Vol. B10 (1979) ACTA PHYSICA POLONICA No 9

ANTIPROTON-PROTON INTERACTIONS AT 22.4 GeV/c AND THE QUARK-PARTON MODEL OF MULTIPARTICLE PRODUCTION

By P. Lichard, A. Mašejová and J. Pišút

Department of Theoretical Physics, Comenius University, Bratislava*

J. Cvach** and A. Valkárová***

Joint Institute of Nuclear Research, Dubna, USSR

(Received February 19, 1979)

We compare the predictions following from the Monte Carlo quark-parton model of multiparticle production with the extensive set of data on antiproton–proton interactions at 22.4 GeV/c in the 2m bubble chamber Ludmila at Serpukhov. The emphasis is being placed upon such data which may give some information about the distribution of quarks and antiquarks during the intermediate stages of the collision.

1. *Introduction*

During the past five years it was shown that the quark-parton model gives a reasonable description [1–12] of many qualitative and sometimes even quantitative features of multiparticle production in hadronic collisions. In the present paper we shall compare the predictions following from the Monte Carlo quark-parton model [6–9] with the data [13–21] on $\bar{p}p$ interactions at 22.4 GeV/c obtained at the bubble chamber "Ludmila" at Serpukhov. The paper is organized in the following way. In the rest of the introduction we briefly describe the standard version [6, 7] of the Monte Carlo quark-parton model. Then in Section 2 we discuss in some details the modifications used in the present study. In Section 3 we compare the predictions of the "standard" and "modified" versions of the model with the data and finally in Section 4 we comment upon the results obtained.

* Address: Department of Theoretical Physics, Comenius University, 81631 Bratislava — Mlynská Dolina, Czechoslovakia.

** On leave of absence from the Institute of Physics, Czechoslovak Academy of Science, Prague, Czechoslovakia.

*** On leave of absence from Nuclear Center of the Charles University, Prague, Czechoslovakia.

The model [6–9] has much in common with the preceding work on quark-parton models of multiparticle production, in particular with the approach of Anisovich and Shekhter [3] and Bjorken and Farrar [4]. In contradistinction to their work we have a somewhat closer connection with the quark-parton model description of deep inelastic electroproduction and, what is practically more important, the model is cast in Monte Carlo program enabling thus (in principle) a comparison with any piece of data. The models of Van Hove and Pokorski [5], Likhoded et al. [11], Das and Hwa [10, 12] are mostly concerned with fragmentation region (large x), where the data from bubble chambers are usually rather meagre.

The model [6, 7] is based on the following intuitive picture of the high energy hadronic reactions: the collision is initiated by the interaction of "wee" partons, in the following stage the two hadrons get excited, gluons are converted to quark (Q)-antiquark ($\overline{\mathrm{Q}}$) pairs and finally rapidity neighbours recombine to stable and unstable hadrons, with mesons being formed by $\mathrm{Q\overline{Q}}$ and baryons and antibaryons by QQQ and $\mathrm{\overline{Q}\overline{Q}\overline{Q}}$ systems. The rules for recombination are described in Ref. [6]. During the recombination stable and unstable hadrons are formed in the ratios given by SU (6) weight factors [3, 4]. In the last stage unstable particles decay. The decay probabilities, taken from the compilation of data by Particle Data Group, are built into the Monte Carlo program.

The following features, constraints and assumptions are explicitly built into the model:

(*i*) energy-momentum conservation,

(*ii*) cut-off on transverse momenta of Q's and $\overline{\mathrm{Q}}$'s,

(*iii*) hadrons are formed by recombinations of Q's and $\overline{\mathrm{Q}}$'s and the following outcomes of recombinations are taken into account: the octet of pseudoscalar and the nonet of vector mesons and the octet and decuplet of baryons. The ratio of vector to pseudoscalar is supposed to be given by spin factors (V/PS = 3) and similarly the ratio of decuplet to octet of baryons is supposed to be equal to D/O = 2,

(*iv*) the occurrence of strange Q's and $\overline{\mathrm{Q}}$'s in the intermediate state is suppressed by the phenomenological factor strange/up = 1:2,

(*v*) valence quarks have a tendency to keep rather large momentum fractions during the collision,

(*vi*) all said above is based on the assumption that Q's and $\overline{\mathrm{Q}}$'s act in a sense "individually" during the evolution of the collision.

As discussed earlier [6] the model cannot describe the diffractive dissociation. This point turns out to be important in making the comparison with the data.

On a technical level the program works roughly as follows. One first generates the exclusive configurations of Q's and $\overline{\mathrm{Q}}$'s in the phase space. Each configuration is then assigned a weight as implied by the expression

$$dP_N(y_1, \overrightarrow{p_{T1}}, \ldots, y_N, \overrightarrow{p_{TN}}) \sim G^n W_{id} V(x_1, x_2, x_3) V(x_4, x_5, x_6)$$
$$\times \exp\left(-\sum_1^N p_{Ti}^2/R^2\right)\delta\left(\sum_1^N \vec{p}_i\right)\delta\left(E - \sum_1^N E_i\right)\prod_1^N dy_i d^2 p_{Ti}. \quad (1)$$

Here N is the total number of Q's and $\overline{\mathrm{Q}}$'s in a particular event, it is the sum of the number of valence Q's and $\overline{\mathrm{Q}}$'s (6 for $\bar{\mathrm{p}}$p collision) and of the number of additionally created

Q's and $\bar{Q}$'s. In this way $N = 6+2n$. G is a parameter regulating the average multiplicity of partons (in what follows "parton" means either a Q or an $\bar{Q}$) and consequently also the average multiplicity of final state hadrons. W_{id} is a factor taking into account the identity of partons being present before the recombination. The explicit form of W_{id} is given in Ref. [6] and its presence is also commented upon in the work of Kuti and Weisskopf [22], where the exclusive configurations of partons were considered for the first time (in connection with the nucleon structure functions in deep inelastic electroproduction). The factors $V(x_1, x_2, x_3)$ and $V(x_4, x_5, x_6)$ are here to give larger weights to configurations with valence partons having larger momentum fractions x_i. For $\bar{p}p$ collisions we have three valence partons in the proton with momentum fractions x_1, x_2, x_3 and three in antiproton with x_4, x_5, x_6. The factors V are taken in the same form as suggested by Kuti and Weisskopf [22], namely

$$V(x_1, x_2, x_3) = (|x_1|\,|x_2|\,|x_3|)^{1/2}, \qquad V(x_4, x_5, x_6) = (|x_4|\,|x_5|\,|x_6|)^{1/2}.$$

