DOUBLE PARTON SCATTERING IN pp COLLISIONS AT $\sqrt{s} = 63$ GeV*The Axial Field Spectrometer Collaboration*

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ABSTRACT

In a study of pp collisions at $\sqrt{s} = 63$ GeV with more than 29 GeV total transverse energy emitted into 1.8 units of rapidity in the central region, we have extracted a sample of 4-jet events and compared it with models of the two sources of 4-jet production: double bremsstrahlung and double parton scattering. The data cannot be described by bremsstrahlung alone, and we extract the fraction of 4-jet events attributed to double parton scattering for various definitions of the 4-jet sample. We determine the double parton scattering/2-jet yield ratio, and this leads to a determination of the proton radius. We discuss the implications of our observations for the general understanding of high- ΣE_T events.

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1. INTRODUCTION

In 1982 the Axial Field Spectrometer (AFS) and UA2 Collaborations demonstrated that pp and $p\bar{p}$ collisions selected by a global transverse energy ΣE_T trigger covering two units of rapidity in the central region are dominated by 2-jet events when a certain threshold in ΣE_T is passed. This threshold grows slowly with $\sqrt{s}$, being ≈ 32 GeV at $\sqrt{s} = 63$ GeV and 70 GeV at $\sqrt{s} = 540$ GeV [1, 2].

These observations established the relevance of the QCD parton model for highly inelastic pp collisions, after a period of controversial ‘jet physics’ at the CERN Intersecting Storage Rings (ISR) and the absence of jets in pp collisions at $\sqrt{s} = 24$ GeV (the ‘NA5 puzzle’ [3]).

Since 1982 the emphasis has shifted from the ΣE_T triggers towards the more efficient jet triggers, and detailed studies of 2- and 3-jet events have been presented [4–6]. The yield and structure of the predicted $2 \rightarrow 2$ and $2 \rightarrow 3$ QCD processes have been verified, and the fragmentation of jets has been analysed.

The medium- and low- ΣE_T events (i.e. events with ΣE_T below the transition to 2-jet dominance) were never satisfactorily described in terms of fundamental theory (QCD). At some stage the mechanism of multiple initial-state gluon bremsstrahlung was a popular candidate for explaining the lack of jet dominance in NA5 [3], but the idea remains a postulate. The essential feature of such a model, implemented in particular by Field [7], is that all medium- and high- ΣE_T events are due to $2 \rightarrow n$ processes ($n = 2, 3, \dots$). As for the AFS data, the Field model is not able to describe the distinct transition from the low- and medium- ΣE_T region ($\Sigma E_T < 25$ GeV), where the total multiplicity is approximately proportional to ΣE_T , to the high- ΣE_T region with approximately constant multiplicity [7].

Whilst the explanation of the medium- ΣE_T events in terms of $2 \rightarrow n$ QCD processes appeared incomplete, a phenomenological description of the ΣE_T events in terms of a two-component model became widely used [8]. This model assumed that an event is due to either a ‘soft’ or a hard collision. The hard collisions are the 2-jet and 3-jet events, etc., described by the QCD-improved parton model. The ‘soft’ events were considered to be due to more complicated processes which cannot be calculated in perturbative QCD but which fall off faster with ΣE_T ($|\eta| \leq 1$) than does the hard component at ISR energies and above. A study by the UA2 Collaboration supports such a picture [9], and it was previously used by us to extract the 1-jet cross-section and by the E609 Collaboration to extract the 2-jet cross-sections [10].

However, the two-component model does not constitute a dynamical explanation of the medium- ΣE_T events, and we believe that the Field model is at best incomplete. It is possible that a fundamental description can be obtained if one includes, in addition to the $2 \rightarrow n$ processes considered by Field, multiple hard-parton interactions, i.e. $m \times (2 \rightarrow n)$ processes.

We address this question experimentally by studying 4-jet events. We find that the majority of the 4-jet events have kinematic features which are better described by hard double parton scattering (DPS) than by double bremsstrahlung (DBS) processes. Double and multiple parton scattering yields have been calculated by several authors [11, 12] but have not previously been demonstrated experimentally.

Measuring the level of DPS is a step towards understanding the intricate interplay between soft and hard hadron physics. Furthermore, measurements of DPS give access to more detailed information on the proton structure, e.g. correlations between the partons.

After describing the apparatus, the data analysis, and the Monte Carlo model in Sections 2 to 4, we present in Section 5 the evidence for DPS. Detailed studies of the properties of the DPS 4-jet events are given in Section 6. The observed DPS/2-jet yield ratio is given in Section 7, and interpreted as a measurement of the proton radius in Section 8. The implications of the DPS processes for the

understanding of the ΣE_T events at various $\sqrt{s}$ values are discussed in Section 9. Section 10 contains the conclusions.

2. APPARATUS AND DATA-TAKING

The data were taken with the Axial Field Spectrometer at the CERN ISR. Proton-proton collisions at $\sqrt{s} = 63$ GeV were recorded for an integrated luminosity of 10 pb^{-1} .

The AFS consisted of a cylindrical drift chamber in a 0.5 T axial magnetic field, and a box-like uranium/copper/scintillator calorimeter surrounding the interaction region [13, 14]. The calorimeter covered 2π in azimuth and had a pseudorapidity coverage varying with azimuth from $|\eta| \leq 0.7$ to $|\eta| \leq 1.2$.

