Physics Letters B 268 (1991) 145–154
North-Holland

PHYSICS LETTERS B

A study of multi-jet events at the CERN $\bar{p}p$ collider and a search for double parton scattering

UA2 Collaboration

Bern–Cambridge–CERN–Dortmund–Heidelberg–Melbourne–Milano–Orsay (LAL)–Pavia–Perugia–Pisa–Saclay (CEN)

J. Alitti [a], G. Ambrosini [b], R. Ansari [c], D. Autiero [d], P. Bareyre [a], I.A. Bertram [e], G. Blaylock [f,1], P. Bonamy [a], K. Borer [g], M. Bourliaud [a], D. Buskulic [c], G. Carboni [d], D. Cavalli [h], V. Cavasinni [d], P. Cenci [i], J.C. Chollet [c], C. Conta [b], G. Costa [h], F. Costantini [d], L. Cozzi [h], A. Cravero [h], M. Curatolo [d], A. Dell'Acqua [b], T. DelPrete [d], R.S. DeWolf [j], L. DiLella [f], Y. Ducros [a], G.F. Egan [e], K.F. Einsweiler [f,2], B. Esposito [d], L. Fayard [c], A. Federspiel [g], R. Ferrari [b], M. Fraternali [b,3], D. Froidevaux [f], G. Fumagalli [b], J.M. Gaillard [c], F. Gianotti [h], O. Gildemeister [f], C. Gössling [k], V.G. Goggi [b], S. Grünendahl [ℓ], K. Hara [g,4], S. Hellman [f], J. Hrivnac [f], H. Hufnagel [k], E. Hugentobler [g], K. Hultqvist [f,5], E. Iacopini [d,6], J. Incandela [h], K. Jakobs [f], P. Jenni [f], E.E. Kluge [ℓ], N. Kurz [ℓ], S. Lami [d], P. Lariccia [i], M. Lefebvre [f], L. Linssen [f], M. Livan [b,7], P. Lubrano [f,i], C. Magneville [a], L. Mandelli [h], L. Mapelli [f], M. Mazzanti [h], K. Meier [f,8], B. Merkel [c], J.P. Meyer [a], M. Moniez [c], R. Moning [g], M. Morganti [d,9], L. Müller [g], D.J. Munday [j], M. Nessi [f], F. Nessi-Tedaldi [f], C. Onions [f], T. Pal [g], M.A. Parker [j], G. Parrour [c], F. Pastore [b], E. Pennacchio [b], J.M. Pentney [f], M. Pepe [f], L. Perini [h,3], C. Petridou [d], P. Petroff [c], H. Plothow-Besch [f], G. Polesello [f,b], A. Poppleton [f], K. Pretzl [g], M. Primavera [d,10], M. Punturo [i], J.P. Repellin [c], A. Rimoldi [b], M. Sacchi [b], P. Scampoli [i], J. Schacher [g], V. Simak [f], S.L. Singh [j], V. Sondermann [k], S. Stapnes [f], C. Talamonti [i], F. Tondini [i], S.N. Tovey [e], E. Tsesmelis [k], G. Unal [c], M. Valdata-Nappi [d,10], V. Vercesi [b], A.R. Weidberg [f,11], P.S. Wells [j,12], T.O. White [j], D.R. Wood [c], S.A. Wotton [j,12], H. Zaccone [a] and A. Zylberstejn [a]

[a] *Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France*
[b] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Via Bassi 6, I-27100 Pavia, Italy*
[c] *Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, F-91405 Orsay, France*
[d] *Dipartimento di Fisica dell'Università di Pisa and INFN, Sezione di Pisa, Via Livornese, S. Piero a Grado, I-56100 Pisa, Italy*
[e] *School of Physics, University of Melbourne, Parkville 3052, Australia*
[f] *CERN, CH-1211 Geneva 23, Switzerland*
[g] *Laboratorium für Hochenergiephysik, Universität Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland*
[h] *Dipartimento di Fisica dell'Università di Milano and INFN, Sezione di Milano, I-20133 Milan, Italy*
[i] *Dipartimento di Fisica dell'Universidà di Perugia and INFN, Sezione di Perugia, via Pascoli, I-06100 Perugia, Italy*
[j] *Canvendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*
[k] *Lehrstuhl für Experimental Physik IV, Universität Dortmund, W-4600 Dortmund, FRG*
[ℓ] *Institut für Hochenergiephysik der Universität Heidelberg, Schröderstraße 90, W-6900 Heidelberg, FRG*

Received 6 July 1991

A study of events containing at least four high transverse momentum jets and a search for double parton scattering (DPS) have been performed using data collected with the UA2 detector at the CERN $\bar{p}p$ Collider ($\sqrt{s}=630$ GeV). The results are in good agreement with leading order QCD calculations. A value of $\sigma_{DPS}<0.82$ nb at 95% confidence level (CL) is obtained for the DPS cross section.

