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Double Pomeron exchange studies in $p\bar{p}$ interactions at 0.63 TeV

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The properties of events having the topology and kinematic features of double Pomeron exchange are described. The data were taken at the CERN $p\bar{p}$ collider at $\sqrt{s}=0.63$ TeV in the UA1 detector. A calorimeter trigger was used to isolate events in which a central cluster of particles was separated from forward particles by large rapidity gaps. The invariant mass M of the central cluster (possibly a colliding Pomeron-Pomeron system) covers the range 10–70 GeV/c^2. The M dependence of charged particle multiplicity distributions in these double Pomeron events is strikingly different from their $\sqrt{s}$ dependence in pp and $p\bar{p}$ interactions.

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I. INTRODUCTION

The concept of Pomeron exchange provides a unified description of forward elastic and diffractive scattering and of total cross sections in hadron-hadron interactions at high energies. Double Pomeron exchange (DPE) is defined as the process $h+h\rightarrow h+X+h$, in which a central cluster (X) is separated by large rapidity gaps from the quasielastic outgoing hadrons (h) [1]. This event configuration has been observed in proton-proton interactions at the CERN Intersecting Storage Rings (ISR) [2,3]. At the maximum ISR c.m. energy of 63 GeV (rapidity range of 8.3 units), the mass M of the central cluster is in the range $M\lesssim 4$ GeV and the event kinematics agree with predictions for the double Pomeron process. At the CERN proton-antiproton collider, with a c.m. energy of 0.63 TeV and rapidity range of 13 units, a more comprehensive study of the double Pomeron exchange process is possible. A recent study at the CERN Collider used the UA2 apparatus along with "Roman Pots" which registered beam particles scattered in the range $1<|t|<2$ (GeV/c)^2 [4]. The average and maximum masses of the central cluster in that experiment are 3 GeV/c^2 and 10 GeV/c^2 respectively.

We describe here a study of double Pomeron exchange in the UA1 detector at the CERN Collider [5]. The hermetic calorimetry of the UA1 apparatus was used to select events with gaps in the pseudorapidity ranges $3<|\eta|<6$. The mass M of the central cluster in this experiment covers the range $10<M<70$ GeV/c^2.

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II. APPARATUS AND TRIGGER

The UA1 detector has been extensively described elsewhere [6]. Here we discuss briefly the components of the detector relevant to the current investigation. The Central Detector measures the momentum and ionization of charged tracks at angles greater than 5° with respect to the circulating beams. It consists of a cylindrical drift chamber (5.8 m long, 2.3 m in diameter) in a magnetic dipole field of 0.7 T. The tracking chamber is surrounded by concentric barrels of electromagnetic and hadronic calorimeters with coverage to within 5° of the beams. Additional calorimetry, both electromagnetic and hadronic, covers the forward region and ensures hermiticity of the UA1 detector for polar angles above 0.2°.

The double Pomeron exchange trigger imposed two conditions: central particle production and large pseudorapidity gaps between the central and forward going particles. Central particle production was imposed with a calorimetric trigger; rapidity gaps were implemented with both overlapping scintillator hodoscopes and calorimeters.

The "pretrigger" consisted of the beam crossing gate in coincidence with a veto on scintillator hodoscopes located at $0.4°<\theta<25°$. (In contrast all other UA1 triggers required in-time hits in these counters to signify a beam-beam collision. Thus double Pomeron events were not included in the UA1 minimum bias sample.) The first level calorimeter trigger required (i) an energy deposition consistent with zero in the forward calorimetry ($0.2°<\theta<5°$), and (ii) positive signal from the central calorimetry ($5°<\theta<90°$). In practice an energy deposition of a few GeV was allowed in (i), consistent with the level of noise in the forward calorimeters.