The calorimeter was segmented in depth into a 6 radiation lengths electromagnetic (e.m.) part followed by a 3.7 absorption lengths hadronic part. The energy resolution $\sigma(E)/E$ for e.m. and hadronic showers in the calorimeter was $18\%/\sqrt{E}$ (GeV) and $42\%/\sqrt{E}$, respectively.

The event sample was selected on line on the basis of the total transverse energy, i.e. all the calorimeter signals were summed up, weighting the individual signals to correspond to the transverse energy in the centre-of-mass system (assuming the interaction to be at the centre of the detector). The threshold was set to 28 GeV, and the data were filtered off line with a threshold of 31 GeV using calibrated, more accurate ADC signals.

Charged-particle tracks were provided by the drift chamber. The momentum resolution was $(\Delta p/p)^2 = (0.025p)^2 + 0.01^2$, and the track acceptance, including reconstruction efficiency, was typically 70%. The losses are due to crossing tracks and two dead regions of azimuth, 16° each. The tracking information is used to reconstruct the vertex and study the longitudinal fragmentation of jets.

Downstream around each of the two beam pipes, were located arrays of scintillation counters (the beam-beam counters), and surrounding the collision region was a barrel-shaped set of 44 scintillation counters, called the inner hodoscope.

A third hodoscope of scintillation counters, located near the beam-beam counters, were used together with these to study the particle multiplicity of the forward jet systems in the pseudorapidity region $2.4 \leq |\eta| \leq 4.0$.

3. DATA ANALYSIS

In the off-line analysis, timing information from the beam-beam counters and the inner hodoscope is used to reject double interactions separated by more than approximately 6 ns. The contamination of double interactions in a given subsample of the high- ΣE_T events varies with the event structure; samples of jet events are less contaminated than samples without jets. With a luminosity of typically $1.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, we calculate that the contamination of double interactions (assumed to be double 2-jet events described by the Duke-Owens structure functions [15] and K-factor, $K = 2$) is less than 1% in our 4-jet sample, when the smallest jet E_T is sufficiently high (≥ 4 GeV).

We have checked that our sample of 4-jet events is essentially free of double interactions by studying the distribution of the number of hits in the forward counters. Single interactions with 15 GeV ΣE_T in the central region have on the average seven hits, so double interactions with 30 GeV central ΣE_T would have on the average 14 hits. Our data with 30 GeV central ΣE_T have on the average 5.5 hits, and the distribution of hits shows no excess around 14 hits. On this basis we estimate that at most 5% of the 4-jet events are double events. This test is important since double proton interactions could give the same 4-jet structures as double parton interactions.

The events are passed through the standard AFS cluster-finding procedure for the calorimeter [4]. Using the reconstructed vertex, the momentum vectors corresponding to the energy clusters are

calculated and transformed to the centre-of-mass system. Special care must be taken to cope with spurious clusters, of typically 100 MeV energy each, generated by the radioactivity of the uranium plates. These clusters have typically most of their energy in the hadronic part containing most of the uranium. Therefore we remove clusters with E_T below 300 MeV if most of their energy is hadronic, otherwise a 100 MeV cut is used. A low cut on e.m. clusters ensures a similar acceptance for neutral and charged pions. No cut on the rapidity of clusters is imposed, but the physical boundaries of the calorimeter walls effectively cut away clusters at an average pseudorapidity of 0.9.

The transverse energy of a particle is defined as

$$E_T = \sqrt{p_T^2 + m^2} , \quad (1)$$

whilst the calorimeter measures

$$E_T = E \sin \theta , \quad (2)$$

where E is the phototube signal and θ its polar angle. The calorimeter has a linear response [14] for e.m. showers, which defines the nominal energy scale. For hadrons the observed energy E is in general not equal to the true relativistic energy $\sqrt{p^2 + m^2}$. This is due to non-linearity in the hadronic response, to back-leakage, and to the non-negligible rest masses. Figure 1 shows the response for charged pions. At high energies the response is 10% too low, and at low energies it is up to 15% too high. The data presented in the following figures are not corrected for these imperfections which, however, are reproduced in the Monte Carlo simulations.

The ΣE_T of the accepted clusters is required to be above 29 GeV. Owing to the non-linearity of the calorimeter, the average true ΣE_T of the accepted 2-jet events is slightly higher than for accepted events composed of mainly low- p_T particles. This leads to a bias towards low- p_T events in our sample, which is however alleviated by the low- E_T cut on clusters.

The distribution of ΣE_T is given in Fig. 2. Threshold inefficiencies, mainly due to the 31 GeV filter cut, are clearly visible. The MC calculations simulate this threshold effect.

A jet-finding algorithm is applied to the clusters: a window of size

$$\Delta\phi \times \Delta\eta = 55^\circ \times 1.0 \quad (3)$$

is moved in the ϕ - η plane until it contains maximum E_T . This defines the first jet. The jet momentum, which defines the jet axis, is given by the sum of the momenta of the clusters inside the window. The procedure is repeated on the remaining clusters to form the second jet, and so on. Only jets with $E_T \geq 4$ GeV are accepted. No specific requirement is imposed on the rapidities of the jet axes. The E_T of jet number n is denoted by E_T^n , and the sum of the E_T 's of jets 1, ..., n is called the 'n-jet E_T '. The spectra of the 2-jet, 3-jet, and 4-jet E_T are given in Fig. 2, where we include only n-jets with a minimum interjet angle $\omega \geq 55^\circ$ (in three dimensions) for the first n jets.