1. Introduction

Since its early operation the CERN $\bar{p}p$ Collider has been an excellent facility for the study of the production properties of high transverse momentum (p_T) jets. Detailed studies have focused on many topics, from the measurement of inclusive jet cross sections and a search for quark substructure, to studies of the dynamics of the production processes and fragmentation properties [1]. In all cases the results have been found to be in good agreement with predictions of perturbative quantum chromo-dynamics (QCD).

In this Letter results are reported on a study of events containing at least four high p_T jets in the final state. The observed production properties are compared to the prediction of leading order QCD calculations. Several authors [2] have suggested an additional mechanism for multi-jet production in hadronic interactions, in which multiple independent hard parton interactions occur within the same $\bar{p}p$ collision. Because of the dominance of the two-jet cross section, these multi-parton interactions should be observed most easily in four-jet final states. Double parton scattering resulting in four-jet final states has been studied and limits on the cross section for this process will be given.

The following section briefly describes the parts of the upgraded UA2 detector of relevance for this analysis, while the event selection is described in section 3. The QCD model used to simulate interactions is described in section 4, and comparison with data is made in section 5. The search for DPS is discussed in section 6.

2. Apparatus and data taking

The UA2 detector was substantially upgraded [3] during the period 1985–1987. Jet identification and energy measurements are now provided over the full azimuthal range $0° < \varphi < 360°$ and the pseudorapidity region $|\eta| < 3$. The calorimeter is divided into a central part (CC) covering pseudorapidities $|\eta| < 1$ and two end caps (EC) covering the region $0.9 < |\eta| < 3.0$. Both CC and EC consist of electromagnetic and hadronic compartments and are subdivided laterally into independent cells. In the EC the two cells closest to the beam axis ($2.5 < |\eta| < 3.0$ and $2.2 < |\eta| < 2.5$) cover 30° in azimuth, while the other cells have constant segmentation $\Delta\varphi = 15°$ and $\Delta\eta = 0.2$. Each cell in the central calorimeter covers $\Delta\varphi = 15°$ and $\Delta\theta = 10°$. The electromagnetic compartments are multilayer lead-scintillator sandwiches with a thickness of 17 radiation lengths (r.l.) in the CC and varying between 17.1 and 24.4 r.l., depending on the polar angle (θ), in the end caps. The hadronic compartments are multilayer sandwiches of iron and scintillator corresponding to about 4.5 (CC) or 7 (EC) absorption lengths, including the electromagnetic part. Cells with only hadronic calorimetry cover the pseudorapidity interval $0.9 < |\eta| < 1.0$ to measure the energy of particles which could otherwise escape detection in the interface between EC and CC modules. Each EC is made up from 12 modules. To minimize dead space in the boundaries between

[1] Present address: University of California, Santa Cruz, CA 95064, USA.
[2] Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA.
[3] Present address: Istituto di Fisica, Università di Palermo, I-90133 Palermo, Italy.
[4] Present address: University of Tsukuba, Tsukuba, Ibaraki 305, Japan.
[5] Present address: University of Stockholm, S-113 46 Stockholm, Sweden.
[6] Also at Scuola Normale Superiore, I-56100 Pisa, Italy.
[7] Present address: Dipartimento di Fisica, Università di Cagliari, I-09100 Cagliari, Italy.
[8] Present address: Deutsches Elektronen Synchrotron, W-2000 Hamburg, FRG.
[9] Present address: Dipartimento di Fisica e INFN di Bologna, Università di Bologna, I-40126 Bologna, Italy.
[10] Present address: Dipartimento di Fisica dell' Università della Calabria e gruppo INFN, Cosenza, Italy.
[11] Present address: Nuclear Physics Laboratory, University of Oxford, Oxford OX1 3RH, UK.
[12] Present address: CERN, CH-1211 Geneva 23, Switzerland.

two neighbouring EC modules, each module has been rotated by 50 mr around its symmetry axis normal to the beam.

