MEASUREMENT OF JET PRODUCTION PROPERTIES
AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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(Submitted to Physics Letters)

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CM-P00071018

ABSTRACT

Jet production properties at $\sqrt{s} = 540$ GeV have been measured in the UA2 detector at the CERN $\bar{p}p$ Collider. Results on the total transverse momentum of the jet system, on the parton density in the nucleon (structure function) and on the two-jet angular distribution are reported. The data are compared with QCD predictions and extrapolations from lower energy experiments.

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1. INTRODUCTION

Experiments at the Cern $\bar{p}p$ Collider ($\sqrt{s} = 540$ GeV) have reported evidence [1-4] for two-jet dominance in the collisions producing a large transverse energy. Most of the final state transverse energy of these events is carried by two jets of collimated hadrons at opposite azimuth. The jet pairs are interpreted as being the fragments of a pair of partons produced in the scattering process of two elementary constituents of the initial p and $\bar{p}$.

In the present Letter the production properties of the jet pairs are studied, irrespective of the fragmentation process. This latter subject is examined in the following Letter [5].

The jet pair, interpreted as the final state parton pair, is considered in its centre of mass system, where the dependence of the cross-section on the scattering angle is measured and compared with QCD predictions for the elementary parton-parton subprocesses. The measurement of the momentum of the two-jet system in the $\bar{p}p$ frame provides information on the dynamics of the initial partons. Its transverse component is due to large angle gluon radiation by the initial state partons, whereas the longitudinal component is directly related to the structure function of the nucleon. This latter is measured and compared with the one observed in neutrino deep inelastic scattering at lower energy.

The data discussed in this Letter have been collected during the 1983 run at the CERN $\bar{p}p$ Collider. The event sample is more than one order of magnitude larger than the previously available one, because more integrated luminosity has been acquired and because the azimuthal coverage of the UA2 calorimeter has been completed. The inclusive single- and two-jet production cross-sections from these data have previously been reported [3].

2. APPARATUS

The UA2 detector has been described in detail elsewhere [6-7]. It consists of a set of coaxial cylindrical proportional and drift chambers (the vertex detector), a magnetic spectrometer in the forward regions and an array of 480 calorimeter cells which are built as a tower structure pointing to the interaction region.

The results discussed here have been obtained primarily with the central calorimeter [7], a highly segmented detector covering the full azimuth ϕ and the interval $|\eta| \leq 1$ in pseudo-rapidity. Each of the 240 cells of the central calorimeter subtends a longitudinal phase-space domain $\Delta\phi \times \Delta\eta \approx 15^\circ \times 0.2$ and is segmented into three longitudinal compartments, a 17 radiation lengths thick electromagnetic section followed by two hadronic ones of 2 absorption lengths each, for a total of 4.5 absorption lengths. The energy resolution is measured from test beam data to be $\sigma_E/E = 0.14/\sqrt{E}$ (E in GeV) for electron initiated showers. It varies from 32% at 1 GeV to 11% at 70 GeV for hadron initiated showers, approximately proportional to $E^{-1/4}$. The uncertainty on the energy scale is less than $\pm 1.5\%$ for the electromagnetic calorimeter and less than $\pm 3.5\%$ for the hadronic one.

3. TRIGGER AND DATA REDUCTION

The trigger used to collect the present data selected $\bar{p}p$ collisions for which the total transverse energy (ΣE_T) in the central calorimeter exceeded a given threshold, typically set at 40 GeV. Background from sources other than $\bar{p}p$ collisions was reduced at the trigger level by requiring a coincidence with two signals obtained from small angle scintillator hodoscopes [8].

In order to reduce the background contamination ($\leq 10\%$ at this level) the subsequent analysis rejected the event if one of the following conditions was satisfied :

- i) the event was associated with an early signal in the small angle scintillator hodoscopes ;
- ii) an abnormally large fraction of the total transverse energy was present in the hadronic compartments (more than 60% in the second one or more than 95% in both together) ;
- iii) the primary $\bar{p}p$ interaction, as reconstructed from the charged tracks measured in the vertex detector, was outside a region of ± 30 cm along the beam direction with respect to the nominal interaction point.

These requirements reduced the background contamination in the data sample to less than 5% independent of ΣE_T . The loss of good events introduced by the trigger and the analysis cuts has been verified to be less than 5%.