Since it is assumed that the interaction is initiated by wee (i.e. non-valence) partons we consider only configurations in which valence partons keep their direction of motion in the c.m. system (those of $\bar{p}$ moving forward and those of p moving backward). In the present paper all quantities refer to the c.m. system of $\bar{p}p$ collision. The remaining factors in Eq. (1) take into account the energy-momentum conservation, the p_T cut-off and the phase space volume ($d^3p/E = dyd^2p_T$). The masses of quarks are fixed at rather small values, namely $m_u = m_d = 10$ MeV/c^2 and $m_s = 160$ MeV/c^2.

After an exclusive configuration of Q's and $\bar{Q}$'s is generated the rapidity neighbours recombine to hadrons (for details see Ref. [6]) and finally unstable particles decay (branching ratios being taken from Particle Data Group tables). In the program there is an option which permits a desired particle to be declared as stable or unstable. If, for instance, we calculate the inclusive spectrum of Λ we declare it as stable, but if we are interested in comparing the inclusive distribution of protons with the data we can declare Λ as unstable (and include thus also protons from its decays).

The described version of the model was used in Refs. [6, 7, 8] and it will be referred to in what follows as the "standard" one.

2. *The "modified" version of the model*

When applying a certain model to more sets of data it is generally wiser to keep the model (if possible) unmodified. This was also the general philosophy in Refs. [6, 7, 8]. On the other hand, the available data on $\bar{p}p$ interactions at 22.4 GeV/c are rather extensive. Having the possibility of comparing the results of the model with so many data one can ask what modifications of the model are indicated by such data. Furthermore, the original version of the model was written almost three years ago and the knowledge of high energy interactions increased considerably (both in theory and in experiment) during that time. Because of that it seems appropriate to think about the possibility of modifying the model.

We shall now discuss two points in which the recent evolution might imply important changes. Nowadays it is generally believed that quarks have a new quantum number, called colour. This means that quarks, apart of other quantum numbers, can be either, say, "red", or "blue", or "yellow". This new degree of freedom has some implications for the weights of parton configurations. In the present model we do not take colour into account explicitly but one can imagine what would be some of its consequences. In an event, say, with 6 hadrons in the final state we have in the intermediate state about 15 partons. There are three degrees of freedom for flavour (u, d, s quarks), two possibilities for spin orientation and three for colour. Altogether we have thus $3 \times 2 \times 3 = 18$ different

TABLE I

The parameters used in the "standard" and "modified" versions of the model

Parameter	Standard	Modified
G	1.98	2.35
R_{val}	0.45	0.80
R_{sea}	0.45	0.50
Number of generated "equivalent events"	5269	2484

In a Monte Carlo generation each event is assigned a weight w_i. The number of "equivalent events" is then defined as

$$N = (\sum_1^n w_i)^2/(\sum_1^n w_i^2),$$

where n is the number of generated events. The number N roughly corresponds to the events obtained in an experiment.

quark states and if taking into account also antiquarks this makes 36 different states. The effects due to identity of partons will be thus rather small. Phrasing the same thing differently we can say that the introduction of colour diminishes the effects due to the identity of partons. To take this into account in a very rough way we have just simply deleted the factor W_{id} from Eq. (1).

There is also another reason which makes somewhat dubious the previously used factor for identical particles. According to the parton model picture of the space-time evolution of hadron collision different rapidity regions get excited in different moments. The factor which takes into account the identity of particles created in different space-time regions is then somewhat uncertain. A complete solution of this problem would require more detailed understanding of the dynamics of the collision.

The next point concerns the question of the transverse momenta of valence partons. The present evidence from large p_T processes, dimuon production (for a discussion and references see e.g. [23]) and the production of hadrons in deep inelastic e^-p collisions indicates that the transverse momenta of partons within hadrons increase with increasing momentum fraction x. The simplest interpretation of this situation is that valence partons have larger transverse momenta that partons from the "sea". As will be shown below this allows us to describe in the phenomenological way the sea-gull effect observed in $\bar{p}p$ interactions at 22.4 GeV/c. In the program one simply changes the term $\exp(-\sum_{1}^{N=2n+6} p_{Ti}^2/R^2)$ in Eq. (1) in the following way

$$\exp(-\sum_{1}^{N} p_{Ti}^2/R^2) \to \exp(-\sum_{1}^{6} p_{Ti}^2/R_{\mathrm{val}}^2)\exp(-\sum_{1}^{2n} p_{Ti}^2/R_{\mathrm{sea}}^2).$$

The third point in which the "modified" version differs from the "standard" one is not related to the recent developments in strong interactions but just reflects an uncertainty present in the model. As already mentioned the present model does not describe the diffractive dissociation. In this way one can determine G by two methods:

(a) one first estimates the contribution of the diffractive dissociation to the topological cross sections and then determines the value of G from the average multiplicity of the remaining non-diffractive component,

(b) alternatively one can fix G by requiring that the topological cross section were well reproduced in the region $n > \langle n \rangle$, where the diffractive component is supposed to have only negligible effects.

In both the "standard" and "modified" versions we have used the procedure (a). The average multiplicity in non-diffractive events was estimated by using the data [17] on σ_{diff}, $\langle n \rangle_{\mathrm{diff}}$, σ_{inel} and $\langle n \rangle_{\mathrm{inel}}$. The constants used in both versions are listed in Table I.

