Parton Description of Soft $\bar{p}p$ Annihilation

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A parton description of soft, high-energy $\bar{p}p$ annihilation is presented in a three-chain model based on the dual topological unitarization scheme. With this model, full, quantitative, zero-parameter predictions are made for inclusive single-particle rapidity distributions and their energy dependence, which are testable in forthcoming $\bar{p}p$ experiments.

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Recently, it has been shown that a very satisfactory description of soft (low-p_T) multiparticle production in high-energy hadronic collisions can be given in a parton framework[1–3] based on the dual topogical unitarization (DTU) scheme[4] for the Pomeron. The resulting two-chain model [see Fig. 1(a)] contains no adjustable parameters[1] and provides a concrete, quantitative realization of the DTU approach to strong interactions. (The sole inputs are parton structure and fragmentation functions determined from hard processes.) Furthermore, the model also reproduces in a simple way all the salient features of high-energy hadron-nucleus collisions.[5] In particular, the result $R_A \equiv \langle N_{ch}\rangle_{hA}/\langle N_{ch}\rangle_{hp} = \frac{1}{2}+\frac{1}{2}\bar{\nu}$, $\bar{\nu}\equiv A\sigma_{in}{}^{hp}/\sigma_{in}{}^{hA}$ is directly related to the fact that there are two chains.

Since the two-chain model works so well, it is natural to search for other tests based on the DTU scheme. This suggests that a reasonable place to look is the three-chain diagram [see Fig. 1(b)] which is expected in DTU to be the dominant contribution to $\bar{p}p$ annihilation. In this paper, I formulate a partonic three-chain model for soft multiparticle production in high-energy $\bar{p}p$ annihilation. The model is fully specified and contains no free parameters. It is used to calculate inclusive single-particle rapidity distributions; these are predicted to rise with energy and have a substantially higher[4,6] rapidity plateau than the Pomeron (two-chain) contribution (see Fig. 2). Such predictions are of particular interest at the present time in view of forthcoming high-energy $\bar{p}p$ experiments at CERN and Fermilab. If these experiments bear out the predictions of the three-chain model, it would provide further evidence in favor of the DTU scheme and again indicate that the description of soft processes in a parton language is not unreasonable.[7]

First recall[1] that the color-separation mechanism which gave the Pomeron contribution in a $\bar{p}p$ collision [Fig. 1(a)] corresponded to an interchange between a quark i_1 with momentum fraction x_1 in the proton and an antiquark i_2 with momentum fraction x_2 in the antiproton. The probability for this interaction was taken to be[1]

$$\rho_{i_1 i_2}{}^{p\bar{p}}(x_1,x_2) = v_{i_1}{}^{p}(x_1)v_{i_2}{}^{\bar{p}}(x_2)/R,$$
$$R \equiv \sum_{i_1,i_2}\int_0^1 dx_1\,dx_2\,v_{i_1}{}^{p}(x_1)v_{i_2}{}^{\bar{p}}(x_2) = 9, \qquad (1)$$

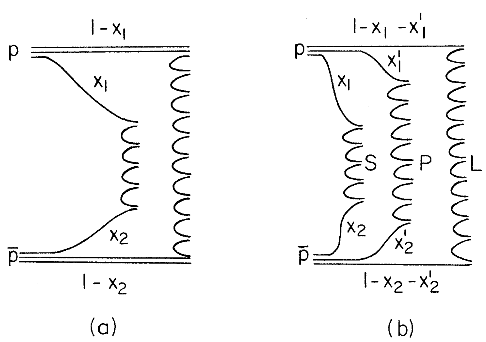

FIG. 1. Multiparticle production in high-energy $\bar{p}p$ collisions in the dual-topological-unitarization scheme. The dominant Pomeron contribution (a) corresponds to two chains $(qq,\bar{q}\bar{q})$ and $(q,\bar{q})$, whereas the annihilation contribution (b) has three $(q,\bar{q})$ chains.