The standard UA2 cluster algorithm, described in detail in refs. [2-3], was used. It consists in joining of cells of the central calorimeter around local energy maxima. A vector momentum is associated to each cluster, with a direction defined by the interaction point and the cluster centroid and with a magnitude given by the cluster energy. This definition is such that the individual clusters are taken to be massless[†]. Finally, the clusters are ranked in order of decreasing transverse energy $E_T^1 > E_T^2 > E_T^3 \dots$

In the following analysis only events with two well-measured jets are retained. The events are required to satisfy the following conditions :

- i) the invariant mass of all the clusters in the central calorimeter with an energy in excess of 3 GeV has to be larger than 45 GeV ;

[†] The effects of this assumption are discussed in ref. [3].

- ii) the two clusters with largest transverse energy in the event must satisfy the conditions $E_T^1 > 10 \text{ GeV}$, $E_T^2 > 10 \text{ GeV}$, $E_T^1 + E_T^2 > 40 \text{ GeV}$. Their momenta must not point to an edge cell and their azimuthal separation, $\Delta\phi^{jj}$, must be larger than 120° .

These criteria yielded a sample of $\sim 3 \times 10^4$ events. The corresponding integrated luminosity is $\int \mathcal{L} dt = 112 \text{ nb}^{-1}$ [8], with a systematic error of $\pm 20\%$.

4. TRANSVERSE MOMENTUM OF THE MULTI-JET SYSTEM

The initial state gluon bremsstrahlung and, to a lesser extent, the intrinsic transverse momentum of the partons in the nucleon are expected to contribute to the transverse momentum p_T^{jj} of the two-jet system.

The final state gluon radiation is taken partially into account by adding vectorially to the first (second) cluster the third one, if it has an energy in excess of 3 GeV and a space angle ω with respect to the first (second) cluster such that $\cos\omega > 0.2$. The addition of further clusters satisfying the same conditions does not affect the experimental distributions within the statistical uncertainties.

Experimentally, p_T^{jj} is the vector sum of two large and opposite momenta and is therefore sensitive to instrumental effects. The two components p_η^{jj} (along the bisector of the two jets in the transverse plane) and p_ξ^{jj} (orthogonal to it and roughly parallel to the two-jet axis) are studied separately, because they are associated with different resolution and systematic effects.

Figs. 1a and 1b show the normalized distributions of $|p_\xi^{jj}|$ and $|p_\eta^{jj}|$ for the two-jet system. The distributions confirm, using a much larger data sample, the results obtained from the 1982 data [2]. The systematic errors, due to the uncertainty on the energy scale and to

the analysis procedure, are estimated to be less than $\pm 10\%$. The r.m.s. of the two distributions are respectively 9.1 GeV for p_{ξ}^{jj} and 7.5 GeV for p_{η}^{jj} , with a negligible statistical error. Note however that the analysis criteria reject events with a very high value of p_T^{jj} and that instrumental effects contribute substantially to the measured widths of the p_{ξ}^{jj} and p_{η}^{jj} distributions, which in a perfect detector are expected to be approximately equal. Therefore the larger width of the p_{ξ}^{jj} distribution results mostly from its greater sensitivity to the energy resolution, p_{ξ}^{jj} being the difference between two large transverse momenta and p_{η}^{jj} the sum of two small components. The resolution on the jet energy measurement can be estimated from a comparison of the two distributions. In the case of a 40 GeV jet the resolution is measured to be 5.5 ± 1.0 GeV, in good agreement with the results of a Monte Carlo simulation of the detector having as input test beam measurements [7].

The dashed lines in Fig. 1 show the result of a QCD calculation [9], which assumes a uniform azimuthal distribution of p_T^{jj} in the ξ - η plane. The average value of p_T^{jj} is predicted to be ~ 9 GeV. The uncertainty of the calculation results mostly from the error on the gluon structure function (gluons radiate more than quarks on the average) and is of the order of $\pm 20\%$. To compare the prediction with the data, a complete Monte Carlo simulation, including all the detector details, was performed. Two-jet events were generated with the above p_T^{jj} distribution. A fragmentation function close to the one observed in the data [2,5] was used. The Monte Carlo event sample was submitted to the same trigger and analysis criteria as the real data. The corresponding distributions, shown as histograms in Fig. 1, are in good agreement with the experimental points. The prediction is sensitive to the assumed colour charges of gluon and quark. As an example, the dashed-dotted line of Fig. 1b shows the distribution [9] expected in the case that gluons radiate like quarks.

The calculation of ref. [9] assumes a fixed parton-parton invariant mass of 60 GeV. The variation of p_T^{jj} as a function of the mass of the jet system, m_{jj} , is predicted to be small. This is a consequence of two opposing effects. The broadening of the p_T^{jj} distribution for a given

parton type with increasing m_{jj} is compensated by a decrease of the fraction of gluons with a corresponding increase of quarks. The average value of p_{η}^{jj} is measured to increase by $20\% \pm 3\%$ (stat.) $\pm 8\%$ (syst.) when m_{jj} varies from 60 to 100 GeV.