The sample of 4-jet events for the present study is selected by requiring 4-jet $E_T \geq 25$ GeV, as indicated in Fig. 2.

4. MONTE CARLO SIMULATIONS

In the further analysis, Monte Carlo calculations are an important tool. We use the program ISAJET [16] to simulate pp collisions, which are passed through the simulated detector, reconstructed by the standard AFS cluster-finding program, and analysed in the same way as the data.

ISAJET includes initial- and final-state gluon bremsstrahlung through the leading logarithm approximation of the parton cascade. The minimum invariant mass of a pair of partons produced in a branching is set to 6 GeV. The partons produced and the beam remnants are fragmented independently, and the parameters of the program were adjusted to fit our 2- and 3-jet data as described in Ref. [5].

We have supplemented ISAJET with the option of producing double parton scattering. For simplicity, these events are not allowed to emit gluon bremsstrahlung, so we adjust the associated event separately and give each 2-jet system an ‘intrinsic’ transverse momentum with a Gaussian width w in each component. The width w is taken to be 1.6 GeV at 2-jet $E_T = 30$ GeV, consistent with previous studies of 2-jet events [5]. We assume that w increases linearly with 2-jet E_T from $w = 1.0$ GeV at 2-jet $E_T = 10$ GeV.

To the extent that independent fragmentation models give realistic descriptions of jet physics, this Monte Carlo model embodies our knowledge of the structure of quark and gluon jets and of the associated event.

This jet model is also used to evaluate the background to observed 4-jet events from 3- or 2-jet events. It demonstrates that the parton model gives a good description of 2-, 3- and 4-jet events, even for jets with observed E_T down to 4 GeV, and that the DPS cross-section can be extracted consistently. Thus the Monte Carlo model is a tool used for designing jet algorithms, for finding kinematical regions where jet physics makes sense, and for allowing a study of the hard-parton dynamics.

5. EVIDENCE FOR DOUBLE PARTON SCATTERING

The main characteristic feature of 4-jet events produced by a $2 \times (2 \rightarrow 2)$ mechanism, as opposed to the $2 \rightarrow 4$ processes such as DBS, is that the four jets can be combined into two 2-jet systems, in each of which the two jets approximately balance their transverse momenta, forming so-called ‘pairwise balanced’ 4-jet systems. We project out this particular feature of the 4-jet kinematics using the ‘imbalance’ variable $\mathcal{J}$, defined by

$$\mathcal{J} = \frac{1}{2} (\vec{p}_{T1}^2 + \vec{p}_{T2}^2) , \quad (4)$$

where $\vec{p}_{T1,2}$ are the total transverse momenta of the two 2-jet systems, selected from the three possible combinations in each event to minimize $\mathcal{J}$. For the $2 \times (2 \rightarrow 2)$ processes the imbalance is expected to be small. The contribution from the primordial k_T of the partons described by the width w defined in Section 4 is $2w^2$ ($= 2.6 \text{ GeV}^2$ at 4-jet $E_T = 30$ GeV), and additional contributions are expected from resolution effects.

We will also consider a similar variable, formed by first boosting the 4-jet system to rest in the transverse plane, and then proceeding as above. Hence the ‘boosted imbalance’ is

$$\mathcal{J}_b = \vec{p}_T^2 , \quad (5)$$

where $\pm \vec{p}_T$ is the minimum total transverse momentum of each 2-jet system after the boost. The latter variable is particularly simple for the $2 \rightarrow 4$ processes, because $d(p_T^2) = 2p_T dp_T$ is a measure of phase space in this projection. Hence the boosted-imbalance distribution for $2 \rightarrow 4$ processes is slowly varying near $\mathcal{J}_b = 0$. The boosted-imbalance spectrum has the advantage of being insensitive to a possible total transverse momentum of the DBS 4-jet system produced by initial-state bremsstrahlung.

Figure 3 gives the distribution of imbalance for various cuts on the smallest interjet angle ω , and the E_T of the smallest jet E_T^4 . The two models of 4-jet production give different predictions for the

imbalance distribution. The data are not consistent with the bremsstrahlung Monte Carlo; there is an excess of events with small $\mathcal{J}$. The best description of the data is obtained by a sum of two components; DPS is dominating, especially when the minimum jet E_T is increased to 5 GeV. Thus we have strong evidence for the presence of the DPS process. The evidence for DBS is less strong, since backgrounds from 2- and 3-jet events would be expected to have similar imbalance distributions to those of the DBS process. In the next section we therefore focus on the balanced events and the study of the DPS process.

The variation of the DPS content with the 4-jet E_T is studied in Fig. 4, this time using the boosted imbalance as an indicator for the DPS process. Comparing Figs. 4a and 3a, one sees that the boosted imbalance distribution gives a peak at zero, i.e. a somewhat cleaner signal for the DPS process. The data are consistent with a DPS fraction decreasing with 4-jet E_T , as expected (see Section 9); the DPS content changes from $(61 \pm 10)\%$ to $(17 \pm_{17}^{30})\%$ when the 4-jet E_T is increased by only 6 GeV.

6. STUDY OF DOUBLE PARTON SCATTERING

The 4-jet sample is divided into a ‘balanced’ and an ‘unbalanced’ part, with $\mathcal{J} \leq 14 \text{ GeV}^2$, and $\mathcal{J} > 14 \text{ GeV}^2$, respectively. The balanced sample is dominated by the DPS events, whereas the unbalanced sample is a mixture of DBS and DPS. We will normally use the sample with $E_T^4 \geq 4 \text{ GeV}$ and $\omega \geq 55^\circ$, for which we estimate (see Fig. 3a) that the balanced set has 66% DPS and the unbalanced one 40% DPS (see Fig. 3a).