Requirement (ii), for a signal (above that of the summed 2440 photomultipliers) in the central calorimeters, introduces a threshold mass for the central cluster. A separate signal in each half of the central calorimeter (inside and outside the ring) was needed to reduce background from cosmic rays and from beam-gas and beam-pipe interactions. This signal consisted of a transverse energy E_T ($E \sin\theta$) above 1.4 GeV, in coincidence with either a localized energy deposition of 1.2 GeV in the electromagnetic section, or a "jet" with $E_T > 3$ GeV. (Here "jet" is the sum of electromagnetic and hadronic calorimeter cells over roughly a 45° cone.) These energy requirements not only reject low mass clusters but can also bias the accepted events towards larger than average transverse momentum. Consequently we kept the required levels as low as possible.

III. DATA SAMPLE

The data presented here were recorded in a few dedicated runs in late 1985, with a total integrated luminosity of 116 nb^{-1}. The 190 000 events on tape were contaminated with non-beam-beam interactions including cosmic-ray events; these were eliminated by requiring tracks to come from a vertex in the beam crossing region. After event reconstruction and removal of non-beam-beam interactions a sample of 33 000 events remained. These will be referred to as "DPE data," without however implying that we have demonstrated these events to be double Pomeron exchange. Of these events about 72% satisfied the two electromagnetic shower trigger condition only, 10% the two jet condition only, and 18% satisfied both.

In this paper the DPE data are compared with "minimum bias" (MB) data recorded with the UA1 detector. The minimum bias trigger [7] required at least one charged particle in each rapidity hemisphere in the range $1.5 < |\eta| < 5.5$. This trigger was implemented with scintillator hodoscopes and accepts almost all of the inelastic cross section except diffractive events.

IV. RAPIDITY PLATEAU

The distribution of the charged particle pseudorapidity η, corrected for acceptance and reconstruction efficiency, is shown in Fig. 1 for both the DPE and MB samples. (The acceptance of the central detector is uniform out to η of 3.5). As expected, the DPE distribution is considerably narrower than MB. The tracks beyond $\eta = 3.2$ in the DPE data are those of low momentum particles which were magnetically bent away from the trigger hodoscopes. The DPE particle density is higher than MB by about 30% in the central region around $\eta = 0$. This is not surprising given the transverse energy requirement in the DPE trigger.

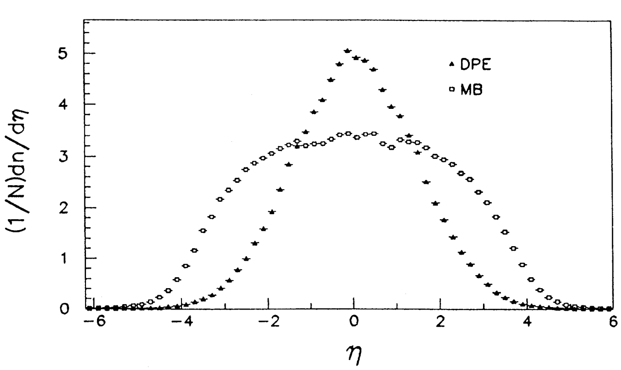

FIG. 1. Comparison of pseudorapidity η for charged particle tracks in DPE (solid triangles) and MB (open squares) events.

Figure 2 shows the invariant mass M of (a) DPE events and (b) MB events for all η and for $|\eta| < 3.2$ (corresponding to the double Pomeron trigger cutoff). Here M is defined as

$$M^2 = \left[\sum_i E_i\right]^2 - \left[\sum_i \mathbf{E}_i\right]^2 , \tag{1}$$

where $\mathbf{E}_i$ is the "energy vector" associated with the individual energy deposition E_i registered in the calorimeter segments. For a fully contained and perfectly measured final state we would find $M = \sqrt{s} = 630$ GeV; for the full MB events in Fig. 2(b) the average value of M is 260 GeV/c^2 indicating that a substantial fraction of the energy is carried by undetected forward particles with $\theta < 0.2°$. If Pomeron-Pomeron collisions are occurring in the DPE trigger events the invariant mass M corresponds to the total Pomeron-Pomeron c.m. energy. The average value of 36 GeV/c^2 for M in the DPE events is an order of magnitude greater than in previous double Pomeron exchange studies because the E_T trigger requirement selects only the high mass tail of the full DPE distribution. However, the relationship $M^2 = s(1-x_1)(1-x_2)$ implies that, for masses exceeding 63 GeV, at least one leading particle has $x < 0.9$, and hence exchanges other than Pomeron will contaminate the highest mass events in our sample.