5. DYNAMICAL DESCRIPTION OF THE HARD SCATTERING PROCESS

The factorization property of the parton-parton cross-sections for any definite initial state parton pair can be generalized [10] in terms of an overall structure function $F(x)$ (sum of all the quark and gluon densities) and an effective parton-parton cross-section $d\sigma/d\cos\theta^*$, obtained from a weighted average over all the elementary subprocesses [11] :

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{S(x_1, x_2)}{x_1 x_2} \frac{d\sigma}{d\cos\theta^*} = \frac{F(x_1)}{x_1} \frac{F(x_2)}{x_2} \frac{d\sigma}{d\cos\theta^*} \quad (1)$$

where x_1 (x_2) represents the fraction of the longitudinal momentum carried by the interacting parton in the proton (antiproton). This analysis has been done with $\alpha_s = 12\pi/23 \ln(Q^2/\Lambda^2)$, where $Q^2 = (p_T)^2$ and $\Lambda = 0.2$ GeV. The results are rather insensitive to these definitions. As an example, a change of a factor 2 in Λ corresponds to a variation of less than 10% in $F(x)$. Equation (1) is valid to the extent that different subprocesses have a similar θ^* behaviour and that the Q^2 dependence in both the structure functions and in $\alpha_s(Q^2)$ is small. Equation (1) does not include higher order QCD corrections, which are usually described by a multiplicative factor $K \lesssim 2$ [12] and give rise to a nonzero transverse momentum for the two-jet system. In the following analysis these higher order effects will be neglected ($K = 1$). The approximation of a small transverse momentum for the two-jet system, $p_T^{jj} \ll m_{jj}$, which is necessary to define θ^* without kinematical ambiguities [13], has been shown to be reasonable in the previous section. This requirement is ensured by retaining events of the data sample defined in sect. 3 only if they have $p_T^{jj} < 20$ GeV and $\Delta\phi^{jj} > 140^\circ$.

From the experimental point of view, the jet 4-vectors p_1 and p_2 are computed from the cluster with the highest transverse energies, according to the following procedure :

- i) the energy of the two highest clusters is corrected to take into account the different calorimeter response for hadrons impinging near the cell boundaries and the loss of energy due to the calorimeter non-linearity and the cluster algorithm [7]. The correction varies from 18% to 1% for jet energies between 20 and 80 GeV, while the dependence on position is less than 10% ;
- ii) the momentum of any other cluster having $E_T > 3$ GeV and separated by an angle ω from the first (second) cluster such that $\cos\omega > 0.2$ is vectorially added to the first (second) cluster momentum. As in the previous section, this correction is meant to take into account the effects of final state gluon bremsstrahlung.

The values of x_1 , x_2 and $\cos\theta^*$ are computed for each event following the convention of ref. [13]. The distributions $S(x_1, x_2)$ and $d\sigma/d\cos\theta^*$ are derived separately, according to the factorization hypothesis (1), as described in detail in the next sections.

6. ANGULAR DISTRIBUTION

The $d\sigma/d\cos\theta^*$ distribution is computed by considering the event distribution in the $\cos\theta^* - \beta^{jj}$ plane, where β^{jj} is the velocity of the two-jet system in the laboratory. The calorimeter acceptance is uniform in a well defined domain in this plane, that depends, for each event, on the two-jet mass and on the interaction position along the beam line. A fiducial domain in the region $\cos\theta^* < 0.6$ can be defined where the acceptance is complete. Different slices of β^{jj} are considered for different regions of $\cos\theta^*$. The overall angular distribution is evaluated by normalizing the different $\cos\theta^*$ distributions to the same area in the

interval where they overlap. The overall normalization is not defined by this method and is chosen by arbitrarily setting the data point at $\cos\theta^* = 0$ equal to 1. Fig. 2 and table 1a show the results. The systematic uncertainties which depend on the relative normalization of different regions in the $\cos\theta^* - \beta_{ij}$ plane are included in the errors. The systematic uncertainties due to the $\cos\theta^*$ resolution (≤ 0.04) and to the definitions of the kinematical variables adopted in this analysis are estimated to be $< 5\%$. In the region of overlap, the data agree well with the results of the UA1 Collaboration [14], within the statistical and systematic errors.