Figure 5 shows two characteristic events. The first event is relatively unbalanced, as is evident from the transverse momenta of the jets shown as an inset. Although there is not much room for four jets in the calorimeter, this event demonstrates that it is possible to have configurations which are unbalanced. The second event is a candidate of DPS, according to its kinematics.

A jet event is naïvely expected to have little energy outside the jet windows and to have the energy concentrated near the jet axes. However, when the jets have relatively low E_T , and are separated by small angles, the topology of the events is visually much less clear than for a high- ΣE_T 2-jet event.

A quantitative study of this question is presented in Fig. 6. The E_T flow as a function of the angle β (in three dimensions) from the jet axis is shown for the two jets of smallest E_T in balanced four-jet events. The distribution is rather wide; the small rise at large angles is due to adjacent jets. According to the Monte Carlo calculations, the average parton p_T of each of the two smallest jets is 5.6 GeV, i.e. they are produced at small Feynman x , where approximately two thirds of the jets are expected to be gluon jets. In our model, gluon jets are given a wider fragmentation than quark jets, according to the studies in Ref. [5]; we see here that this model describes the angular profile in Fig. 6a well.

Figure 6b gives the distribution of the E_T outside the jet windows. The agreement of the model with the data is the result of an adjustment of the associated event in the model; it has an average multiplicity of 1.6 times that of a minimum-bias event at the reduced $\sqrt{s}$. When the model is used to extract the DPS cross-section, the result depends critically on this level. The reason for this sensitivity is that the model is used to correct for the contribution from the beam jets in the jet regions.

As an extra check that our 4-jet events are consistent with an underlying 4-parton structure we study in Fig. 6c the z -distribution for the two smallest jets in balanced 4-jet events, where z is the momentum component of the charged particles along the jet axis, scaled with the jet energy: $z = p_L/E_{\text{jet}}$. The measured tracks have been corrected for resolution and acceptance effects, leading to a systematic error of $\pm 10\%$. The observed momentum of the jet (formed by the clusters inside the window) is used as an estimate of E_{jet} . According to the Monte Carlo, this is correct on the average. All tracks with angle from the jet axis $\beta \leq 50^\circ$ are included in the z -distributions. No correction is

made for the contribution of particles from the beam jets or from the other jets. Our z -distribution is therefore not directly comparable to the z -distributions (especially at low z) published by the TASSO Collaboration [17] and shown in Fig. 6c. The TASSO data are for e^+e^- annihilations at $\sqrt{s} = 14$ GeV corresponding to a ‘jet energy’ of 7 GeV, close to our average observed jet momentum of 6.6 GeV. The good agreement with TASSO at $z > 0.3$, corresponding to $p_L \geq 2$ GeV, shows that the content of high- p_T particles in our smallest jets is consistent with the interpretation in terms of underlying hard partons.

Figure 7 gives the distribution of the smallest interjet angle ω , and the E_T of the smallest jet E_T^4 , for balanced and unbalanced 4-jet events. We compare these distributions with the expectations from the bremsstrahlung and DPS Monte Carlos. A characteristic feature of bremsstrahlung is the approximate structure

$$dN(\text{jets})/dE d\theta \propto 1/E\theta, \quad (6)$$

where E and θ are the energy and angle of the emitted quantum. The ω distribution of the data is distorted by the finite size of the jet and our choice of the jet window size, so at $\omega = 65^\circ$ the acceptance for 4-jet events starts to decrease. The unbalanced events, which are expected to be relatively enriched with DBS events, are in good agreement with the bremsstrahlung Monte Carlo. It is non-trivial that the bremsstrahlung Monte Carlo describes DBS correctly, since ISAJET does not have the exact $2 \rightarrow 3$ or $2 \rightarrow 4$ QCD matrix elements but produces multijet events by a probabilistic cascade of partons from the outgoing and incoming partons of the primary $2 \rightarrow 2$ scattering. Interference between the many sources of bremsstrahlung is ignored. Thus the agreement with the unbalanced events gives confidence that the Monte Carlo has the correct gross features of bremsstrahlung and consequently gives a reliable prediction for the shape of the imbalance distribution for DBS 4-jet events in Figs. 3 and 4.

The balanced events have slightly larger interjet angles and a flatter spectrum of the smallest jet E_T than is predicted for balanced DBS. This is to be expected, since DPS events do not exhibit the collinear or infrared divergences. These deviations corroborate the need for a different 4-jet production mechanism, namely DPS. Indeed the DPS model describes the balanced 4-jet events better.

For a quantitative study of the background to 4-jet events, we restrict the Monte Carlo sample to events with at most three partons in the central region with $p_T \geq 3$ GeV. We know that such a sample reproduces all the basic features of 2- and 3-jet events, in particular the level and fluctuation of the E_T flow outside the jet regions [5]. When 4-jet events are reconstructed from this sample, we get the yield indicated by the dotted curves in Fig. 7. We see that this background becomes important as E_T^4 decreases, and 4 GeV is a reasonable lower limit.