3. *The comparison with the data*

The present model contains some of the basic assumptions of the quark-parton description of the hadronic collisions and the general constraints (energy-momentum conservation and p_T cut-off). More details of the dynamics were not specified. In this situation we shall make no attempt at the detailed comparison, but we shall rather look at the qualitative agreement or disagreement of the model with the data. In this way we hope to locate those features of the data which are most significant for studying the dynamics of the collision and which will deserve more attention in the future.

We have done two Monte Carlo calculations, one in the "standard" and the second in the "modified" version. In general one can say that in most cases the two versions give rather similar results, notable exceptions being the topological cross sections for large multiplicities and the sea-gull effect. In most cases we shall therefore present only the results obtained in one of the two versions.

Average multiplicities

The results are summarised in Table II and compared with the data. A look at the Table II shows immediately that there is a marked disagreement in the average multiplicity of ϱ^0. In the model, as mentioned above, we have put the ratio of directly produced vector/pseudoscalar mesons as being equal to 3. This is what immediately follows from the SU(6) arguments applied to the recombination process [3]. Most of the available data on strong interactions (including the $\bar{p}p$ at 22.4 GeV/c) indicate that this ratio is lower by the factor of 3 (vector/pseudoscalar $\approx$ 1). Still, the analysis of the 40 GeV/c π^-p data from the propane bubble chamber group at Dubna [24] and the results of the Split-Field--Magnet group at CERN-ISR [25] are consistent with the value V/PS = vector/pseudoscalar ≈ 3 (for directly produced particles). The situation is thus far from being settled but it should be stated clearly that the 22.4 GeV/c data in $\bar{p}p$ interactions seem to require

TABLE II

Average multiplicities of particles produced in $\bar{p}p$ interactions at 22.4 GeV/c

Particle	Modified	Standard	Data
all negative	2.47 ±0.03	2.40 ±0.02	2.35 ±0.03 [18]
π^+	1.82 ±0.05	1.75 ±0.03	1.91 ±0.02 [20]
π^0	2.30 ±0.03	2.26 ±0.02	1.86 ±0.09 [13]
p	0.57 ±0.02	0.59 ±0.01	0.41 ±0.02 [20]
Δ^{++}	0.086±0.006	0.078±0.004	0.115±0.003 [19]
ρ^0	0.43 ±0.01	0.42 ±0.01	0.21 ±0.05 [14]
Λ/Σ^0	0.081±0.006	0.047±0.002	0.027±0.005 [13]
K_S^0	0.092±0.006	0.055±0.003	0.058±0.003 [13]
K^+	0.104±0.006	0.055±0.003	
Δ^+	0.38 ±0.01	0.40 ±0.01	
Δ^0	0.105±0.006	0.126±0.005	
Δ^-	0.006±0.001	0.005±0.001	
ρ^+	0.36 ±0.01	0.36 ±0.01	
K^{*+}	0.079±0.006	0.046±0.002	
ω	0.43 ±0.01	0.44 ±0.01	
ϕ	0.036±0.004	0.018±0.002	
η	0.060±0.004	0.050±0.003	

the lower value of the V/PS ratio. In our program this ratio may be considered as a free parameter and in further, more detailed, studies it should be lowered[1].

In this context it is very interesting to look at the Δ^{++}/p ratio. Table II shows that the results, obtained with the SU(6) motivated ratio D/O = baryon decuplet/baryon octet = 2, look reasonable. The reason why V/PS following from SU (6) arguments is probably wrong and D/O right lies presumably in the differences between the masses of the multiplets. If, say, a Q and an $\bar{Q}$ can recombine to a PS or to a V meson the masses are relevant and the factor 3 following from the SU(6) should be multiplied by some function $f(m)$, m is the mass of recombining $Q\bar{Q}$ system[2]. This is clearly one of the problems which deserve further study.

[1] Experimentally, this question can be definitely solved only by the clean data on ρ^0 production observed via $\rho^0 \to \mu^+\mu^-$ decay. The data [26] not yet covering the full x-range indicate V/PS ~ 1 but the result is not definite. In the 40 GeV/c region the problem might be solved perhaps at the RISK streamer chamber [27].

[2] Such arguments were proposed by Likhoded [28]. It is an attractive possibility to build such a procedure in a simple way into the Monte Carlo program, say, if $m_{Q\bar{Q}} < 400$ MeV/c^2 the product of the recombination is a PS-meson, if $m_{Q\bar{Q}} > 400$ MeV/c^2 a V-meson. However, the present version of the model does not have such an option.

Topological cross sections

The data [18] are compared with the model calculations in Fig. 1. Apart of the lowest charged multiplicities, which are expected to be influenced considerably by the diffractive

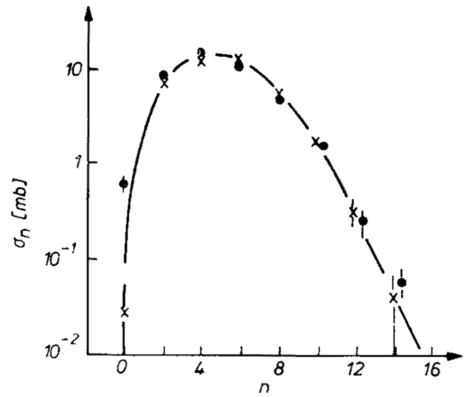

Fig. 1

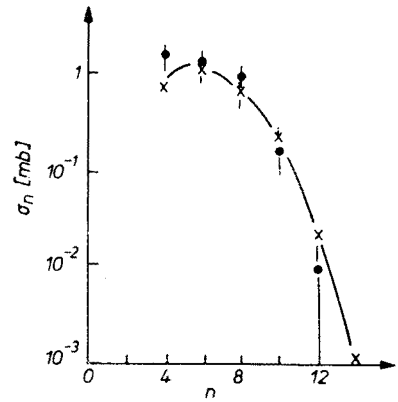

Fig. 2

Fig. 1. Topological cross sections in $\bar{p}p$ interactions at 22.4 GeV/c compared with the model calculations. The data [18] are denoted by dots, the results from the "modified" version by crosses connected by the solid line to guide the eye

Fig. 2. Topological cross sections for Δ^{++} production. The data [19] are denoted by dots, results from the "modified" version by crosses connected by the solid line

dissociation processes, the agreement is quite good. In Fig. 2 we present the topological cross sections for the Δ^{++} production. The comparison looks favourable on a rough qualitative level.