The observed angular distribution can be compared with the predictions of different theories. A Rutherford-like scattering process (t-channel exchange of a vector boson) gives rise to a distribution that is proportional to $[\sin(\theta^*/2)]^{-n}$, with $n = 4$, whereas scalar gluon theories give rise to distributions with $n \leq 2$. The data do not agree over the full $\cos\theta^*$ range with any such simple parametrization. However, the region of $\cos\theta^* \geq 0.3$ can be fitted with $n = 3.94 \pm 0.18$. This clearly shows the dominance of processes with a t-channel exchange of a vector boson in the forward region and rules out any scalar gluon theory (see ref. [15] for other experimental results on the gluon spin). The data are well reproduced by a sum of different processes like that predicted by QCD [11]. Much simpler models also agree with the data (for example, the angular distribution due only to s- and t-channel exchanges of a vector boson by spin 1/2 fermions agrees with the experimental points).

The observed distribution is compared in Fig. 2 with the QCD prediction for the dominant parton-parton subprocesses [11] which lie in the area between the two dashed lines. The statistical and systematic errors are such that the relative importance of the different subprocesses cannot be measured. An overall QCD prediction, obtained from a sum of all the subprocesses, each weighted by a factor depending on the structure functions (derived from ref. [16]), gives good agreement. This curve is shown as a full line normalized to the data.

7. STRUCTURE FUNCTION

The function $S(x_1, x_2)$, defined in eq. (1) is computed by weighting each event with an acceptance factor w which accounts for the probability to observe the event :

$$w^{-1} = \int_0^{C_{\max}} (d\sigma/d\cos\theta^*)_{\text{QCD}} d\cos\theta^* \quad (2)$$

where $C_{\max}$ (function of the observed values of x_1 and x_2) is the maximum detectable value of $\cos\theta^*$ in the fiducial region and $(d\sigma/d\cos\theta^*)_{\text{QCD}}$ is the QCD parametrization of the angular distribution. The effective structure function $F(x)$ is evaluated according to eq. (1) for 10 bins of x between 0.05 and 0.60. The effects of the resolution in x and of the variation of the acceptance as a function of the vertex position have been taken into account. One should note that, if the usual definition of the higher order correction factor K were adopted, the result of the measurement would be the product $\sqrt{K} \cdot F(x)$. Fig. 3 and table 1b show the values with their statistical errors. An empirical fit (shown as a full line in Fig. 3) of the form $F(x) = A \exp(-\alpha x)$ gives $A = 6.2 \pm 0.1$ and $\alpha = 8.3 \pm 0.1$. The systematic errors, due to the resolution, to the definition of the kinematics and to the uncertainty on the luminosity, are $\pm 30\%$.

Evidence for the factorization of the cross-section (1) is illustrated in Fig. 4. The independence of the angular distribution of x_1 and x_2 is tested separately from the factorization of $S(x_1, x_2)$ into $F(x_1) \cdot F(x_2)$. Fig. 4a shows the value of the ratio $(d\sigma/d\cos\theta^*)_a / (d\sigma/d\cos\theta^*)_b$ as a function of $\cos\theta^*$. The indices a and b refer to different mass slices, and, therefore, to different values of x_1 and x_2 . A constant value of this ratio corresponds to the independence of $d\sigma/d\cos\theta^*$ of mass and, as a consequence, to the validity of the first part of the factorization hypothesis. Fig. 4b shows the ratio $S(x_1, x_2) / S(x_1, x_2 + \Delta x)$ as a function of x_1 for different intervals of x_2 and a fixed value $\Delta x = 0.05$. The second part of the factorization test is verified if the different x_2 intervals lie on constant lines. If, moreover, the structure function $F(x)$ is well approximated by an exponential, the various lines coincide, because the ratio is independent of x_2 .

As a further test of the experimental method, the single- and two-jet cross-sections have been computed from the measured structure function, the angular distribution and the two-jet transverse momentum distributions. The agreement with the published results [2-3] is good within $\pm 20\%$.

The structure function agrees with the one reported in ref. [14] in the region $x \geq 0.10$, to within the statistical and systematic uncertainties. Since that analysis assumed $K = 2$, those points (shown in Fig. 3) have been multiplied by $\sqrt{2}$.

The parton density of ref. [16], extrapolated to this experiment ($\langle Q^2 \rangle \approx 2000 \text{ GeV}^2$), is shown in Fig. 3 as a dashed line. This structure function has been calculated assuming $F(x) = g(x) + 4/9 q(x)$, where $g(x)$ is the gluon structure function and $q(x)$ is the sum over all the quark and antiquark densities. Part of the overall scale factor (~ 1.4) may be attributed to higher order corrections, not taken into account in the computation of $F(x)$. The two distributions agree well in shape both in the region of small x , where $F(x)$ is dominated by the gluon density, and of high x , where mainly valence quarks are present.