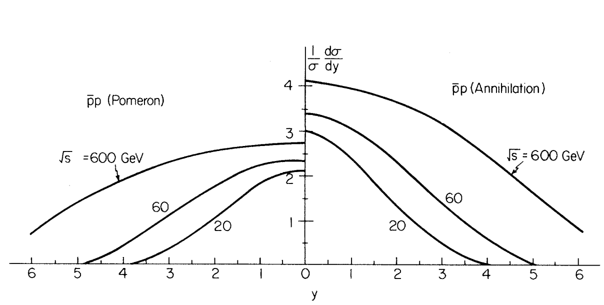

FIG. 2. The inclusive distribution $\sigma^{-1}d\sigma/dy$ vs rapidity y for $\bar{p}p \to$ charged particle $+X$ at c.m. energies $\sqrt{s}$ $=20$, 60, and 600 GeV. Only one side of the distributions are drawn, since they are symmetric about $y=0$. The Pomeron contribution is shown on the left and the annihilation contribution is on the right.

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where $v_i^p(x)$ are valence-quark structure functions which are known from hard processes.[8] Since the structure functions are sharply peaked near $x=0$, this region provides the main contribution to Eq. (1). The general philosophy was to assume that the probability of color separation was proportional to the structure functions of quarks involved. So, by analogy, the obvious choice for the probability of the three-chain contribution of Fig. 1(b) to $\bar{p}p$ annihilation is[9]

$$\rho_{i_1,i_1';i_2,i_2'}{}^{p\bar{p}}(x_1,x_1';x_2,x_2') = v_{i_1}{}^p(x_1)v_{i_1'}{}^p(x_1')v_{i_2}{}^{\bar{p}}(x_2)v_{i_2'}{}^{\bar{p}}(x_2')/R',$$
$$R' \equiv \sum_{\substack{i_1,i_1',\\ i_2,i_2'}} \int dx_1 dx_1' dx_2 dx_2' v_{i_1}{}^p(x_1)v_{i_1'}{}^p(x_1')v_{i_2}{}^{\bar{p}}(x_2)v_{i_2'}{}^{\bar{p}}(x_2'). \tag{2}$$

The above-mentioned color separation produces three $(q,\bar{q})$ chains, which are labeled $S(x_1$ to $x_2)$, $P(x_1'$ to $x_2')$ and $L(1-x_1-x_1'$ to $1-x_2-x_2')$ in Fig. 1(b). In general, for a $(q,\bar{q})$ chain C extending from x_A to x_B (i.e., q carries momentum x_AP, $\bar{q}$ carries momentum $-x_BP$, P = incident momentum in the overall $\bar{p}p$ c.m. frame, $s=4P^2$), the quark momentum P_c in the chain c.m. frame and the rapidity Δ_c of the center of chain C with respect to the overall $\bar{p}p$ c.m. frame are given by[10]

$$2P_c = (x_Ax_Bs)^{1/2}, \quad 2\Delta_c = \ln(x_A/x_B). \tag{3}$$

The contribution to the inclusive rapidity distribution for particle h due to a single $(q,\bar{q})$ chain C is given by

$$dN_c{}^h(y-\Delta_c,P_c)/dy = \begin{cases} \bar{x}_c D_{q\to h}(x_c), & y \geq \Delta_c, \\ \bar{x}_c D_{\bar{q}\to h}(x_c), & y < \Delta_c, \end{cases}$$
$$x_c = |\mu_\pi \sinh(y-\Delta_c)/P_c|, \quad \bar{x}_c = (x_c{}^2 + \mu_\pi{}^2/P_c{}^2)^{1/2}. \tag{4}$$

In Eq. (4) y = rapidity of the detected particle h in the overall $\bar{p}p$ c.m. frame, $\mu_\pi = 0.33$ GeV is the transverse pion mass, and $D(x)$ are parton fragmentation functions which can be determined from hard processes.

