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TRANSVERSE MOMENTUM DISTRIBUTION
IN POMERON-POMERON COLLISIONS AT THE CERN ISR

ABCDHW Collaboration

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ABSTRACT

Proton-proton interactions which result in a central cluster of mass M_x and two quasi-elastically scattered protons are generally described by Pomeron-Pomeron scattering. A study of this process at ISR energies with the Split Field Magnet detector is carried out in terms of transverse momentum behaviour for the centrally produced system of particles. The inclusive p_T distribution for central hadrons is measured up to 3 GeV/c. For $p_T < 1.2$ GeV/c, the p_T distribution is exponential. Using a subsample of exclusive events, this exponential shape is shown to originate from a phase-space-like decay of M_x when convoluted with a transverse component of the Pomeron momentum. In the high p_T range, the shape of the p_T distribution strongly depends on Feynman- x of the scattered protons in a way that can be described by hard parton scattering.

1. INTRODUCTION

An important concept in "soft" hadronic physics is that of the Pomeron, hypothesized in Regge theory to explain the elastic scattering of hadrons: the Pomeron trajectory is the Regge trajectory associated with the exchange of the quantum numbers of the vacuum. In Quantum Chromodynamics (QCD) a satisfactory understanding of the actual mechanism of "Pomeron exchange" does not yet exist, because of the difficulty in performing calculations in the "non-perturbative" regime of soft hadronic collisions. However, there are suggestions that Pomeron exchange could be described by multi-gluon exchange with possible quark and gluon loops [1,2] (fig. 1(a)).

Data on diffractive scattering are usually interpreted with optical or geometrical models and no investigations intended to reveal the role of partons have been done. Only recently an ISR experiment studying the fragmentation of a diffractive system produced in pp interactions has claimed evidence for Pomeron interaction with a single valence quark in the beam proton [3].

In the following we study the pion p_T distribution in the process

$$pp \rightarrow ppX, \quad X \rightarrow \pi^\pm + \dots \quad (1)$$

($\sqrt{s} = 62$ GeV), where the particles in system X have rapidities $|y| < 1.5$ and the final-state protons have Feynman-x near 1. This process is expected to be dominated by Double Pomeron Exchange (DPE), and is labelled DPE in the text. The centrally produced particles are believed to be created in the Pomeron-Pomeron collision as in the scheme of fig. 1(b). The data presented indicate the existence in these processes of a soft and also of a hard component.

2. DATA SELECTION

The data taking was carried out at the CERN Intersecting Storage Rings (ISR) at a c.m. energy $\sqrt{s}$ of 62 GeV using the Split Field Magnet (SFM) spectrometer [4]. The detector was an ensemble of multiwire proportional chambers. It consisted of a central system surrounding the interaction region and of two forward telescopes along the outgoing beam directions.

A magnetic field of ~ 1 T was perpendicular to the beams. The geometry of the system was conceived to have up-down and forward-backward symmetry. A system of time-of-flight counters was used for particle identification in the central region.

The trigger logic required two fast forward tracks, one in each telescope, in coincidence with at least one track in the central detector. A veto logic against tracks at intermediate polar angles was designed to select events where the detected particles were at low rapidities and well separated from the two forward-backward tracks. The final integrated luminosity was 50 nb^{-1} .

The data have been processed with the standard SFM programs for full event reconstruction. Only events with two positive forward tracks at large Feynman- x ($|x_F| > 0.7$) in opposite directions have been accepted for further analysis. A requirement of a good event vertex determination has also been applied. Our final sample consists of 200 000 events compatible with reaction (1). The average proton $|x_F|$ is 0.93; the central cluster X has an average multiplicity of about five charged particles, all at small rapidity ($|y| < 1.5$) [5]. Proton momenta are measured with a precision of $\Delta p/p \sim 7\%$ on the average. The data cover a range of proton 4-momentum transfer squared $|t|$ between 0.08 and 1.5 GeV^2 .