8. CONCLUSIONS

The dynamical mechanism of two-jet production at $\sqrt{s} = 540 \text{ GeV}$ has been studied. It has been observed that the system of high transverse momentum jets carries only a small total transverse momentum, giving support to the parton origin of the jets and showing that only a limited fraction of the initial parton energy is radiated into soft fragments at large angle. The differential cross-section at parton level has been studied as a function of the scattering angle in the two-jet centre of mass. The density of the partons in the nucleon (structure function) has been measured and compared with the one observed in neutrino deep inelastic scattering at lower energy. These observations have been found to be in good agreement with QCD predictions and extrapolations from lower energy domains.

ACKNOWLEDGEMENTS

This experiment would have been impossible without the collective effort of the staffs and coordinators of all accelerators involved in the CERN $\bar{p}p$ Collider, whom we gratefully acknowledge.

We are very thankful to F. Bonaudi and V. Hungerbühler whose contributions to the early phase of this experiment have been invaluable.

We deeply thank the technical staffs of the institutes collaborating in UA2 for their important contributions.

We are grateful to the UA4 Collaboration for providing the signals from their small-angle scintillator arrays.

We have enjoyed many fruitful discussions with colleagues from the theory departments. In particular we thank M. Greco for making QCD calculations available to us prior to publication.

Financial supports from the Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung to the Bern group, from the Danish Natural Science Research Council to the Niels Bohr Institute group, from the Institut National de Physique Nucleaire et de Physique des Particules to the Orsay group, from the Istituto Nazionale di Fisica Nucleare to the Pavia group and from the Institut de Recherche Fondamentale (CEA) to the Saclay group are acknowledged.

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TABLE 1

a) Angular distribution in the
two jet centre of mass.

b) Effective structure function.

$\cos\theta^*$	$\frac{d\sigma/d\cos\theta^*}{d\sigma/d\cos\theta^* _{\theta^*=90^\circ}}$	x	F(x)
.00-.05	1.000 $\pm$.022	.05-.10	4.080 $\pm$.102
.05-.10	.979 .022	.10-.15	2.194 .010
.10-.15	.999 .022	.15-.20	1.372 .015
.15-.20	1.089 .023	.20-.25	.937 .017
.20-.25	1.132 .024	.25-.30	.664 .019
.25-.30	1.177 .024	.30-.35	.450 .024
.30-.35	1.307 .029	.35-.40	.343 .032
.35-.40	1.497 .035	.40-.45	.286 .039
.40-.45	1.721 .046	.45-.50	.137 .035
.45-.50	2.095 .064	.50-.60	.065 .029
.50-.55	2.552 .097		
.55-.60	3.452 .190		

The listed errors are only statistical. The systematic errors are less than 5% for the angular distribution and $\pm 30\%$ for the structure function.

FIGURE CAPTIONS

1. a) Normalized distribution of $|p_{\xi}^{jj}|$, the component of the two-jet transverse momentum along the two-jet axis. The dashed line is a QCD prediction [9], while the histogram represents the prediction after detector smearing.
 b) The same as a), but for $|p_{\eta}^{jj}|$, the component of the two-jet transverse momentum along the bisector of the two jets. The dotted-dashed line is the prediction of ref. [9] assuming the same colour charge for gluons as for quarks.

2. Distribution of the scattering angle in the two-jet centre of mass. The normalization is defined setting the value at $\cos\theta^* = 0$ equal to 1. All the different QCD subprocesses [11] (except the pure s-channel one $q_1\bar{q}_1 \rightarrow q_2\bar{q}_2$), separately normalized to the data, lie in the area between the two dashed curves. The full line is the overall QCD prediction discussed in the text, normalized to the data. Also the region corresponding to scalar gluon theories [15] is shown.

3. Effective structure function. The full points are the results of this experiment and the open points are derived from ref. [14]. The full line represents an exponential fit to the data, while the dashed lines are computed from neutrino deep inelastic scattering [16], taking into account scaling violation effects.

4. a) Ratio between the angular distribution of the sample of events with $m_{jj} > 75$ GeV and the events with $m_{jj} < 75$ GeV.
 b) Ratio $S(x_1, x_2)/S(x_1, x_2 + \Delta x)$ (see eq. (1) in the text) for different x_2 slices and $\Delta x = 0.05$. The horizontal lines correspond to the slope of $F(x)$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b