The mean total calorimetric energy $\sum_i E_i$ measured in the DPE events is 40 GeV, so that the average energy carried down the beam pipe ($\theta < 0.2°$) is 590 GeV. The projection of $\sum \mathbf{E}_i$ transverse to and along the beam axis is shown in Fig. 3. The rms value of the transverse component, 2.3 GeV, is comparable to the measurement error, implying negligible transverse momentum for the central cluster as expected for a low four-momentum transfer process. The width of the distribution of the longitudinal component of $\sum \mathbf{E}_i$ implies a rms momentum along the beam of around 19 GeV/c for the DPE central cluster. Overall, the kinematic properties of the central cluster in the DPE trigger events are consistent with expectations for double Pomeron exchange. The forward baryonic systems are confined within the beam pipe, and we cannot detect whether they are unchanged or have been scattered into diffractively excited states. In either case the large rapidity gaps should ensure that predominantly Pomeron exchange is occurring. However we cannot exclude the possibility that, at some level, fluctuations may give a large rapidity gap even in nondiffractive events.

The differential cross section $d\sigma/dM$ is predicted to fall as $1/M$ in double Pomeron exchange [8]. In these data the dependence of $d\sigma/dM$ on M is much steeper than $1/M$. However, the mass distribution is biased by

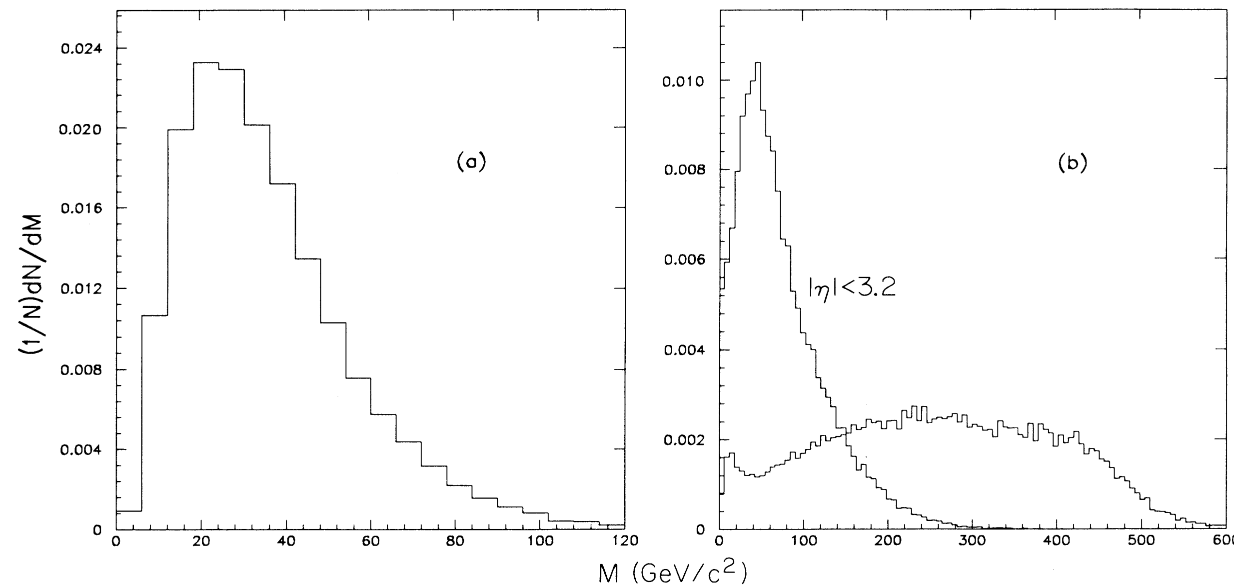

FIG. 2. The cluster invariant mass M in (a) DPE events, (b) MB events for the full η range and for the restricted range $|\eta| < 3.2$.