3. DATA ANALYSIS

3.1 Pion P_T distribution in $pp \rightarrow pp \pi^+ \pi^-$

Out of the main sample, a subsample of 12 500 exclusive events (4-constraint kinematic fits) with only two central pions of opposite charges has been extracted to study the process

$$pp \rightarrow pp \pi^+ \pi^-, \quad (2)$$

which has been discussed in a recent paper [6]. In particular, the $(\pi^+ \pi^-)$ invariant-mass spectrum (fig. 1(c)) between threshold and $1.7 \text{ GeV}/c^2$ has been studied: a significant $f^0(1270)$ ($J^{PC} = 2^{++}$) signal appears above a large low-mass continuum with no sign of ρ^0 ($J^{PC} = 1^{--}$) production. Other experiments have shown data with similar features [7], partly in a complementary range of proton 4-momentum transfer [8] (see also fig. 4 (d)).

The data exhibit contributions from s and d wave excitation only, the former being mainly responsible for the low-mass continuum.

Fig. 2(a) shows the p_T^* distribution for central pions in the rest frame of the $(\pi^+\pi^-)$ system for different mass slices of $M(\pi^+\pi^-)$. p_T^* is the transverse momentum with respect to the incident Pomeron direction, i.e. the direction of the proton momentum transfers. Superimposed on the data are the expectations for a two-body decay into pions for a mass M_X at rest. We have assumed pure s wave behaviour from threshold up to $1 \text{ GeV}/c^2$ and also in the region above $1.5 \text{ GeV}/c^2$. In the range 1 to $1.5 \text{ GeV}/c^2$ a superposition of s and d ($m = 0$) waves in the percentages obtained from a fit to the mass spectrum [6] has been used ($(47 \pm 8)\%$ d-wave). An estimate of the detector angular acceptance has been included. A good description of the data is obtained up to $1.5 \text{ GeV}/c^2$. In the highest mass bin the distribution is well reproduced in the higher p_T^* range, while an excess is observed with respect to the s wave prediction in the lower p_T^* range, due to contributions from the d wave and the interference with the s wave which have been neglected.

In fig. 2(b) the pion p_T distribution is plotted in M_X bins in the overall proton-proton centre-of-mass frame (pp c.m.s.); in this case p_T is computed with respect to the incident proton direction. In this frame a tail in the p_T distribution develops beyond the $(\pi^+\pi^-)$ system limit of $M_X/2$ in each mass bin and has an exponential shape: $dN/dp_T^2 \propto \exp(-a p_T)$. The region between 1 and $1.5 \text{ GeV}/c^2$ has a larger slope which could arise from the f^0 (d wave) enhancement superimposed on the s wave continuum.

A transverse boost of the central system from the rest frame to the pp c.m.s. is needed to produce the observed effects. This transverse boost originates from the transverse component of the momenta of the two Pomerons which have an exponential $\exp(-bt)$ behaviour in the proton 4-momentum transfer squared, t . The variations of the transverse and longitudinal components of the Pomeron momentum with the central M_X mass are shown in fig. 2(c). The average longitudinal component of the Pomeron momentum is observed to increase linearly with increasing mass M_X , while the average transverse component is independent of the central M_X mass with an average $\sim 400 \text{ MeV}/c$.

When integrated over all $(\pi^+\pi^-)$ masses the pion p_T distribution in the pp c.m.s. (fig. 2(d)) has a maximum followed by an exponential behaviour from $p_T \sim 0.7$ GeV/c up to 2 GeV/c with slope $a \approx 5.6$ (GeV/c) $^{-1}$. Detector acceptance has been determined to play no significant role for $p_T > 0.5$ GeV/c.

3.2 Pion p_T distribution in $pp \rightarrow pp \pi^+\pi^-\pi^+\pi^-$

In fig. 2(e) the p_T distribution for pions in DPE events with four central pions is superimposed on the pion p_T distribution for DPE events with two central pions. The exponential behaviour observed for the two-pion events is maintained in the four-pion events, where it is further extended to lower values of p_T .