Inclusive distributions in transverse momentum

The inclusive p_T-distribution of positive pions is shown in Fig. 3. The agreement for $p_T \lesssim 0.8$ GeV/c is quite good. At higher values of p_T probably the effects of hard collisions of hadron constituents are of some importance and it is therefore not surprising that the model predicts lower $d\sigma/dp_T^2$ at $p_T \gtrsim 0.8$ GeV/c. Pions in the final state appear quite frequently as products of resonance decays and this makes their p_T distribution much steeper than those of directly (this means: by recombination not followed by a decay) produced resonances. This effect (already discussed in Ref. [29] in πp collisions) is nicely seen in Fig. 3 where the slope of ϱ^0 is much lower than that of the π^+. The model reproduces well this feature of the data.

The same effect is seen in Fig. 4 where the distributions of protons and Δ^{++} in the transverse momentum are plotted. Here, however, the conclusions are less certain since both p and Δ^{++} are predominantly produced in the fragmentation region of the target where the diffractive dissociation (not described by the present model) may be important. Still,

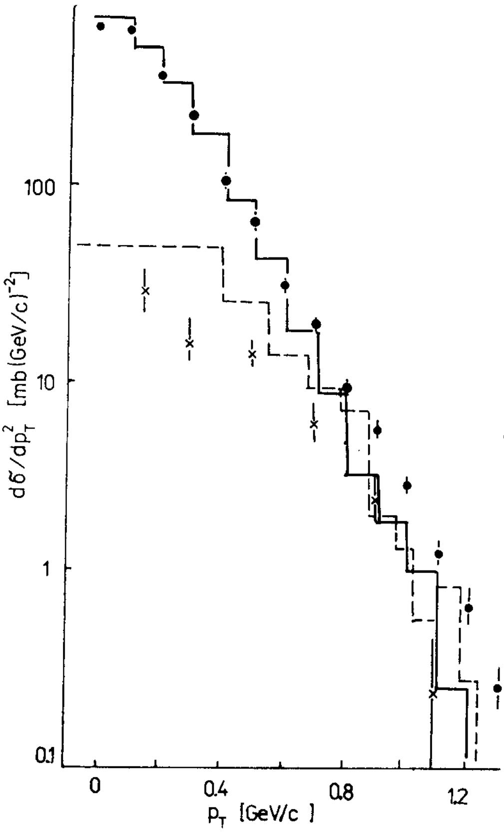

Fig. 3

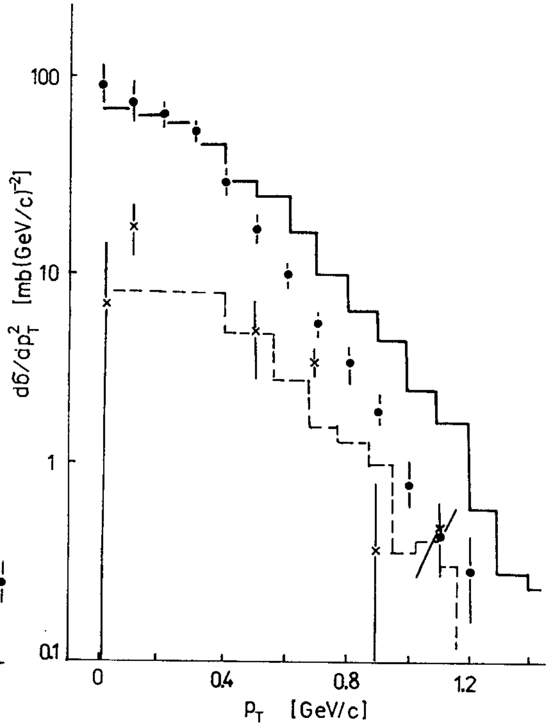

Fig. 4

Fig. 3. The inclusive distribution $d\sigma/dp_T^2$ of π^+ and ρ^0. The data on π^+ [20] (ρ^0 [14]) are denoted by dots (crosses), the results of the "modified" version by solid (dashed) histogram

Fig. 4. The inclusive distribution $d\sigma/dp_T^2$ of protons and Δ^{++}. The data on protons [20] (Δ^{++} [19]) are denoted by dots (crosses), results from the "modified" version by solid (dashed) histogram

the apparent discrepancy in the shape of the p_T-distribution of protons indicate clearly that the production of baryons is not completely understood and that the problem requires further effort.

Single particle inclusive distributions in x and in rapidity

The distribution of positive pions in rapidity is shown in Fig. 5. The "modified" version of the model reproduces the data quite well. Differences between the "standard" and the "modified" versions are clearly seen in Fig. 5. They are due to differences between the transverse momenta of valence quarks in the two versions. Larger transverse momenta ("modified" version) prohibit pions to have larger longitudinal momenta in the c.m. frame and this leads to the suppression of $d\sigma/dy$ in the fragmentation region.