This estimate of the background is done within our jet model. We believe that 2- and 3-jet events are the dominant background, since in the observed 4-jet events the largest jet contains typically 9 GeV, the events contain many high- p_T particles (see Figs. 5 and 6c), and the structure of the events agrees with our jet model. However, one might ask whether there could be other sources of high- ΣE_T events of a genuinely non-jet nature which simulate 4-jet events. We have not attempted to rule out this possibility, mainly because we have no realistic model of non-jet high- ΣE_T events. However, if our 4-jet events were mainly due to non-jet processes, we would be faced with the puzzle of why the imbalance distributions in Figs. 3 and 4 display an excess of balanced 4-jet events.

The DPS events are expected to have independent azimuthal orientation of the two 2-jet axes in the event. We study this aspect in Fig. 8 for balanced 4-jet events; the inset illustrates how we define the azimuthal difference $\Delta\phi$ between the two axes. The jets are paired to minimize the imbalance given in Eq. (4), and the axis for a jet pair is defined as the direction of the vector difference of the jet

momenta. We observe that only events at large $\Delta\phi$ are accepted by our jet reconstruction procedure. This is understood from the poor acceptance for $\omega \leq 65^\circ$.

The DPS events with approximately overlapping jets are entering the sample of 2-jet events studied in Ref. [4]. We estimate that DPS events with p_T of each jet ≥ 4.5 GeV constitute at most 1.5% of the 2-jet sample, so the presence of DPS events hardly affects the properties or abundance of observed 2-jet events.

The number of hits in the forward/backward counters in 2-, 3-, and 4-jet events with total jet $E_T \geq 25$ GeV has also been studied. We find that the average number of hits is the same within 5% for these event classes, i.e. there are no large differences in the multiplicity of the spectator fragmentation in the region $2.4 \leq |\eta| \leq 4.0$ covered by these counters. In particular, the balanced (DPS) 4-jet events do not deviate from the unbalanced 4-jet events or the 3-jet events due to bremsstrahlung.

7. THE DPS/2-JET YIELD RATIO

We have chosen to give the DPS yield relative to the 2-jet yield at the same total jet E_T , since this yield ratio is insensitive to uncertainties in the absolute energy scale of the calorimeter.

In the jet E_T interval 28–30 GeV we observe 770 2-jet events and 85 4-jet events. We find that $(60 \pm 15)\%$ of the 4-jet events are due to DPS, so the (uncorrected) DPS/2-jet yield ratio is $51/770 = 6.6\%$.

We now adjust the abundance of DPS events in the Monte Carlo model such that the DPS/2-jet yield ratio of the simulated events is 6.6%. Within the model we find that events observed with 4-jet $E_T = 29$ GeV correspond to events with $\langle E_T \rangle = 31$ GeV on the parton level.

Using the adjusted model, we can give the DPS/2-jet yield ratio in a well-defined kinematical region with no restrictions on the interjet angles and corrected for fragmentation and acceptance effects. At total 2-jet or 4-jet $E_T = 31$ GeV, for events with jet axes inside $|\eta| \leq 0.7$, and with a minimum E_T of a 2-jet subsystem in 4-jet systems of $1/3 E_T (= 10.3$ GeV), we find the DPS/2-jet yield ratio to be

$$\text{'DPS/2-jet'} = 6\% \pm 1.5\% (\text{stat.}) \pm 2.2\% (\text{syst.}) . \quad (7)$$

The systematic error includes the uncertainties in the parameters of the fragmentation model, i.e. the level of the beam-jet multiplicity associated with 4-jet events. The error does not include any dependence on the fragmentation scheme (independent versus string fragmentation) used in the jet acceptance calculation; we have used independent fragmentation.

Our result can also be stated as: In an ‘ideal parton detector’ which detects the E_T of all hard partons with $|\eta| \leq 0.7$ with no fragmentation or resolution effects, no contribution from the beam-jets and no restrictions on the interparton angles, the DPS events, where at least $1/3$ of the total E_T is in each two-parton system, constitute $6\% \pm 1.5\% \pm 2.2\%$ of the two-parton events at the same ΣE_T .

8. ESTIMATE OF THE PROTON SCALE

In this section we describe a simple DPS model and compare the expected yields with the data. Within this framework a parameter can be determined, which is related to the mean transverse separation of a pair of partons.

Consider the 2-parton cross-section (the 2-jet spectrum) calculated from the lowest-order (LO) QCD matrix elements and the Duke–Owens structure functions [15] using $\Lambda = 200$ MeV, $Q^2 = 1/3(\Sigma E_T)^2$, and $\alpha_s = 12\pi/(25 \log Q^2/\Lambda^2)$. We write the cross-section for the production of 2-parton events at a certain total E_T and $\sqrt{s}$ as

$$\text{'2-jets'} = K \frac{d\sigma^{\text{LO}}(E_T, \sqrt{s})}{dE_T d\eta_1 d\eta_2}, \quad (8)$$

where K accounts for the higher-order QCD corrections. The cross-section for DPS events at a certain total parton E_T is constructed by folding the 2-parton spectrum once with itself and dividing by a parameter κ , which has the dimension of an area:

$$\frac{d\sigma(E_T, \sqrt{s})}{dE_T d\eta_1 d\eta_2 d\eta_3 d\eta_4} \Big|_{\eta_i=0} = \frac{1}{2} \frac{K^2}{\kappa} \int_{E_{T0}}^{E_T - E_{T0}} \frac{d\sigma^{\text{LO}}(E'_T, \sqrt{s})}{dE'_T d\eta_1 d\eta_2} \frac{d\sigma^{\text{LO}}(E_T - E'_T, \sqrt{s} - E/2)}{d(E_T - E'_T) d\eta_3 d\eta_4} dE'_T. \quad (9)$$

Here E_{T0} is the lower cut-off for the E_T of a 2-parton subsystem. The factor of $1/2$ reflects that we view the proton as a classical bunch of partons, so the number of interactions is described by Poissonian statistics [12]. Energy conservation is taken into account in Eq. (9) in the following way: One interaction occurs at the full collision energy $\sqrt{s}$, whilst the other occurs at $\sqrt{s} - E/2$, i.e. the collision energy reduced by the average energy of the 2-jet systems.