3.3 Inclusive p_T Distribution

The inclusive p_T distribution for central pions is studied for our full data sample on reaction (1) where the central system X has an average charged multiplicity of ~ 5 . The following criteria have been added to the selection procedure: (a) the central system should consist of at least two charged central particles; (b) an event is accepted when both proton momenta are measured with good precision ($\Delta p/p < 10\%$); (c) only central tracks with $\Delta p/p < 30\%$ are considered; (d) a particle is included in the p_T distribution only when it is found in the small azimuthal angular region of $\pm 20^\circ$ around the horizontal plane (perpendicular to the magnetic field) where the average $\Delta p/p$ is 7%. Detector angular acceptance mainly affects low p_T particles and its effect has been investigated by separately studying positive and negative particles, which have different polar angle acceptance. No distortion of the inclusive p_T distribution is found for $p_T > 0.5$ GeV/c. Correction factors which take into account the momentum resolution and a possible background from spurious tracks are applied for $p_T > 2$ GeV/c; these factors range from 0.86 at 2.1 GeV/c to 0.5 at 3 GeV/c.

Fig. 3 shows the inclusive p_T distribution in the pp c.m.s. for central pions with $p_T > 0.5$ GeV/c in events where the final-state protons in reaction (1) are at very large Feynman-x ($|x_F| > 0.9$). The

data are compared to the inclusive p_T distribution for pions produced in normal inelastic (Minimum Bias (MB)) proton-proton reactions [9]. Two observations emerge. First, for $p_T < 1.2$ GeV/c the distribution for DPE events with all central multiplicities has the exponential behaviour already observed in the exclusive central two-pion sample. A similar exponential behaviour is observed in MB events. Second, in the high p_T range DPE data still preserve the exponential behaviour while MB data show the characteristic flattening which has been attributed to hard parton scattering as first suggested by Berman, Bjorken and Kogut [10]. A similar behaviour is also seen in photon-photon interactions ($e^+e^- \rightarrow e^+e^- + X$), where the inclusive p_T distribution for hadrons has an exponential low p_T behaviour followed by a flattening for $p_T > 1.2$ GeV/c. This has been interpreted as evidence for photon point-like coupling to quarks [11].

In DPE events the pion p_T distribution shows an exponential behaviour up to 3 GeV/c. The behaviour at high p_T changes when more energy is transferred to the central system, by selecting lower Feynman- x protons. This procedure shifts the phase-space limit to higher p_T values for the central particles. Fig. 4(a) shows the p_T distribution for centrally produced hadrons in events with two final-state protons with $|x_F| > 0.7$. At lower p_T one still observes an $\exp(-5.6 p_T)$ behaviour, while at higher p_T a deviation from the exponential shape develops. When comparing with fig. 3 a clear trend becomes visible. The p_T distribution flattens out with decreasing proton Feynman- x and approaches the p_T distribution for pion production in MB events, where no proton selection is applied.

3.4 Correlation between central and forward particles

Fig. 4(b) shows the azimuthal angle ϕ distribution for the final-state protons. The angle ϕ is calculated with respect to the highest p_T central particle ($p_T > 1.5$ GeV/c). A tendency of both protons to recoil against the central particle with highest p_T , "trigger particle", is observed.

In fig. 4(c) the proton behaviour is investigated more in detail. In pp c.m.s. we define p_L as the momentum component along the proton beam direction and p_x as the momentum component perpendicular to p_L projected onto $\vec{p}_T$ of the trigger particle (see fig. 4(b)). The coordinate system

is set such that the trigger particle has $p_x > 0$ and $p_L > 0$, "trigger side". The average p_x of final-state protons on the trigger side and opposite to the trigger side is plotted in bins of proton p_L . The data show a proton recoil against the trigger particle. This effect is more important on the trigger side and increases with increasing proton p_L .

We have investigated the existence of detector effects which could shift the average of the p_x distribution for final-state protons away from zero, and no biases have been observed. In particular, the proton p_T range covered in this experiment is shown in fig. 4(d). The bulk of the events falls within the accepted range.

3.5 Expectations from hard parton scattering

Hard scattering calculations do account for the high p_T shape of the inclusive p_T distribution in normal inelastic pp events. In the following it is studied whether central production of pions at high p_T in reaction (1) is compatible with current hard scattering models.

A hard parton scattering model, described in ref. [12], has been successfully used to describe the main features of high p_T hadron production in pp events at the CERN ISR. It is a QCD-inspired Monte-Carlo program which simulates pp events with four jets in the final state. Two transverse jets originate from the scattered partons, while two spectator (longitudinal) jets originate from those incident partons not participating in the interaction.