Probably the most serious discrepancy between the model and the data is shown in Figs. 6 and 7 where we have plotted the inclusive cross sections for $\bar{p}p \to p+X$ in the c.m. rapidity and in the Feynman x. In Fig. 7 we have displayed separately also the data on proton x-distributions in different topologies. It is immediately seen that the shape of the proton distribution following from the model is basically different from the two

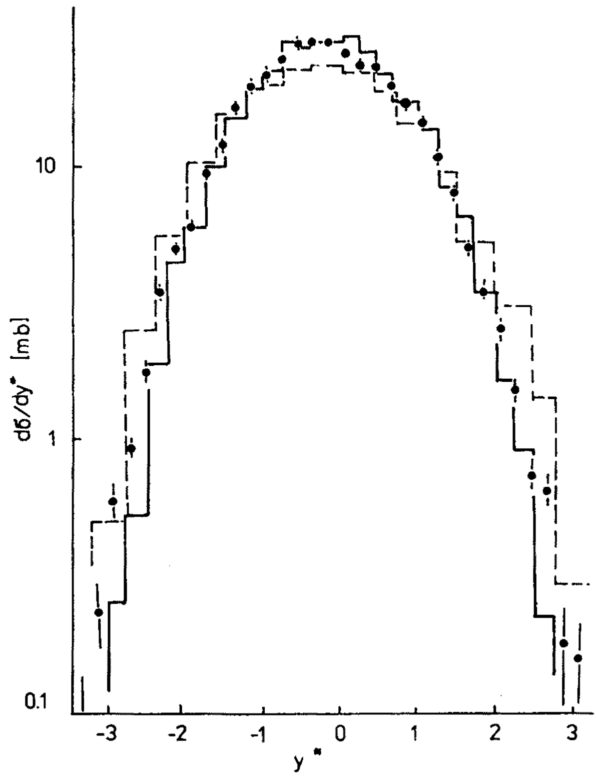

Fig. 5. The distribution of π^+ in rapidity. The data [20] indicated by dots, the results of the "modified" version by the solid and those from the "standard" version by the dashed histogram. Decay products of Λ and K^0_S are not included

prong data and more similar to 4- and 6-prong ones. The discrepancy in 2-prong events is not very surprising since the model does not describe the diffractive dissociation. In a future study of this problem one would need high statistics results from the model for proton distributions in different topologies and compare them with the data.

Nevertheless, on the basis of Figs. 6 and 7 it seems to be almost inevitable to shift the proton distribution to larger values of $|x|$ by changing the model in one respect. The proton x-distribution is very sensitive to the distribution of valence quarks before the recombination and Eq. (1) may be too rough approximation to reality.

One should presumably study in more detail the distributions of Q's and $\bar{Q}$'s before the recombination which are given by more sophisticated distributions than that given

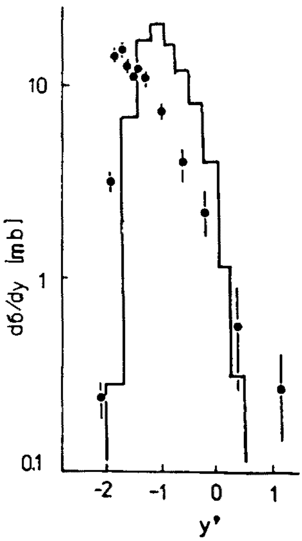

Fig. 6

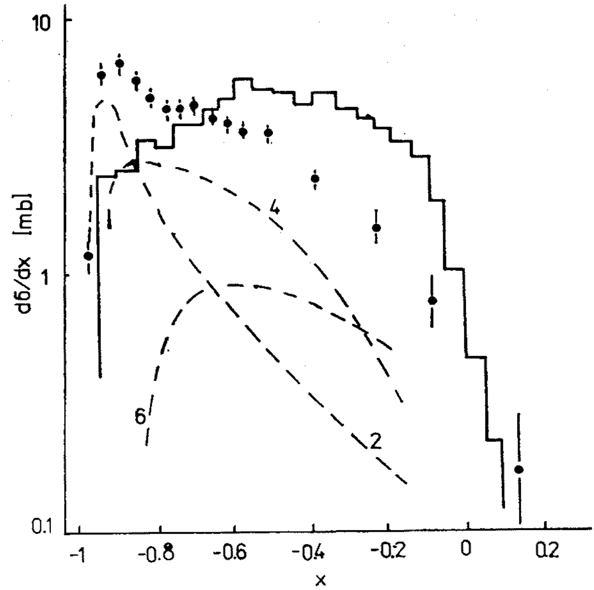

Fig. 7

Fig. 6. The inclusive distribution of protons in the c.m. rapidity y^*. The data [20] are represented by dots, the results from the "modified" version by the solid histogram

Fig. 7. The inclusive distribution of protons in Feynman x. Data [20] — dots, results from the "modified" version of the model — the solid histogram. The dashed lines give proton distribution in 2-, 4- and 6-prong events, respectively

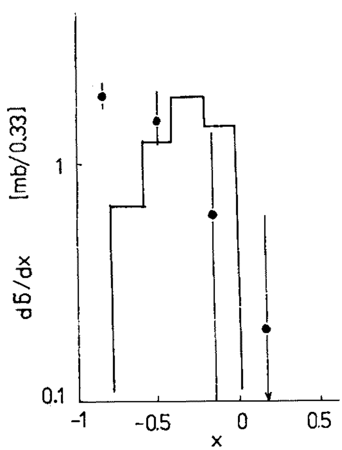

Fig. 8. The inclusive distribution of Δ^{++} in Feynman x. The data [19] — dots, the results from the "modified" version — solid histogram

by Eq. (1), e.g. the factors $V(x_1, x_2, x_3)$ and $V(x_4, x_5, x_6)$ would be modified by $V(x_1, x_2, x_3) \to \prod_1^3 |x_i|^\alpha$ and each of the sea quarks in Eq. (1) would receive an additional factor $f(x) = C(1-x)^\beta$. Taking $\alpha > 1/2$ and $\beta > 0$ would result in distributions which have valence quarks pushed more to large and sea quarks to low values of $|x|$. A similar Ansatz for the distribution of Q's and $\overline{\text{Q}}$'s was recently considered by De Grand and Miettinen and by a broader collaboration at Fermilab [30].

In Fig. 8 we present the data and our results for the inclusive Δ^{++} production. Here, however, the fluctuations are, for the time being, so large that any conclusions are hardly possible.