The initial absolute calibration of the calorimeter was obtained by exposing every cell to beams of electrons, pions and muons of known momenta. The calibration stability has been monitored by measuring the calorimeter response to radioactive sources (^{60}Co). The accuracy of this relative response monitoring has been measured by periodic recalibrations of a part of the calorimeter using test beams. The uncertainty on the absolute calibration is determined to be $\pm 1\%$ for the electromagnetic energy scale and $\pm 2\%$ for the hadronic energy scale. Since hadronic jets deposit typically one half of their energy in the electromagnetic compartment, the uncertainty on the absolute energy scale is $\pm 1.5\%$.

The calibration procedure ensures a correct energy measurement for particles with momenta equal to those of the calibration beam. Since a jet fragment typically carries a small fraction of the original parton momentum, jet energy measurements are sensitive to deviations from calorimeter linearity at low momenta. Test beam measurements performed with the end cap calorimeter showed deviations from linearity at very low momenta (below 1 GeV). For example, only 70% of the total energy of a charged pion with a momentum of 200 MeV is measured in the calorimeter. The test beam results are well reproduced by simulations of hadronic showers based on ref. [4] and parametrizations of the calorimeter response are included in the detector simulation model.

The analysis presented here is based on data recorded during the 1988 and 1989 Collider runs at $\sqrt{s}=630$ GeV. Events are selected by a multi-level trigger [5] that, at the lowest level, is obtained from a coincidence between a minimum bias signal, ensuring the presence of an inelastic $\bar{p}p$ collision, and requirements on the total transverse energy measured in the calorimeter cells and single- and two-jet triggers [6]. Multi-jet triggers are then formed at the second trigger level, requiring the presence of at least four jets with transverse momentum in excess of 8 GeV.

The luminosity measurement [7] is provided by eight scintillator telescopes at small angles to the beams, four on each side of the detector. The data presented in this letter correspond to an integrated luminosity of $\int \mathscr{L}\, dt = 7.6 \pm 0.4$ pb^{-1}, where the error is dominated by a 4.7% uncertainty in the knowledge of the $\bar{p}p$ total inelastic cross section.

3. The data

Jets are identified through their energy deposition pattern in the calorimeter according to the following algorithm. Adjacent cells with transverse energy in excess of 400 MeV are joined into clusters. Cluster centre and radius in the θ and φ directions are defined from the individual azimuthal and polar angles of the cells belonging to the given cluster with the appropriate energy weighting. Only clusters above 15 GeV in transverse energy and within the range $|\eta| < 2$ are retained. For each event the n jets are sorted in decreasing order of transverse energy and labelled from 1 to n. Exclusive topologies are selected by requiring $E_{T,n+1} < 10$ GeV.

In addition to the previous kinematical cuts some further requirements are necessary to suppress a luminosity dependent background resulting mainly from multiple $\bar{p}p$ collisions within the same bunch crossing. These events are characterized by the presence of jets with large reconstructed radii and, at the same time, large amounts of unclustered energy in the calorimeter. Only events where the jet system carries at least 40% of the total transverse energy measured in the whole calorimeter are retained. For an n-jet event an average cluster radius for the jet system has been defined as $R = \sum_i (r_i/n)$, where $r_i = (r_{\theta i}^2 + r_{\phi i}^2)^{1/2}$, and required to be less than 20°. Finally, to select events well contained in the calorimeter the missing transverse momentum is required to be less than 20 GeV.

The combination of the above cuts retains 9947 four-jet, 281 five-jet and 7 six-jet events. Using the total integrated luminosity, these give uncorrected observed cross sections $\sigma_4 = 1.3$ nb, $\sigma_5 = 0.037$ nb and $\sigma_6 = 0.0009$ nb, respectively. The largest contribution to the error on these cross sections originates from systematic uncertainties that are studied through Monte Carlo simulations and will be discussed later.

4. The QCD multi-jet model

The present study relies on comparisons between measured distributions associated with the multi-jet data and the QCD predictions. It is therefore necessary to describe the QCD model and its implementation in a Monte Carlo simulation.

