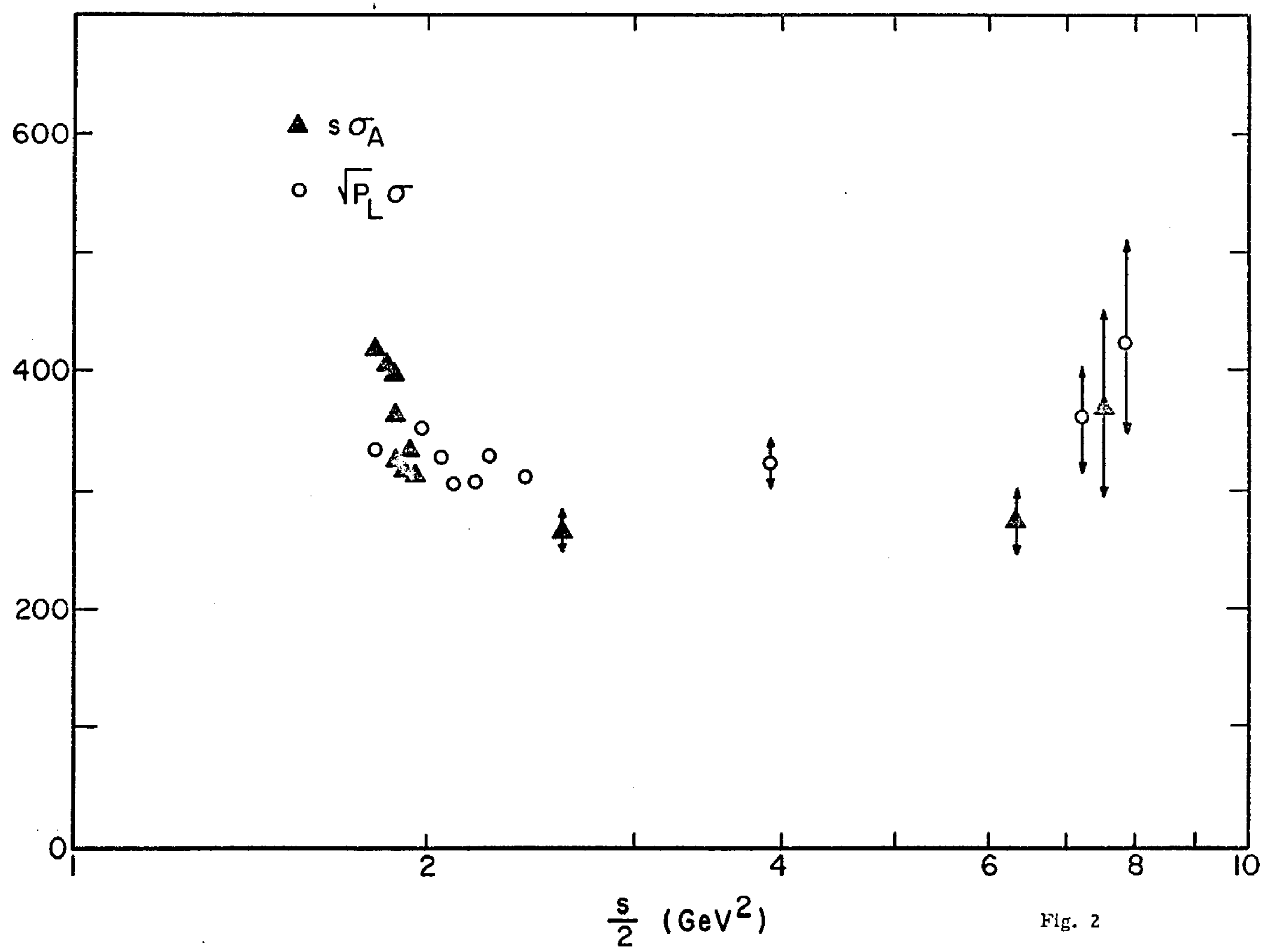


Fig. 2