the transverse energy requirement in the trigger, and by the pseudorapidity cut at $\eta = 3.2$.

The cluster mass distribution in Fig. 2(a) indicates that the trigger reaches full efficiency only for masses $M \geq 24$ GeV/c^2 and Feynman $x = 0.96$ for the outgoing baryonic systems. The calculations of Streng [8] give a cross section ≈ 5 μb for double Pomeron exchange with $M \gtrsim 24$ GeV/c^2 at $\sqrt{s}$ of 630 GeV and $x_{\min} = 0.96$. The actual cross section corresponding to all the events in Fig. 2(a) is 0.3 μb. The relative smallness of the observed cross section is ascribed to the stringent rapidity gap cuts applied in the trigger.

V. CHARGED PARTICLE MULTIPLICITY

In this section the charged particle multiplicity in the DPE data is examined over the invariant mass range $10 < M < 70$ GeV/c^2. The data are compared with pp and e^+e^- results for the comparable $\sqrt{s}$ range $10 < \sqrt{s} < 70$ GeV. We also make comparisons with the multiplicities measured for different rapidity intervals in "minimum bias" $p\bar{p}$ interactions at $\sqrt{s}$ of 546 GeV. Lastly, the phenomenological particle production model of Giovannini and Van Hove [9] is used to provide a framework for comparing double Pomeron and minimum bias data at energies reached at the CERN Super Proton Synchrotron S$p\bar{p}$S.

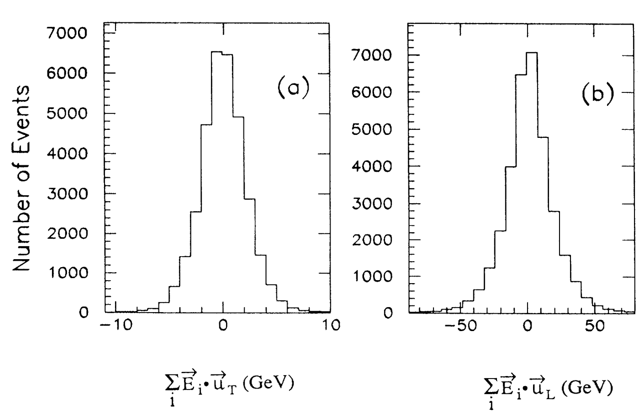

FIG. 3. The projection of $\sum_i \mathbf{E}_i$ in DPE events: (a) transverse to the beam axis, (b) parallel to the beam axis.

Figure 4 shows the mean charged particle multiplicity $\langle n \rangle$ corrected for acceptance and reconstruction efficiency, as a function of the central cluster mass M in the DPE data. As previously noted, M is the Pomeron-Pomeron c.m. energy when double Pomeron exchange is occurring. The data for $10 < M < 70$ GeV/c^2 are well described by an expansion to second order in $\ln(M)$:

$$\langle n \rangle = a + b\ln(M) + c\ln^2(M)\ , \qquad (2)$$

with values 2.89 ± 0.24, -1.67 ± 0.07, and 0.53 ± 0.01 for a, b, and c, respectively.

Similar parametrizations of $\langle n \rangle$ vs $\sqrt{s}$ are known to work well for pp [10] and e^+e^- hadrônic final states [11]. These are compared to the DPE data in Fig. 4, where we equate M with the $\sqrt{s}$ of the e^+e^- and pp systems. The mean multiplicity is seen to be similar to the e^+e^- and pp data at the lowest values of M but to rise significantly faster than the e^+e^- and pp data as M ($\sqrt{s}$) increases.