The inclusive distribution of pions with fixed p_T in rapidity

In Fig. 9 we present the results on inclusive y^*-distribution of π^+ with fixed p_T. The agreement is generally good on a qualitative level. The Ludmila collaboration found in analysing the data [20] that the maximum of the distributions is shifted somewhat to negative values of y^* (the π^+ with a large p_T has a mild tendency to move, in the c.m. frame, in the same direction as the incident proton). It would be nice to understand this qualitatively and in fact the present model should have such an effect (there are more up-quarks

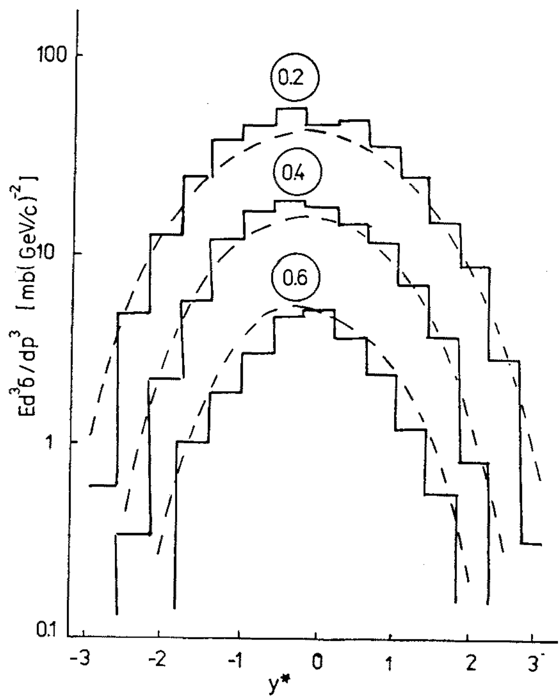

Fig. 9. The inclusive rapidity distribution of π^+ with a fixed value of transverse momentum. The data [20] are denoted by dashed lines and the results following from the "modified" version by solid histogram. The corresponding p_T in GeV/c are indicated in circles. The data and the results represent invariant cross sections integrated over $\langle p_T-0.1, p_T+0.1\rangle$

on the side of proton and these have rather large transverse momenta). Unfortunately, the limited statistics of our present calculation does not permit any detailed study of the effect. It is however certainly one of the features which should be studied in more detail in the future.

The sea-gull effect

In Fig. 10 we present the $\langle p_T^2 \rangle$ of π^+ versus the x. Both the data and the results of our calculations have a similar shape, the errors of the calculations being rather large. The data indicated an asymmetry in the shape of the sea-gull and the model seems to reproduce

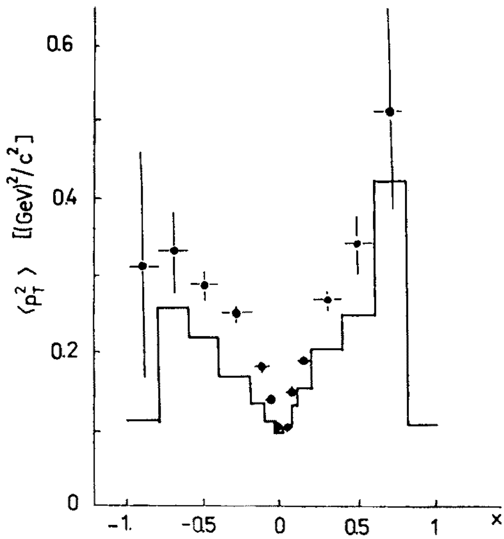

Fig. 10. The sea-gull in production of π^+ in $\bar{p}p$ interactions at 22.4 GeV/c. The data [33] are denoted by dots and the calculations according to the "modified" version of the model by a solid histogram

this asymmetry. The origin of the asymmetry is however not clear. Naive attempts at explaining the asymmetry seem to run against the simple interpretation of the asymmetry of the data in Fig. 9. As pointed out there, one naively expects that π^+'s on the proton side (negative values of x) should have somewhat larger transverse momenta. The data shown in Fig. 9 do give a mild support to this simple minded expectation. However, both the data and the results presented in Fig. 10 indicate just the opposite tendency. The production of ϱ^0 followed by $\varrho^0 \to \pi^+\pi^-$ cannot be made responsible for the effect (ϱ^0 is symmetrical with respect to $x \to -x$) and the production of ϱ^+ followed by $\varrho^+ \to \pi^+\pi^0$ works exactly in the opposite direction — one expects more ϱ^+ being produced on the proton's side.

The origin of the asymmetry and its interpretation in the sea-gull in $\bar{p}p$ interactions is thus a question which deserves further detailed study. It would be particularly interesting to see the data given in Figs. 9 and 10 separately for annihilation and non-annihilation components. Naively one could expect some differences. In annihilations the valence

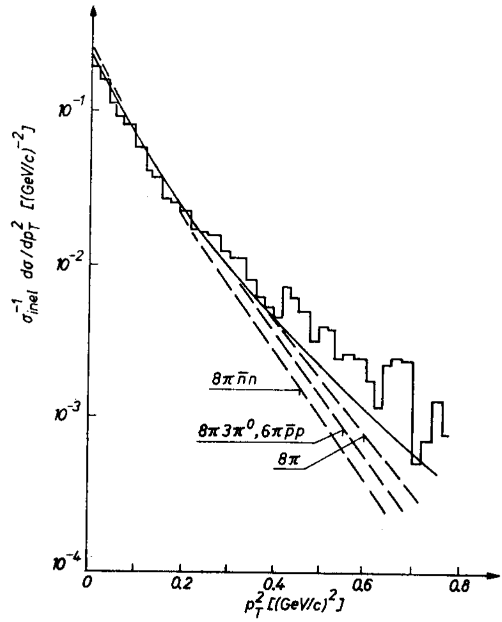

Fig. 11a. The p_T-distribution for 8-prong events in $\bar{p}p$ interactions at 22.4 GeV/c. The histogram denotes the experimental data [33], the full line represents our results obtained in the "standard" version of the program and the dashed lines were produced by Jadach's program GENRAP [31] for the channels indicated in the figure. The results and the data are normalized to the same total number of events