In the spirit of the Kuti–Weisskopf model [18] we assume no correlations between the partons in κ , apart from the overall constraint from energy conservation. The correlation between the transverse positions of the partons is accounted for only through the scale κ . Formula (9), valid at zero rapidity of the jets, was generalized to finite rapidities and used in ISAJET with the usual fragmentation of the partons into hadrons.

There are large theoretical uncertainties associated with this model. Our particular procedure for treating energy conservation is just one of several reasonable choices. If energy conservation is neglected altogether, i.e. if $\sqrt{s} - E/2$ is replaced by $\sqrt{s}$ in Eq. (9), the DPS yield is increased by a factor of approximately 4 for (corrected) 4-jet $E_T = 31$ GeV. The K factor is taken to be energy-independent and equal to 2, consistent with our measurements of the 2-jet spectrum [4]. Since the DPS yield is proportional to K^2/κ , and the 2-jet yield to K , the observed DPS/2-jet yield ratio is proportional to K/κ .

The parameter κ in Eq. (9) is now determined by comparing the DPS/2-jet yield ratio of the data with the model. We find

$$\kappa = 5 \text{ mb}. \quad (10)$$

In order to relate the parameter κ to the size of the proton, and to compare our determination with the values expected from other data on the proton, we consider a simplified model of the proton, where the partons are uniformly distributed inside a spherical volume of radius r . As an ansatz, the radius is determined by taking the non-single-diffractive cross-section $\sigma_{\text{NSD}} = 30$ mb at $\sqrt{s} = 63$ GeV to be the geometrical cross-section of the colliding spheres: $\sigma_{\text{NSD}} = \pi(2r)^2$, i.e. $r_{\text{NSD}} = 0.49$ fm.

The probability of producing a 2-jet system in a NSD collision is obtained by dividing the 2-jet cross-section by σ_{NSD} . The probability of producing two 2-jet systems is then the product of the corresponding probabilities [the factor $1/2$ from Poissonian statistics is written explicitly in Eq. (9)]; however, we must correct for the fact that hard parton interactions occur more often in central collisions than in NSD collisions in general. Given that there is a hard collision, the average impact parameter is smaller than in NSD events, and the average overlap is therefore larger, leading to an enhanced probability for the second hard scattering. We compute this enhancement to be a factor of 2.32, and hence our ansatz for the scale κ is $\kappa(\text{ansatz}) = \sigma_{\text{NSD}}/2.32 = 13$ mb. Conversely, having determined κ , the radius of the proton is given by the relation

$$2.32 \kappa = \pi(2r)^2 , \quad (11)$$

giving

$$r = 0.3 \text{ fm} . \quad (12)$$

The observed value of κ is approximately three times smaller than expected from our simple proton model. A possible interpretation is that the partons participating in the hard processes are confined to a smaller region inside the proton. One can speculate that the harder partons ($x \geq 0.2$) form a small proton core, which is surrounded by a cloud of sea partons or pions accounting for the proton size suggested by the NSD cross-section. This is equivalent to introducing correlations between the partons.

If instead the matter distribution is taken to be a three-dimensional Gaussian of the form $dn \propto \exp[-R^2/(2D^2)] d^3R$, we derive the following relation between κ and D :

$$\kappa = 8\pi \cdot D^2 , \quad (13)$$

giving

$$D = 0.14 \text{ fm} . \quad (14)$$

Partons with such Gaussian wave function will have a certain transverse momentum [19] ('intrinsic k_T '), and Drell-Yan pairs produced by annihilation of such partons are expected to have an average transverse momentum

$$\langle q_T \rangle = \sqrt{(\pi/4) \langle q_T^2 \rangle} = \sqrt{\pi/(2D)} = 1.2 \text{ GeV (expected)} . \quad (15)$$

The observed $\langle q_T \rangle$ in pp collisions at pair mass = $0.22 \sqrt{s}$ (corresponding to the x-region studied by us) depends strongly on $\sqrt{s}$, indicating contributions from multiple soft gluon bremsstrahlung [20]:

$$\begin{aligned} \langle q_T \rangle &= (0.85 \pm 0.1) \text{ GeV} \quad (\sqrt{s} = 19 \text{ GeV}) , \\ \langle q_T \rangle &= (2.2 \pm 0.3) \text{ GeV} \quad (\sqrt{s} = 62 \text{ GeV}) . \end{aligned} \quad (16)$$

We conclude that the observed $\langle q_T \rangle$ at $\sqrt{s} = 62 \text{ GeV}$ is consistent with $D = 0.14 \text{ fm}$.

Similarly, observations of higher-twist processes involving the pion valence quarks lead to a surprisingly 'small' pion scale [21].