Figure 5 shows the DPE charged particle multiplicity distributions plotted in the Koba-Nielsen-Olesen (KNO) variables $\langle n \rangle P(n)$ and $n/\langle n \rangle$ for the mass intervals $10 < M < 20$, $20 < M < 30$, and $50 < M < 70$ GeV/c^2. We note that KNO scaling does not hold across the $10 < M < 70$ GeV/c^2 range and that the scale breaking takes the form of a shrinkage in width with increasing M.

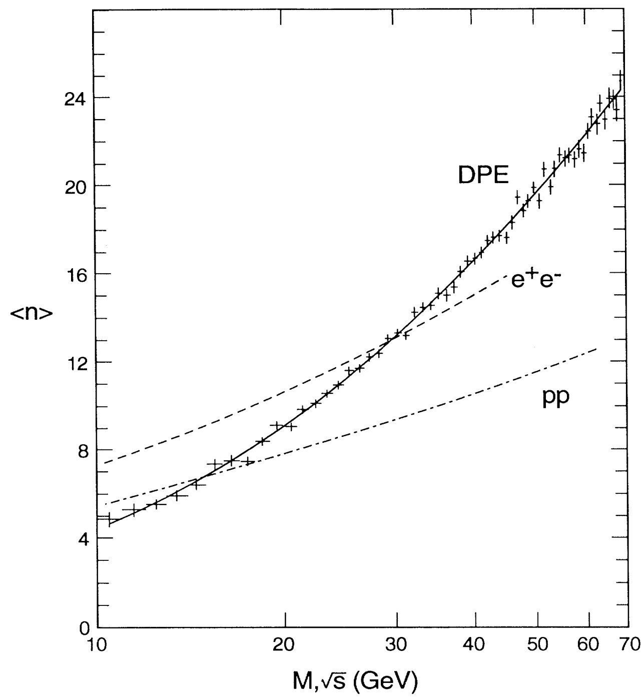

FIG. 4. The mean charged particle multiplicity $\langle n \rangle$ as a function of invariant mass, M, for DPE events. The solid curve is a second order fit to the data in $\ln(M)$. Also shown are similar fits in $\ln(\sqrt{s})$ to pp [10] and e^+e^- [11] multiplicity data.

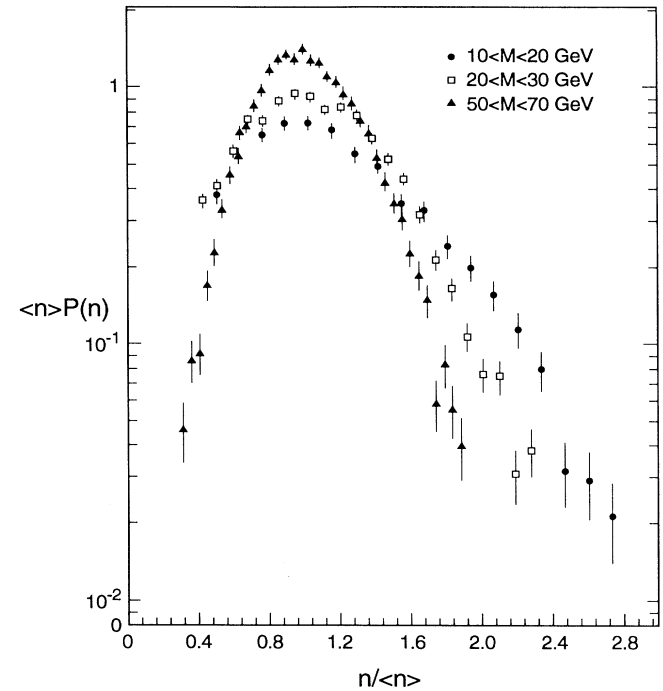

FIG. 5. Charged particle multiplicity distributions for DPE events plotted in the KNO variables for the mass intervals 10–20 GeV/c^2, 20–30 GeV/c^2, and 50–70 GeV/c^2.