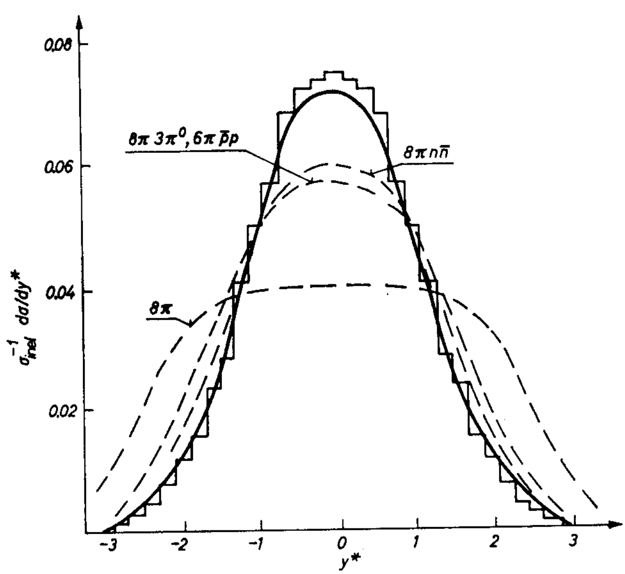

Fig. 11b. The c.m. rapidity distribution of the charged particles in 8-prong events. The symmetrized data [33] (histogram) are compared with the "standard" version of the Monte-Carlo quark-parton model and with results obtained by the program GENRAP [31]. Notation is the same as Fig. 11a

quarks are not consumed by forming leading nucleons and (assuming that valence quarks are responsible for effects seen in Figs. 9 and 10) one would expect to see even stronger effects in annihilations.

As follows from the arguments presented in the next section a deeper understanding of the $\bar{p}p$ interactions can be reached only by detailed studies of exclusive channels. As an illustration of this point we present in Figs. 11a and 11b experimental semi-inclusive p_T and y^*-distributions for events with 8 charged prongs. The data are compared with results following from the Monte Carlo quark-parton model and with some exclusive channels generated by Jadach's program GENRAP [31]. Note that combinations of channels generated by GENRAP cannot give a good agreement with the data (such combinations would be lower than the data for $y^* \approx 0$) whereas the quark-parton model does well in this respect.

4. *Comments and conclusions*

In the preceding section we have compared the results following from the simple Monte Carlo quark-parton model with the data on $\bar{p}p$ interactions at 22.4 GeV/c.

The purpose of this comparison was not to give the "final" interpretation of the data by the quark-parton model but rather to separate the interesting and perhaps deeper aspects of the data from less interesting ones. Such a localization of interesting aspects is in our opinion a necessary prerequisite both for further studies of $\bar{p}p$ interactions at this particular energy and for further possible improvements of the model[3]. From this point of view the interesting aspects of the data are just those which can hardly be explained by the present simple-minded model.

We shall now list such interesting features of the data and the aspects of the model with which they are closely connected:

a) *The cross section for the production of* ϱ^0 *and other vector meson resonances.* This is related to the V/PS ratio in the recombination of $Q\bar{Q}$ pairs to mesons and to the dynamics of the recombination. If adjusting V/PS ratio just on the phenomenological level, one should study the distribution of ϱ^0 in rapidity and the dependence of the ϱ^0 production on different topologies to see whether the simple phenomenological procedure can describe various features of the ϱ^0 production. The production of other vector mesons is equally interesting from the same point of view.

b) *The production of* Δ^{++} *and perhaps also of other members of the baryon decuplet.* This gives decuplet/octet ratio for baryons and in connection with the ratio V/PS can elucidate the role played by the mass of the hadron in the process of recombination.

c) *The interplay of the inclusive* p_T *distributions of* ϱ*-mesons and pions and, similarly, of* Δ^{++} *and protons.* This seems to be more or less understood on a qualitative level but a quantitative description of the data might be useful. It definitely provides a complementary information on the relationship between resonance and stable particle production.

[3] As mentioned in some detail in the introduction the model, as it stands, has built in only some basic assumptions of the quark-parton description of hadronic collisions and the general constraints (energy-momentum conservation and p_T cut-off).

d) *The inclusive x and y*-distributions of protons.* In this point the data may well disagree with the model even after the subtraction of the diffractive component. This would presumably require reformulation of the model in the sense indicated in the preceding section. The corresponding changes would push valence partons more strongly to the ends of the available rapidity region and sea partons more into the central region.

e) *The apparent (or real) inconsistency between the asymmetry of the $d\sigma/dx$ for π^+ production at fixed p_T and the asymmetry of the sea-gull (see Figs. 9 and 10).* The explanation of the origins of the two asymmetries would be also very useful.

In concluding we shall make a general remark concerning the description of the $\bar{p}p$ interactions by the quark-parton picture. As an example we shall use the present model but the comments are most likely applicable also to other quark-parton approaches. The data indicate that at 22.4 GeV/c the annihilation channels make together something less than 20% of the cross section. The present model is based on the assumption that the hadronic reaction is initiated by the interaction of wee partons of the two colliding hadrons and that the valence partons keep their direction of motion. The model permits however such configurations of valence and sea partons that during the recombination all valence quarks recombine with their rapidity neighbours to mesons. We shall refer to this mechanism as to the "recombinative component" of the $\bar{p}p$ annihilation. The cross section $\sigma_{\rm ann,rec}$ for this component is about 11% of the total recombinative cross section: $\sigma_{\rm ann,rec} \approx 11\% \, \sigma_{\rm rec}$, whereas the annihilation cross section is about 20% at the Ludmila experiment energy. This means that our model can describe only about a half of the annihilation cross section and for the rest we have to include some modifications into the model. As suggested recently by Goldberg [32] a significant contribution to the $\bar{p}p$ annihilation may come from the collisions in which (at the very beginning) a Q from the proton annihilates with an $\bar{Q}$ from the antiproton[4]. This mechanism may be called the "single annihilation" component. Apart of this there can be, of course, also "double" and "triple" annihilation components, the latter including for instance the $\bar{p}p \to \pi^+\pi^-$ channel. There are still some channels which perhaps do not fall into this classification, for instance the $\bar{p}p \to K\bar{K}\pi$ which may result from the recombination following the subprocess $u\bar{u} \to s\bar{s}$ or $d\bar{d} \to s\bar{s}$.