9. DISCUSSION OF ΣE_T TRIGGERED EVENTS

In Fig. 9 we summarize the predictions of our simple DPS model given by Eq. (9). To get agreement with our measurement, we take $\kappa = 5 \text{ mb}$, and for simplicity we assume that this value of the scale is valid at all x . We give the yield of 4-jet events from DPS relative to the yield of 2-jet events at the same total E_T . The yields are expressed per unit of pseudorapidity for jets in the transverse configuration. The low- E_T cut for the E_T of a 2-jet subsystem is taken as a fixed fraction of ΣE_T ($p_T^{\text{jet}} \geq 1/6 \Sigma E_T$). The interjet angles are required to be greater than 60° , and since all jets are at zero rapidity, this cut is equivalent to a separation in azimuth of at least 60° ; the DPS yield is reduced to $1/3$ by this cut.

By choosing ‘dimensionless cuts’ on the 4-jet kinematics, the expected DBS yield becomes very simple. The variation of the DBS yield is only due to the variation of α_s with ΣE_T and to the different $(2 \rightarrow 4)/(2 \rightarrow 2)$ yield ratios for gg and qq scattering, for example. The DBS subprocesses have been calculated to lowest order in α_s [22]. For the particular cuts in Fig. 9, the DBS/2-jet yield ratio is expected to be [23]

$$\begin{aligned} (uu \rightarrow 4)/(uu \rightarrow 2) &= 0.037 \tilde{\alpha}_s^4/\alpha_s^2, \\ (gg \rightarrow 4)/(gg \rightarrow 2) &= 0.106 \tilde{\alpha}_s^4/\alpha_s^2, \end{aligned} \quad (17)$$

where $\tilde{\alpha}_s$ and α_s are the strong couplings at the scales of 4-jet and 2-jet events, respectively. We choose the scale of the 2- and 4-jet events to be $Q = \frac{1}{2}\langle p_T^{\text{jet}} \rangle$ and use $\alpha_s = 12\pi/(25 \log Q^2/\Lambda^2)$ with $\Lambda = 200$ MeV. The resulting prediction for the DBS yield is shown by the dashed lines in Fig. 9. The lower dashed line is for qq scattering (represented by uu scattering) which is dominant for $\Sigma E_T \gtrsim 30$ GeV at $\sqrt{s} \lesssim 63$ GeV, and the upper dashed line is for gg scattering dominant for $\Sigma E_T \lesssim 50$ GeV at $\sqrt{s} \gtrsim 630$ GeV.

We now see from Fig. 9 that the 4-jet yield is expected to be dominated by DPS, when the total E_T is lower than a certain threshold, which is approximately 35 GeV at $\sqrt{s} = 63$ GeV and approximately 60 GeV at $\sqrt{s} = 630$ GeV. For $\sqrt{s} \leq 40$ GeV we expect the DPS process to dominate over DBS at all ΣE_T .

These thresholds lie consistently below or near the thresholds for the onset of 2-jet dominance. A practical consequence of this is that in order to demonstrate the presence of DPS above the ‘background’ of DBS, it is necessary to study 4-jet events at values of ΣE_T below or near the transition to 2-jet dominance.

For $\sqrt{s} = 63$ GeV, the DPS yield is expected to drop rapidly with ΣE_T , consistent with our data (see Fig. 4). For $\sqrt{s} = 630$ GeV we see that as ΣE_T decreases from 90 GeV to 40 GeV the DPS yield is predicted to increase by one order of magnitude relative to DBS.

The prediction for the DPS yield at higher values of $\sqrt{s}$ relies on the assumption that the proton scale x determined at $x = 0.2$ – 0.3 also applies at, for example, $x = 0.03$, which is relevant for the observation of DPS events at $\Sigma E_T = 40$ GeV and $\sqrt{s} = 630$ GeV. If the proton scale is larger for these partons, the expected DPS yield is correspondingly smaller.

Let us finally consider the question whether the hard multiple parton interactions are at the origin of the non-2-jet high- ΣE_T events in general. The non-2-jet component mentioned in the introduction has a characteristic $\sqrt{s}$ and ΣE_T dependence which is qualitatively reproduced by the DPS process: the DPS yield falls off faster with ΣE_T than the 2-jet yield at ISR energies and above, as observed for the non-2-jet component, and at $\sqrt{s} = 24$ GeV the DPS yield is not decreasing with ΣE_T , corresponding to no transition to 2-jet dominance.

The DPS cross-sections measured by us are rather small—6% of the 2-jet cross-section at $\Sigma E_T = 31$ GeV with a cut-off at $p_T^{\text{jet}} = (1/6)\Sigma E_T = 5.2$ GeV. However, from Fig. 9 we see that this ratio is expected to increase by a factor of 3.6 when ΣE_T is decreased from 31 to 22 GeV. Thus it is expected to be 22% at $\Sigma E_T = 22$ GeV with a cut-off at $p_T^{\text{jet}} = (1/6)\Sigma E_T = 3.7$ GeV. If the p_T cut-off is lowered to, for example, 2 GeV, the yield is further increased, and triple, quadruple, etc. interactions start to be important. In fact, an arbitrary large multiple/single scattering yield ratio can be obtained by a sufficiently low cut-off.

Sjöstrand [12] has studied whether the medium- and high-multiplicity minimum-bias events can be described with a multiparton scattering model implemented within the framework of string fragmentation. Using a K/x ratio one order to magnitude smaller than measured by us, and a cut-off at parton $p_T = 1.6$ GeV, the model describes well the general features of multiplicity distributions

and correlations in minimum-bias $p\bar{p}$ events at $\sqrt{s} = 546$ GeV. The very low cut-off of 1.6 GeV is the most controversial point of such a model. It is not known whether perturbative QCD makes sense at such low momentum transfers. However, if the model uses the surprisingly high value of K/κ measured by us, the cut-off can be somewhat increased and the model appears more reasonable.