In recent years it has emerged that the shapes of e^+e^-, pp, and $p\bar{p}$ multiplicity distributions are well described over a wide energy range by the negative binomial (NB) distribution [12,13]. For example the UA5 Collaboration has shown that the charged multiplicity of nonsingle diffractive pp and $p\bar{p}$ interactions is well described by the NB distribution from $\sqrt{s}=10$ GeV to $\sqrt{s}=546$ GeV [14]. (The UA5 "minimum bias" trigger excluded elastic and single diffraction dissociation events.) The NB distribution is specified by two parameters $\langle n \rangle$ and k which are observed to vary smoothly with s. In pp and $p\bar{p}$ data the parameter k^{-1} is well fitted by the form [15]

$$k^{-1}=-0.104+0.085\ln(\sqrt{s}) , \quad (3)$$

where $\sqrt{s}$ is in GeV. The parametrization of $\langle n \rangle$ as a second order expansion in $\ln(s)$ has been noted earlier [Eq. (2)].

Table I summarizes the $\langle n \rangle$ and k^{-1} values obtained in NB fits to the DPE charged multiplicity distributions and shows that the DPE data are also compatible with the NB form.

Figure 6 compares the mass dependence of k^{-1} for the DPE data with the $\sqrt{s}$ dependence of k^{-1} for pp and $p\bar{p}$ data as parametrized in Eq. (3). While k^{-1} rises with $\sqrt{s}$ for the pp and $p\bar{p}$ data, the DPE data exhibit the contrary trend. (Note that the Poisson distribution is a special case of a negative binomial with $k^{-1}=0$.) Thus the pp and $p\bar{p}$ distributions deviate increasingly from the Poisson form as $\sqrt{s}$ increases, while the DPE distributions become more Poissonian as M increases.

The UA5 Collaboration has also studied minimum bias multiplicity distributions in different rapidity intervals in

TABLE I. Data on charged particle multiplicities in double Pomeron exchange interactions for a range of M values. The parameters $\langle n \rangle$ and k^{-1} were obtained by fitting charged multiplicity distributions with the negative binomial distribution. $\bar{N}$ and n_c are the parameters of the cluster model of Giovannini and Van Hove [9] calculated from Eq. (4).

M (GeV/c^2)	$\langle n \rangle$	k^{-1}	$\bar{N}$	n_c	$\chi^2/N_{\rm DF}$
10–20	7.68±0.09	0.149±0.012	5.12±0.13	1.54±0.02	1.28
20–30	11.39±0.07	0.083±0.004	8.02±0.12	1.42±0.01	2.75
30–40	14.72±0.07	0.059±0.003	10.60±0.13	1.39±0.01	1.82
40–50	17.94±0.08	0.050±0.002	12.84±0.17	1.40±0.01	1.86
50–60	21.69±0.08	0.042±0.002	15.43±0.17	1.41±0.01	1.11

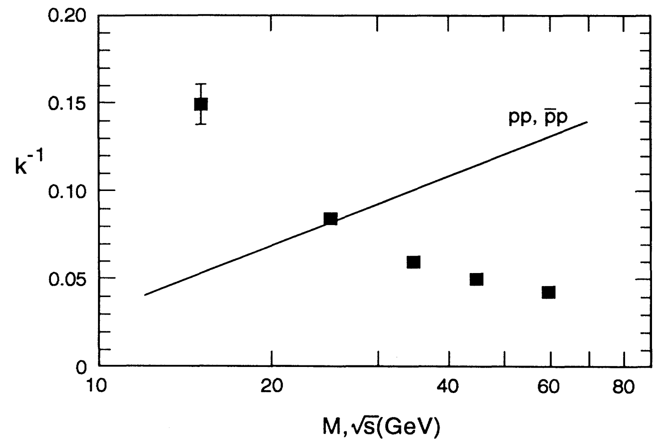

FIG. 6. The M dependence of the negative binomial parameter k^{-1} for the DPE data (solid squares) compared to the $\sqrt{s}$ dependence for pp and $p\bar{p}$ data [Eq. (3)].