The QCD multi-jet model is essentially based on the matrix element calculation of ref. [8] (KS) and ref. [9] (BGK). The BGK programme calculates the complete matrix elements for tree level contributions up to order α_s^5 and also provides optionally several approximate calculations. A comparison of these much faster approximate calculations with the experimental data is interesting in order to estimate multi-jet backgrounds at the next generation of hadron colliders. The exact calculation of BGK has been used in comparisons with the four- and five-jet data. Approximate expressions for the matrix elements (ESFAG), where only the purely gluonic diagrams are included in the calculation and an effective structure function [10] [#1] is used to account for diagrams including quarks, have been used for comparison with the five-jet data. The KS programme calculates matrix elements for tree level contributions up to α_s^4. Approximate expressions for the matrix elements, where only the quark–antiquark diagrams are evaluated and the effective structure function approximation is used, have been used for comparison with the four-jet data.

For all the calculations the parton distributions have been chosen to be those of ref. [12] with $\Lambda_{QCD}=200$ MeV, and the QCD scale Q^2 was defined as the square of the maximum transverse energy of the final state partons. The absolute cross sections are sensitive to these choices, through α_s, which enters the calculation of the n-jet cross sections with the nth power. The sensitivity of the absolute QCD cross section to Λ_{QCD} and the choice of Q^2 scale has been studied at parton level only by varying the structure functions among the sets of refs. [12–15] and using different choices of Q (average p_T or di-jet invariant mass of the event). Within these choices the theoretical uncertainty associated with the lack of knowledge on Q^2 and Λ_{QCD} is approximately a factor 2 on σ_4.

Finally, to avoid divergences in the matrix elements, due to the bremsstrahlung nature of gluon radiation, only final state partons well separated in phase-space and above a certain p_T threshold are considered. This has been implemented in the model by retaining only events with parton transverse energies and space separation greater than 12 GeV and 30° respectively. The uncertainties on the absolute cross sections for exclusive n-jet final states due to the choice of these cuts are estimated to be smaller than the theoretical uncertainties quoted in the previous paragraph.

The hadronization of the outgoing partons is accomplished using a model based on the fragmentation function of ref. [16], modified to allow for gluon radiation from the original partons. After being radiated according to a bremsstrahlung energy spectrum, the gluons are fragmented independently. This fragmentation model, when used in conjunction with the UA2 calorimeter pattern recognition, produces additional clusters in 5% of the events for cluster transverse energies greater than 15 GeV. This ensures that the jets in the final state are predominantly associated to the hard-scattering matrix element and do not originate from the soft fragmentation process.

The acceptance of the UA2 calorimeter and the details of the detector response have been included in the calculations using a Monte Carlo simulation. The underlying event, produced by interactions of the spectator partons, has been simulated by superimposing real events, collected with a minimum bias trigger, on the jets generated by the hard collision.

The multi-jet trigger used at the second level in the UA2 trigger scheme is very efficient in collecting multi-jet events. However, the final sample is formed by events originating from several first level jet trigger streams. An algorithm simulating these jet triggers, and reproducing the observed data rates, has been written and implemented within the Monte Carlo simulation of the QCD model. This ensures that possible trigger biases are taken into account and allows a determination of the trigger efficiency for DPS events.

Finally, an independent fast approximation model (NGLUON) [10] has been compared to the four- and five-jet data. This approximate method is based on the observation that for a particular helicity state of the gluons the amplitude for the process $gg\to(n-2)g$ has a simple analytical form. All the remaining helicity amplitudes are then assumed to give the same

[#1] For an experimental measurement of the effective structure function see ref. [11].

contribution and an effective cross section is obtained from the analytical amplitude result simply by multiplying by a combinatorial factor and using the effective structure function approximation. A complete simulation, including fragmentation and detector modelling has not been performed. However the detector angular resolving power, studied by superimposing pairs of two-jet events, has been included and the parton level cut-offs have been modified to mimic the cuts used in the analysis. For this parton level study each parton is required to be within the fiducial $|\eta| < 2$ range and to have a transverse energy in excess of 15 GeV. These values have been chosen to be as close as possible to those used in the final analysis.