The complete inclusive distribution for hadron h in $\bar{p}p$ annihilation is obtained by superposing the rapidity distributions from the three chains S, P, and L, with a weight corresponding to the probability of color separation ρ[Eq. (2)],[9] so that

$$\frac{1}{\sigma}\frac{d\sigma}{dy}\bigg|_{\text{anni}}^{\bar{p}p\to h}(s,y) = \sum_{\substack{i_1,i_1',\\ i_2,i_2'}} \int dx_1 dx_1' dx_2 dx_2' \rho_{i_1,i_1';i_2,i_2'}{}^{p\bar{p}}(x_1,x_1';x_2,x_2') \times\left[\frac{dN_s{}^h(y-\Delta_s,P_s)}{dy} + \frac{dN_P{}^h(y-\Delta_P,P_P)}{dy} + \frac{dN_L{}^h(y-\Delta_L,P_L)}{dy}\right], \tag{5}$$

where ρ, P, Δ, and dN/dy are given by Eqs. (2)–(4).

For numerical predictions, let us consider the specific case where h is any charged particle. (In practice, this essentially means $h=\pi^\pm$.) We take the quark and antiquark fragmentation functions into charged particles from Ref. 1 as determined from e^+e^- data,[11] and the proton structure functions from Ref. 8. These choices fully specify (both shape and overall normalization) the inclusive single-charged-particle rapidity distribution in $\bar{p}p$ annihilation. The results for various energies are shown in Fig. 2. For comparison, the Pomeron (two-chain) contribution is also plotted.[1]

At large y, the rapidity distribution in $\bar{p}p$ annihilation comes mainly from quark (or antiquark) fragmentation and corresponds to a power-law behavior $(1-x)a$ where $a=1-2$. This is a slower falloff than the large y rapidity distribution due to Pomeron exchange which comes mainly from diquark fragmentation and has an approximate behavior $(1-x)^3$. Also, at any given energy, the annihilation distribution is considerably higher than that due to Pomeron exchange, and the annihilation plateau height rises faster with energy (Fig. 3). Asymptotically ($s\to\infty$), one obtains the central plateau height ratio (and also the multiplicity ratio) to be $\frac{3}{2}$—the approach to asymptopia

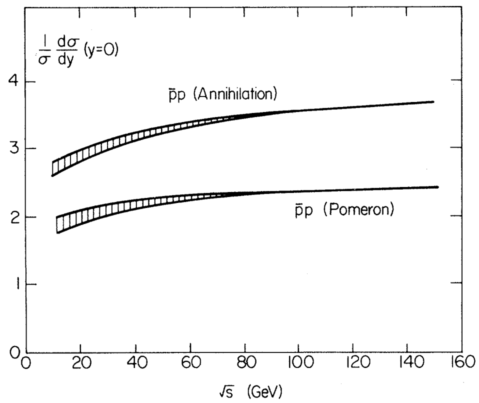

FIG. 3. The energy dependence of the central plateau height in $\bar{p}p$ collisions.

having the behavior $\frac{3}{2}-(c/\sqrt{s})$. The asymptotic value $\frac{3}{2}$ is, of course, expected from naive chain counting.[6] Since the incident $\bar{p}p$ energy is shared by the three chains formed during annihilation; so, at low energies, the momentum in one of the chains is sometimes too small to justify a one-dimensional jet description in terms of fragmentation functions. This uncertainty can be crudely estimated from low-energy Stanford Linear Accelerator Center e^+e^- data,[11] and is approximately $\lesssim 10\%$, as shown in Fig. 3.

Although we have only discussed inclusive charged-particle production, predictions for any type of hadronic trigger are readily obtainable from Eq. (5). It would be interesting to see if our quantitative predictions for rapidity distributions and rising plateaus will be experimentally verified. Qualitatively, it is encouraging to note that existing $\bar{p}p$ multiplicity data show that annihilation events do have above-average multiplicities,[6,12] consistent with the expectations of DTU.

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[9]The integrals on x_1, x_1', x_2, and x_2' are constrained by momentum conservation $x_1+x_1' \leq 1$, $x_2+x_2' \leq 1$. We satisfy these constraints very simply by taking the integration limits to be 0 to $\frac{1}{2}$. This procedure is justified since the structure functions are peaked near $x=0$, and the region $x \geq \frac{1}{2}$ gives a small contribution.

[10]Eqs. (3) have $O(m_Q^2/s)$ corrections (m_Q = quark mass) which are easy to compute (see Ref. 2) but are small at high energies. Accurate formulas have been used for numerical work.

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