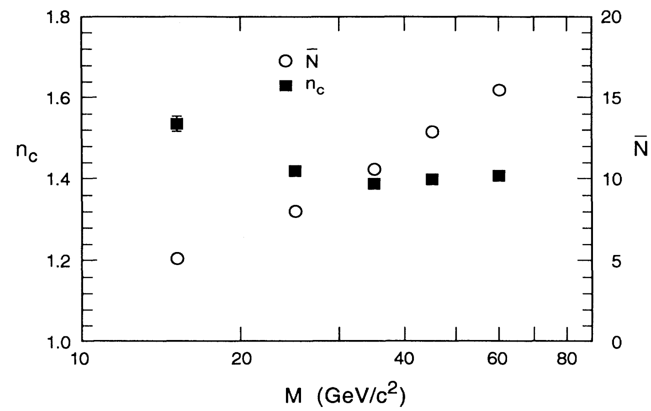

FIG. 7. The M of the average number of clusters, $\bar{N}$ (open circles), and the average multiplicity per cluster n_c (solid squares).

$p\bar{p}$ interactions at $\sqrt{s}$ of 546 GeV [16]. Again the NB distribution provides excellent fits to these distributions for a k^{-1} decreasing from 0.63 at $|\eta|<0.2$ to 0.40 at $|\eta|<3.0$. Recalling that $M \propto e^{\Delta\eta}$ at fixed $\sqrt{s}$, the decrease of k^{-1} with increasing M, for the DPE data in Fig. 6 seems to mirror the rapidity dependence observed by UA5. However k^{-1} is smaller by an order of magnitude in the DPE events.

Several models have been proposed to explain the relationship of the negative binomial distribution to particle multiplicities [9,17–19]. For example in the model of Giovannini and Van Hove [9] the NB distribution arises from the independent emission of clusters or "clans" with a Poissonian distribution; each cluster then decays with a logarithmic multiplicity distribution. The average number of particles per cluster n_c and the average number of clusters per event $\bar{N}$ are directly related to the NB parameters:

$$\bar{N}=k\ln(1+\langle n\rangle/k), \quad n_c=\frac{\langle n\rangle/k}{\ln(1+\langle n\rangle/k)} . \tag{4}$$

Multiplicity distributions have been extensively analyzed within the framework of this two-stage picture. For both e^+e^- and hadronic interactions the number of clusters in a given pseudorapidity interval is approximately constant with $\sqrt{s}$, while the average number of charged particles per cluster increases strongly with energy [12,13].

The dependence of $\bar{N}$ and n_c on M in DPE events is shown in Fig. 7 and Table I, and differs significantly from that observed in other reactions. The average number of clusters increases from 5.1 for $10<M<20$ GeV/c^2 to 15.4 for $50<M<60$ GeV/c^2 while the cluster charged multiplicity is approximately constant at around 1.4. For MB events at $\sqrt{s}$ of 546 GeV the UA5 experiment finds eight clusters with an average of 3.8 charged particles for the full η range; for $|\eta|<3$ there are five clusters. UA5 also reports that the $\bar{N}$ is approximately independent of $\sqrt{s}$ between 63 GeV (pp) and 900 GeV ($p\bar{p}$) [9].

VI. JET PRODUCTION

The large cluster mass in this experiment opens the possibility of exploring perturbative QCD in double Pomeron exchange. We used the standard UA1 clustering algorithm [20] to identify jets with transverse energy E_T above 5 GeV. (The E_T value of 5 GeV has previously been identified as the threshold above which clusters have a substantial component ($\approx 80\%$) of QCD jets [21].) Copious jet production is observed: 49% (5%) of events have one or more jets with E_T above 5 (10) GeV.