5. Comparison with data

Given the limited statistics of the five- and six-jet data samples, a complete comparison was carried out only for the four-jet data. Unless otherwise specified all the simulated distributions are normalized to the data and the errors shown are statistical only.

A four-jet system can be entirely described by nine variables, three describing the orientation of the jet system in space and six describing its internal configuration. The general topology of the event can be described by the sphericity distribution. This has been computed defining the cluster axes as the lines joining the cluster centroids to the nominal interaction vertex and assigning three-momenta to the massless jets according to their reconstructed energies in the centre-of-mass system. Fig. 1 shows the invariant mass and sphericity for four-jet events. The QCD calculation of KS is represented by the solid histogram and is in good agreement with the data. No significant deviation from this QCD prediction is observed.

A more detailed understanding of the features of four-jet events can be obtained by examining the distributions of the six space angles, $\cos \Omega^*_{ij}$, in the centre-of-mass system. Only five of these angles are independent variables, the last one being fixed by the invariant mass of the jet system. Four of these angles are shown in fig. 2 where the solid histograms represent the QCD prediction resulting from the KS Monte Carlo simulation. The data are well described by

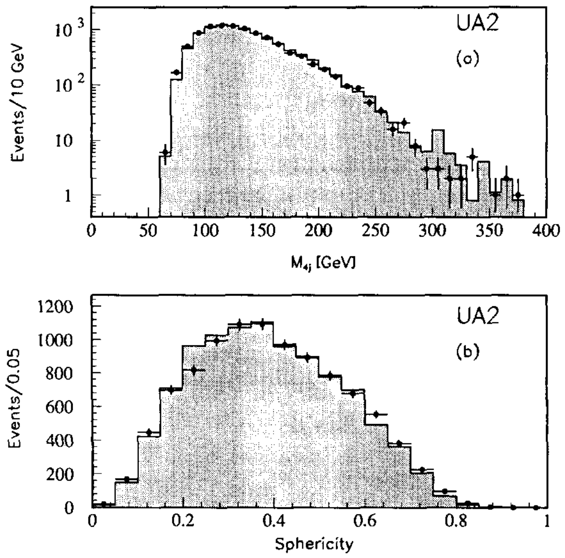

Fig. 1. Invariant mass (a) and sphericity (b) of the four-jet system. Only statistical errors are shown. The solid histograms represent the results of the leading order calculation of ref. [8] followed by the full detector simulation.

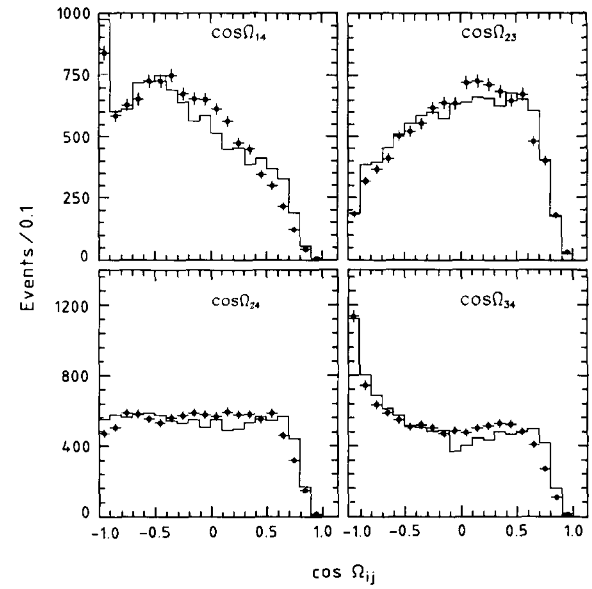

Fig. 2. Four of the six space angles in the centre-of-mass system. The data points are plotted against the leasing order calculation of ref. [8] followed by the full detector simulation.

leading order QCD. The expected enhancements in the regions of small angular separation, characteristic of bremsstrahlung radiation, are significantly dampened by the angular resolution of the calorimeter. Topologies where the four-jets are evenly distributed in two opposite hemispheres (2 versus 2) or unbalanced (1 versus 3) can also be recognized.