Much work is needed to establish the relevance of multiple hard parton scattering as a basis for the non-2-jet component of low- and medium- ΣE_T events. Details of the impact parameter correlations and the double parton structure functions have to be studied. A search for the DPS (and double Drell-Yan) process at fixed-target and collider experiments would be of great interest.

10. CONCLUSIONS

We have analysed a sample of 4-jet events and found an excess of pair-wise balanced 4-jet events, which we interpret as being due to double-parton scattering (DPS). Compared with a model of gluon bremsstrahlung, the balanced events have a harder spectrum of the smallest jet E_T and larger interjet angles. The relative abundance of DPS is consistent with a decrease with ΣE_T . We find the same average charged-particle multiplicity in the forward region ($2.4 \leq |\eta| \leq 4.0$) in DPS as in single-scattering events.

The DPS/2-jet yield ratio at the same total jet $E_T = 31$ GeV and in a specified kinematical region (see Section 7) is found to be $6\% \pm 1.5\%$ (stat.) $\pm 2.2\%$ (syst.), where the systematic error does not include fragmentation scheme dependence. This measurement is based on jet acceptance calculations using an independent fragmentation scheme.

We have compared this yield with a specific model of DPS, and determined a crucial parameter in the model, the effective area $\kappa = 5$ mb at $x = 0.2-0.3$. However, this result depends on the details of the model; for example, it assumes the partons to be uncorrelated in x .

Finally, we point out that the multiple parton scattering processes, when extended to lower p_T of the partons, are expected to lead to large cross-sections, and this mechanism is a candidate for understanding the non-2-jet component observed in medium- ΣE_T events. Further searches for DPS at collider and fixed-target energies would be very interesting, as well as theoretical studies of the multiparton structure of the proton.

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Figure captions

- Fig. 1 : The response of the AFS calorimeter to charged pions.
- Fig. 2 : Transverse energy spectra for the data sample used in the analysis. The energies are uncorrected (see Fig. 1). The sample is selected by requiring $\Sigma E_T \geq 29$ GeV. The spectrum of the 2-jet, 3-jet, and 4-jet E_T is given for this sample. A minimum jet E_T of 4 GeV and a minimum interjet angle (ω) of 55° are required. The 4-jet sample used in the analysis is selected by 4-jet $E_T \geq 25$ GeV.
- Fig. 3 : The distribution of the imbalance variable $\mathcal{J}$ for our (uncorrected) data and the predictions of the two model calculations including full detector simulation etc. Figures (a)–(d) correspond to various cuts on the E_T of jet 4 (E_T^4) and interjet angle (ω) as indicated. The data are fitted to a sum of the two components. The results of the fit are the fractions of DPS indicated, and the model curves are normalized accordingly.
- Fig. 4 : The distribution of the ‘boosted imbalance’ $\mathcal{J}_b$ (see text) in three different intervals of the 4-jet E_T ; $E_T^4 \geq 4$ GeV and $\omega \geq 55^\circ$ are required.
- Fig. 5 : Two examples of 4-jet events. The imbalance $\mathcal{J}$ (see text and Fig. 3) and the smallest interjet angle ω are given. The insets give the momenta of the jets in the transverse plane. Events (a) and (b) are likely to be due to DBS and DPS, respectively. Notice that only a little E_T (typically 3–4 GeV) falls outside the indicated jet windows, although these cover only 1/3 of the total acceptance region.
- Fig. 6 : a) The transverse energy flow $dE_T/d\beta$ as a function of the angle β from the jet axes for the two smallest E_T jets in balanced 4-jet events. The minimum interjet angle is required to be large ($\omega \geq 65^\circ$), since the jet profile is better revealed for well-separated jets. b) The distribution of the E_T outside the jet windows in balanced 4-jet events. c) The distribution of the scaled longitudinal momenta $z = p_L/E_{\text{jet}}$ for the charged particles within 50° from the jet axis in the two smallest jets in balanced 4-jet events with $\omega \geq 65^\circ$. The data are compared with related measurements for jets from 14 GeV e^+e^- annihilations [17].
- Fig. 7 : Distribution of: (a) and (b) the smallest interjet angle ω , (c) and (d) the E_T of jet 4 for balanced and unbalanced events. The MC calculations are normalized to the same number of events as the data. The dashed curve represents a Monte Carlo estimate of the contamination of events which do not contain at least four partons with $p_T \geq 3$ GeV; the normalization of this curve is inferred from the 2-jet and 3-jet abundances in the data.
- Fig. 8 : Distribution of the azimuthal difference between the axes of the two 2-jet systems for balanced 4-jet events.
- Fig. 9 : The 4-jet cross-section relative to the 2-jet cross-section. The DPS cross-section (solid lines) for pp or $p\bar{p}$ collisions at various values of $\sqrt{s}$ (in GeV) are expressed for jets produced at 90° to the beam according to Eq. (9). Each parton in the DPS events is required to have at least 1/6 of the total jet E_T , i.e. we set $E_{T0} = E_T/3$ in Eq. (9). The scale κ in Eq. (9) is set to 5 mb to agree with our measurement. The expected DBS cross-section with the same cuts is shown as dashed lines [22, 23].

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9