For the study of the present experimental situation, the model incorporates the following features:

- (a) Interacting partons are gluons or quarks. The Bjorken x distribution of partons inside a beam proton has a $x^{-1} (1-x)^n$ behaviour ($n = 3$ for quarks, 5 for gluons).
- (b) Each of the two spectator systems produces in the fragmentation a proton with large Feynman x . Therefore, the partons participating in the interaction have very low Bjorken x (typically < 0.1). At $\sqrt{s}$ (proton-proton) = 62 GeV, the c.m. energy of the parton-parton scattering system is ~ 6 GeV.

- (c) An energetic central particle ($p_T > 1.5$ GeV/c) is produced. Because of (b), even if more partons were contributing to Pomeron exchange, this condition forces only one of them to carry most of the energy.

In fig. 4(a) model calculations for central production of high p_T particles are superimposed on the data for $p_T > 2$ GeV/c. Results are shown for $X_F > 0.7$ and $X_F > 0.9$ for the two forward protons. A satisfactory description of the previously observed high p_T behaviour in reaction (1) is obtained.

In this model, a parton inside a proton has a transverse momentum k_T . The parton k_T distribution is assumed to be gaussian. Production of high p_T particles is enhanced by parton k_T . Local momentum conservation inside a beam proton requires the spectator system to compensate the k_T of the interacting parton, leading to a characteristic azimuthal asymmetry of the spectator fragments. Expectations from the hard parton scattering model for different values of the average parton k_T are compared to the data in figs 4(b) and 4(c). The model calculations are consistent with the trend of the data. The values for K_T and $X_B \cdot P_{\text{beam}}$ ($X_B = \text{Bjorken } X$) of interacting partons in high p_T DPE events as obtained with the model calculation are observed in fig. 4(e) to lie on the extrapolation of the average p_T and p_L of the Pomeron in DPE events with a small central mass.

4. CONCLUSIONS

The process

$$pp \rightarrow ppX \quad (3)$$

(at $\sqrt{s} = 62$ GeV), where X is a system of low rapidity particles ($|y| < 1.5$) and the final-state protons have Feynman- x near 1 is generally interpreted as dominated by Pomeron-Pomeron scattering, the system X being created in the Pomeron-Pomeron collision.

In this paper we have focused on the p_T distribution of central charged pions ($X \rightarrow \pi^\pm + \dots$) with p_T up to 3 GeV/c.

At low p_T (< 1.2 GeV/c) the distribution has an exponential shape with slope ~ 5.6 (GeV/c) $^{-1}$. This behaviour is studied with a sample of exclusive events with only two central charged pions:

- (a) In the rest frame of the central system (Pomeron-Pomeron c.m.s.) with mass M_X the p_T^* distribution has the expected shape for a dominantly s wave two-body decay.
- (b) In the proton-proton c.m.s. the p_T distribution has a tail beyond the $(\pi^+\pi^-)$ system limit of $M_X/2$, with an exponential shape:

$$dN/dp_T^2 \propto \exp(-a p_T).$$

A transverse boost of the central system from the rest frame to the pp c.m.s. produces the observed effects. This transverse boost originates from the transverse component of the two Pomerons (proton momentum transfers). The average transverse component of the Pomeron momentum is observed to be independent of the mass M_X of the central system, with value ~ 400 MeV/c. The average longitudinal component of the Pomeron momentum linearly increases with increasing M_X .

An exponential decrease with identical slope is also observed for the pion p_T distribution in events with four central pions.

The inclusive central pion p_T distribution in reaction (3), where X has an average charged multiplicity of ~ 5 , still preserves the low p_T exponential behaviour observed in the exclusive two central pion sample.

At high p_T the shape of the p_T distribution for central pions in reaction (3) strongly depends on Feynman-x of the scattered protons. An exponential behaviour up to 3 GeV/c is observed when $|x_F| > 0.9$. When protons of lower Feynman-x are included, a flattening for $p_T > 1.5$ GeV/c with respect to the exponential low p_T shape develops. This behaviour can be described by a hard parton scattering model where low Bjorken-x partons interact and a large Feynman-x particle is produced in the fragmentation of each of the two spectator systems which carry most of the beam energy. Hard parton scattering model calculations also predict a

long range correlation between forward protons and central particles, which is observed in the data. Both protons tend to recoil against that central particle with highest p_T .