An interesting study is the measurement of the inclusive p_T-spectrum for multi-jet events and its comparison to the absolute prediction of the exact and approximate leading order QCD calculations. The observed (acceptance uncorrected) inclusive p_T spectrum is shown in figs. 3 and 4. Each jet contributes one entry to these distributions and the data points represent the measured spectra for four-jet, five-jet and six-jet data samples. The four- and five-jet data are compared with several leading order QCD predictions, whereas the very limited sample of six-jet data is only shown to indicate the qualitative relations between the spectra. In fig. 3 the solid lines represent the exact calculation of BGK for four- and five-jet production. In fig. 4 the solid line represents the calculation of KS for four-jet events. The dash-

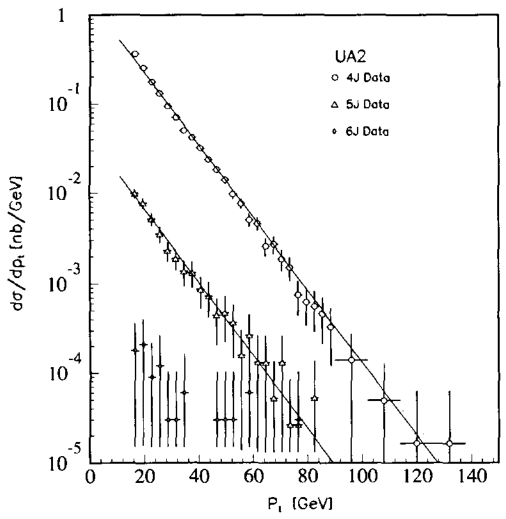

Fig. 3. Measured inclusive p_T spectra for multi-jet events: (○) four-jet events, (△) five-jet events, (◇) six-jet events. The spectra are not corrected for acceptance. The overall, p_T independent, systematic uncertainty is not shown, whereas the p_T dependent part has been added quadratically bin by bin to the statistical error. The two solid lines represent the absolute prediction of the leading order QCD calculation of ref. [9] for four and five jets.

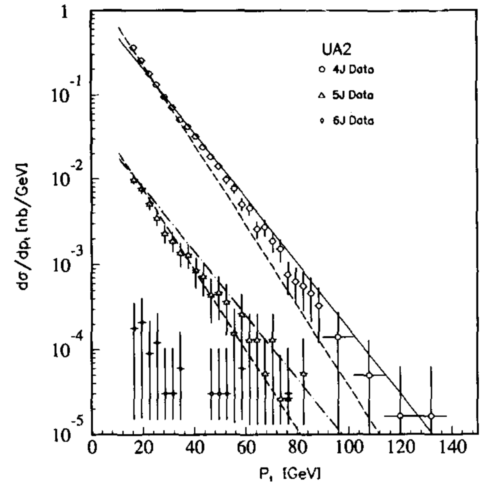

Fig. 4. Comparison of the inclusive p_T spectrum resulting from the approximate QCD calculations described in the text to the multi-jet data. The solid curve represents the calculation based on the work of ref. [8] for four jets. The dash-dotted line is the result of the ESFAG approximation of ref. [9], while the two dashed curves are the results of the parton level study of the NGLUON approximation of ref. [10].

dotted line is the result of the ESFAG approximation of BGK for five-jet events. Finally, the two dashed lines show the results of the NGLUON approximation for four and five jets. In this case the four-jet cross section has been normalized to the exact BGK case. The main purpose of the study in this case is to examine whether the overall shape of the inclusive p_T-spectrum can be described by an analytical calculation based on purely gluonic matrix elements only. Within the statistical errors the spectra predicted by the leasing order QCD calculations, exact or approximate, are in good agreement with the measured data, although the high p_T regions are not completely reproduced by the approximation. This is not surprising, in view of the lack of the relevant quark–antiquark contributions in this model. The results for the absolute cross sections and the comparison with the measured values are tabulated in table 1. For the particular choice of structure functions and Q^2 which has been made, the exact calculations agree in absolute normalization with the data.