Within the QCD framework the Pomeron may be modeled as a multiparton system in which jets are produced by hard parton-parton scattering [22,23]. For dijet events both the fraction (x) of Pomeron momentum carried by the interacting partons and their scattering angle (θ^*) in the parton-parton rest frame are calculable, provided that the transverse momenta of the Pomerons are negligible. As noted earlier the measured transverse momentum of the Pomeron-Pomeron system can be neglected. The x distribution for dijet events with $|\eta_{\rm jet}|<1.5$ and E_T thresholds of 5 and 7 GeV is shown in Fig. 8. Although the distribution has not been corrected

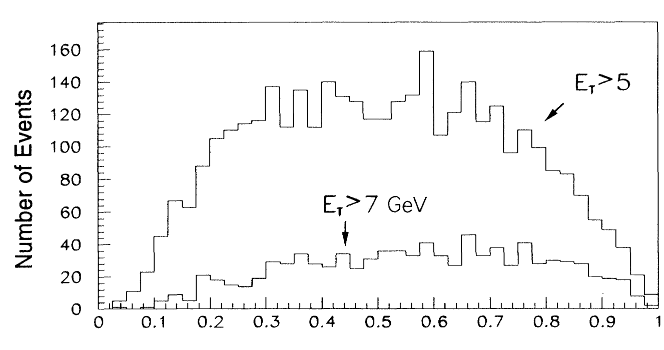

FIG. 8. The distribution of parton momentum x in Pomeron-Pomeron collisions which produce jet pairs with $E_T \geq 5$ (7) GeV, assuming a multiparton structure of the Pomeron.

for detector acceptance or selection criteria, it suggests a relatively hard partonic structure function for the Pomeron.

VII. SUMMARY

A total of 33 000 events with the topology of double Pomeron exchange have been recorded in $p\bar{p}$ interactions at $\sqrt{s}$ of 0.63 TeV with integrated luminosity 116 nb^{-1}. The calorimetric trigger restricted particle production to the pseudorapidity range $|\eta|<3$. The resulting central particle cluster has invariant mass M in the range 3–70 GeV/c^2 and kinematical properties consistent with production via double Pomeron exchange. Jets are copiously produced in the DPE trigger events consistent with a multiparton structure of the Pomeron.

Charged particle multiplicity distributions in e^+e^-, pp, and $p\bar{p}$ are well described over a wide energy range by the negative binomial (NB) distribution [12,13]. We find that the DPE multiplicity distributions in this experiment are similarly compatible with the NB form. We have used the NB parameters $\langle n \rangle$ and k^{-1} to compare charged particle multiplicity distributions for DPE events at $10<M<70$ GeV/c^2 with pp, $p\bar{p}$, and e^+e^- over the same $\sqrt{s}$ range. The mean charged particle multiplicity $\langle n \rangle$ is found to rise faster for DPE events than for e^+e^- or pp (Fig. 4). The mass dependence of the NB parameter k^{-1} in DPE events is strikingly different from the corresponding $\sqrt{s}$ dependence in pp and $p\bar{p}$ interactions. Within the framework of the cluster ("clan") model of Giovannini and Van Hove [9] these differences can be interpreted as a rapid growth in cluster production $\bar{N}$ with increasing mass M in DPE events compared to a very weak dependence of $\bar{N}$ on $\sqrt{s}$ in pp and $p\bar{p}$ interactions.

There has long been interest in the possibility that Pomeron-Pomeron interactions may be enriched in s-, c-, and b-quark production relative to hadron-hadron interactions. In this experiment kaons were identifiable by dE/dx only for momenta below 0.5 GeV/c and hence a definitive search for enhanced kaon or open charm production was not feasible.

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