The transverse and longitudinal momentum components of the interacting partons as evaluated with the above model extrapolate smoothly to higher M_X the behaviour of the Pomeron in DPE events with a small central mass.

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FIGURE CAPTIONS

Fig. 1 (a) Example of gluon ladders and quark loops which may sum to produce a Pomeron trajectory.

(b) Double Pomeron exchange in $pp \rightarrow ppX$.

(c) Uncorrected $(\pi^+\pi^-)$ invariant mass distribution for the reaction $pp \rightarrow pp\pi^+\pi^-$ at $\sqrt{s} = 62$ GeV from ref. [6].

Fig. 2 (a) Uncorrected p_T^* distribution for central pions in the rest frame of the $(\pi^+\pi^-)$ system for different slices of $M(\pi^+\pi^-)$; p_T^* is computed with respect to the incident Pomeron direction, i.e. the direction of the proton momentum transfer. Dashed lines are calculations for a two-body decay of the central mass (see text).

(b) Uncorrected pion p_T distribution in bins of $M(\pi^+\pi^-)$ in the proton-proton centre-of-mass frame (pp c.m.s.); p_T is computed with respect to the incident proton direction.

(c) Average transverse and longitudinal components of the proton momentum transfer (Pomeron momentum) in the pp c.m.s. as a function of the mass of the central $(\pi^+\pi^-)$ system (corrected for acceptance).

(d) Uncorrected p_T distribution for pions centrally produced in the reaction $pp \rightarrow pp\pi^+\pi^-$ (pp c.m.s.).

(e) Uncorrected p_T distribution for pions centrally produced in the reaction $pp \rightarrow pp\pi^+\pi^-\pi^+\pi^-$, superimposed on fig. 2(d). The two sets of data points are normalized to the same value at 1 GeV/c.

FIGURE CAPTIONS 2 (Cont'd)

Fig. 3 Corrected inclusive p_T distribution for pions centrally produced in events $pp \rightarrow ppX$ at $\sqrt{s} = 62$ GeV, where the final-state protons are at very large Feynman- x ($|x_F| > 0.9$) and X is a system of low rapidity ($|y| < 1.5$) particles (full dots). The data are compared with the inclusive p_T distribution for pions produced in normal inelastic proton-proton reactions at $\sqrt{s} = 53$ GeV [9] (open dots). The two data sets are normalized to the same value at 1 GeV/c.

Fig. 4 (a) As fig. 3 but final-state protons with $|x_F| > 0.7$. Hard parton scattering calculations (see text) are superimposed on the data. The relative scale is obtained by normalizing the model calculation to the corresponding data at $p_T = 2$ GeV/c.

(b) Azimuthal angle ϕ distribution for final-state protons. The angle ϕ is calculated with respect to the central particle with highest p_T (> 1.5 GeV/c). Model calculations (see text) are shown for different values of the parton transverse momentum k_T .

(c) Proton average momentum component p_x along $\vec{p}_T$ of the central "trigger" particle (see text and fig. 4(c)) as a function of the proton p_L in the pp c.m.s.. The "trigger" particle has $p_x > 0$ and $p_L > 0$. Model calculations (see text) are shown for different values of parton k_T .

(d) p_T range for final-state protons in pp DPE events covered in this experiment. The region for $p_T < 0.25$ GeV/c is covered in the experiment of ref. [8].

(e) As fig. 2(c) but including the hard scattering model values for K_T and $X_B \cdot P^{\text{beam}}$ ($X_B = \text{Bjorken } X$) of interacting partons in high p_T DPE events (see text).

Fig. 1

Fig. 2(a)

Fig. 2(b)

Fig. 2(c)

Fig. 2(d)

Fig. 2(e)

Fig. 3

Fig. 4(a)

Fig. 4(b)

Fig. 4(c)

Fig. 4(d)

Fig. 4(e)