Several sources of systematic uncertainties have to be considered. The uncertainty on the absolute energy scale of the calorimeter results in a p_T-dependent error, which using the approximate form $\exp(-bp_T)$

Table 1
Uncorrected multi-jet cross sections. The Monte Carlo results, for n-jet production, are absolute predictions of leading order QCD calculations obtained using the structure functions set of ref. [10], $\Lambda_{QCD}=200$ MeV and $Q^2=E^2_{t\,max}$. BGK and KS refer to the calculations of ref. [8] and ref. [9], respectively. The EXACT calculation and the ESFAG approximation are described in the text. The theoretical uncertainty resulting from the lack of knowledge on Q^2 and Λ_{QCD} is approximately a factor of 2 on σ_4. The overal systematic error on the measurement amounts to 51%.

m	σ (BGK) [nb]		σ (KS) [nb]	σ (DATA) [nb]
	EXACT	ESFAG		
4	1.28	–	1.21	1.31
5	0.040	0.047	–	0.037
6	–	–	–	0.0009

for the jet spectra with $b=0.1$ GeV^{-1}, has been computed for each p_T bin and added in quadrature to the statistical error of the measurement. The overall error resulting from energy scale uncertainties is 23%. The contribution to the systematic uncertainty resulting from the limited knowledge of the calorimeter response to low energy hadrons amounts to 28%. Fluctuations of the underlying event, studied by varying the number of minimum bias events superimposed on the jets of the generated hard collision, result in an error of 20%. The largest contribution to the systematic uncertainty is caused by the limited knowledge of the fragmentation process. This effect has been estimated by varying the parameters of the model and corresponds to a maximum variation of 40%. The overall p_T independent systematic error, estimated by adding all contributions in quadrature, amounts to 51%.

6. Search for double parton scatterings

In a simple model of multi-parton interactions the cross section for DPS can be written as

$$\sigma_{DPS}=\frac{1}{2}\frac{\sigma_2^2}{\sigma_{eff}},$$

where σ_2 is the two-jet cross section and σ_{eff} is interpreted as a scale parameter related to the distance among the partons inside the proton. Theoretical speculations suggest σ_{eff} to be smaller than the total inelastic hadronic cross section, measured to be approximately 40 mb [17]. The factor of two in the denominator has been suggested by the authors of ref. [18] and originates from the poissonian nature of the probability of having multiple interactions. A measurement of σ_{DPS} provides direct information on the scale parameter σ_{eff}. Evidence for DPS has been reported by the AFS Collaboration [19] from a study of multi-jet events at the CERN ISR (pp collisions at $\sqrt{s}=63$ GeV).

The good description of the four-jet data sample in terms of standard QCD processes, which are dominated by double bremsstrahlung (DB), suggests that very little room is left for other multi-jet production mechanisms, such as DPS. In order to quantify this statement a modified version of the PYTHIA generator [20], in which two hard scatterings are forced to occur within the same p̄p collision, has been used to mimic DPS events. The acceptance of the calorimeter and the details of its response have been simulated as in the QCD model described above.

Given the substantial similarities among DPS and DB events the search for DPS is carried out on a statistical basis. In a four-jet final state, resulting from the simultaneous interaction of two pairs of constituent partons, the expectation is to find pairwise correlations among the final state jets. The main feature is the presence of two jet pairs, each with jets balanced in transverse momentum and produced at opposite azimuthal angles.

Based on these considerations a variable sensitive to the presence of such two jet pairs has been constructed [21]. This variable is defined as

$$2S^2=\min\left(\frac{|\boldsymbol{p}_{Ti}+\boldsymbol{p}_{Tj}|^2}{|\boldsymbol{p}_{Ti}|+|\boldsymbol{p}_{Tj}|}+\frac{|\boldsymbol{p}_{Tk}+\boldsymbol{p}_{Tl}|^2}{|\boldsymbol{p}_{Tk}|+|\boldsymbol{p}_{Tl}|}\right),$$

where the minimization is performed over the three possible permutations of jet pairs. For a DPS event S should be close to zero, because of the transverse momentum balance of the two jet pairs. Gluon radiation (initial and final) and wrong jet assignment because of the fragmentation and the intrinsic detector resolution for the measurement of transverse momentum imbalance result in an S distribution that is smeared and slightly shifted with respect to the naive expectation. This is shown in fig. 5a where Log(S) has been