A deeper understanding of the annihilation processes (hopefully possible within the quark-parton model) requires the disentangling of the various components with estimates of their contributions to the annihilation cross sections (together with the corresponding energy dependences).

Such a study of the origins of the annihilation requires a sample of events about which it is known that they contain no baryons in the final state. At present one can only hope that such samples can be obtained by combining events from exclusive channels (4C and 1C) fits with identified particles in the final state.

The appallingly complicated picture of the $\bar{p}p$ annihilation sketched above is a sad but unavoidable consequence of the general scheme of the quark-parton models in which one treats partons (during the collision) as individual objects.

---

[4] Goldberg [32] has considered only the annihilations of $Q\bar{Q}$ to vector mesons but sophisticated versions describing the $Q\bar{Q}$ annihilation in a way more or less similar to e^+e^- annihilation [8] are clearly possible.

We thought it appropriate to mention this explicitly here since this indicates that in describing $\bar{p}p$ interactions one can meet some features of the data which are due to specific properties of the annihilation channels and may not be understandable from the given version of the model. From this point of view it would be very useful to study pp and $\bar{p}p$ interactions at similar energies at the same time.

The authors are indebted to the members of the Ludmila collaboration for valuable discussions, for comments on preliminary version of the manuscript and for the kind permission to use their unpublished data. We would also like to thank K. Šafařik for useful discussions and comments.

REFERENCES

[1] R. P. Feynman, *Photon-Hadron Interactions*, W. A. Benjamin, 1972.
[2] J. D. Bjorken, E. A. Paschos, *Phys. Rev.* **185**, 1975 (1969).
[3] V. V. Anisovich, V. M. Shekhter, *Nucl. Phys.* **B55**, 455 (1973); V. V. Anisovich et al., *Nucl. Phys.* **B55**, 474 (1973); V. N. Guman, V. M. Shekhter, *Nucl. Phys.* **B99**, 523 (1975).
[4] J. D. Bjorken, G. R. Farrar, *Phys. Rev.* **D9**, 1449 (1974).
[5] L. Van Hove, S. Pokorski, *Nucl. Phys.* **B86**, 243 (1975); S. Pokorski, L. Van Hove, *Acta Phys. Pol.* **B5**, 229 (1974).
[6] V. Černý, P. Lichard, J. Pišút, *Phys. Rev.* **D16**, 2822 (1977).
[7] V. Černý, P. Lichard, J. Pišút, *Phys. Rev.* **D18**, 2409 (1978).
[8] V. Černý et al., to be published in *Phys. Rev.* D (1979).
[9] V. Černý et al., *Monte Carlo approach to multiparticle production in quark-parton model — charge distributions and fluctuations*, Bratislava preprint 1978, to be published in *Phys. Rev.* D.
[10] W. Ochs, *Nucl. Phys.* **B118**, 397 (1977); K. P. Das, R. Hwa, *Phys. Lett.* **68B**, 459 (1977).
[11] V. V. Knyazev, A. K. Likhoded, V. A. Petrov, A. N. Tolstenkov, preprint IHEP Serpukhov OTF 77-106 (1977) and other preprints by A. K. Likhoded et al.
[12] D. V. Duke, F. E. Taylor, *Phys. Rev.* **D17**, 1788 (1978).
[13] E. G. Boos et al., JINR Dubna El-11665 and El-11666 (1978).
[14] D. I. Ermilova et al., JINR Dubna El-11190 (1978).
[15] E. G. Boos et al., *Nucl. Phys.* **B121**, 381 (1977).
[16] E. G. Boos et al., *Nucl. Phys.* **B128**, 269 (1977).
[17] B. V. Batunya et al., *Phys. Scr.* **15**, 305 (1977).
[18] L. N. Abesalashvili et al., *Phys. Lett.* **52B**, 236 (1974).
[19] E. G. Boos et al., JINR Dubna El-11257 (1978); Alma Ata-Dubna-Helsinki-Moscow-Prague collaboration, *Study of the reaction $\bar{p}p \to \Delta^{++}(1236)+X$ at 22.4 GeV/c*, Prague preprint, 1978.
[20] E. G. Boos et al., *Nuovo Cimento* **47A**, 377 (1978).
[21] Alma Ata-Dubna-Helsinki-Moscow-Prague collaboration, *Estimation of single particle distributions of $\bar{p}p$ annihilation reactions at 22.4 GeV/c*, Prague preprint, 1978.
[22] J. Kuti, V. F. Weisskopf, *Phys. Rev.* **D4**, 3418 (1970).
[23] V. Černý, P. Lichard, J. Pišút, *Acta Phys. Pol.* **B9**, 901 (1978).
[24] V. G. Grishin, Talk at the VI-th seminar on multiparticle production, Dubna, June 1978, to be published in the Proceedings.
[25] G. Jancso et al., *Nucl. Phys.* **B124**, 1 (1977).
[26] K. J. Anderson et al., *Phys. Rev. Lett.* **37**, 799 and 803 (1976).
[27] Private communication from J. Böhm, E. M. Levin, V. I. Petrukhin, V. M. Shekhter and other members of the RISK collaboration.
[28] A. K. Likhoded, private communication.

[29] P. Schmid, Proc. of the XVIII Int. Conf. on High Energy Physics, Tbilisi, July 1976.
[30] T. A. De Grand, H. I. Miettinen, J. Ranft et al., Fermilab preprint, in preparation and private communication from J. Ranft and D. Duke; T. A. De Grand, H. I. Miettinen, *Phys. Rev. Lett.* **40**, 000 (1978).
[31] S. Jadach, *Comp. Phys. Commun.* **9**, 297 (1975).
[32] H. Goldberg, *A quark-parton model of* $\bar{p}p$ *annihilation*, preprint, Northeastern University Boston, contributed to the IV European Antiproton Symposium, Strasbourg, June 1978.
[33] Ludmila collaboration, to be published.