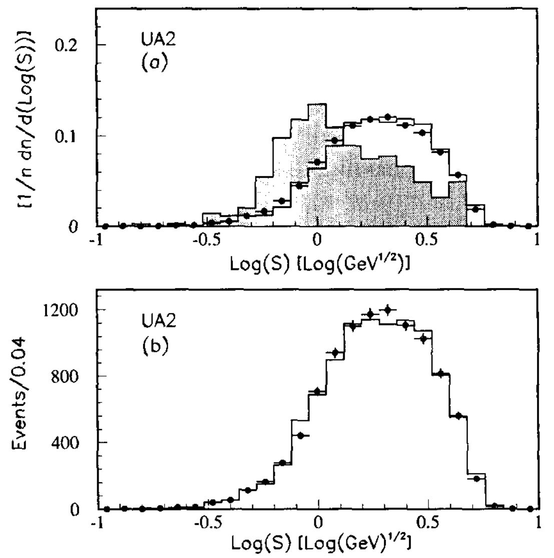

Fig. 5. (a) Log(S) distribution for the four-jet data (points), double parton scattering Monte Carlo events (hatched histogram) and double bremsstrahlung Monte Carlo events (solid histrogram). To avoid problems of normalization the areas of all the histograms have been set to unity. (b) The comparison of the best fit (solid histogram) to the distribution measured for the data.

plotted for the data together with the events of the double bremsstrahlung QCD Monte Carlo and the double parton scattering events generated by the modified version of PYTHIA. To emphasize the different shapes all the distributions have been normalized to the same area and Log(S), rather than S itself, has been used. The accumulation of DPS events for values of Log(S) near zero is due to the finite resolution of the detector for transverse momentum balance.

The DPS content of the four-jet data sample is determined in the following way. The four-jet sample is assumed to be an unknown mixture of two classes of events, resulting from DPS and DB processes. The Monte Carlo simulations of DPS and DB events have been used to extract the predicted shapes of the Log(S) distribution. Such distributions are then weighted with factors N_{DPS} and N_{DB} and the weighted sum is then compared to the distribution measured for the four-jet data using a minimum χ^2 method. The reliability of this fitting method has been verified using Monte Carlo event samples, constructed from known amounts of DPS and DB simulated events. The same Monte Carlo study shows that Log(S) is the most sensitive variable found for detecting a possible signal from multiple interactions.

The χ^2 per degree of freedom as a function of the DPS content of the four-jet sample reached a minimum for 755 ± 165 DPS events. The best fit, including the DPS and DB contributions, is compared to the distribution measured for the data in fig. 5b.

The number of events found by the fit has been converted to a cross section by correcting for various efficiency factors and including the systematic uncertainties. These uncertainties associated with the detector modelling have been studied by varying the calorimeter response, its energy scale and the simulation of the underlying event in the calculation of the predicted DPS and DB shapes of the Log(S) distributions and by repeating the fit. The overall systematic uncertainty from these sources corresponds to ± 109 DPS events.

The combined efficiency of the analysis cuts has been evaluated using the PYTHIA generated DPS events and it amounts to $(60 \pm 25)\%$. The uncertainty on this number originates mostly from the limited knowledge of the calorimeter response to low energy particles. The trigger efficiency for DPS events has been estimated to be $(91.5^{+8.5}_{-9.2})\%$ using the trigger algorithm implemented in the Monte Carlo simulation. The geometrical acceptance, expressing the probability that the two jet pairs of a DPS event are reconstructed in the UA2 calorimeter as a four-jet event, has been measured using Monte Carlo simulations. This acceptance amounts to $(34.4 \pm 3.5)\%$. The global correction factor is $\varepsilon_{\mathrm{t}} = (18.8 \pm 5.5)\%$.

Finally, before converting the observed number of DPS events to a cross section one more source of background has to be subtracted. With the improved performances of the CERN $\bar{p}p$ Collider during the 1988 and 1989 runs the probability of having multiple $\bar{p}p$ interactions within the same bunch crossing averaged 10%. If both interactions result in two-jet pairs then this class of events is indistinguishable from the DPS signal and its contribution has to be statistically subtracted. Using the leading order calculation of ref. [8] and the full detector modelling this background is estimated to be 60 ± 40 events, where the error is dominated by the uncertainty on the two-jet cross section.

The cross section for DPS production is evaluated from the formula

$$\sigma_{\mathrm{DPS}} = \frac{N_{\mathrm{DPS}} - N_{\mathrm{b}}}{\int \mathscr{L} \mathrm{d}t \cdot \varepsilon_{\mathrm{t}}},$$

where N_{DPS} is the number of events found by the fit, N_{b} is the number of background events, $\int \mathscr{L} \mathrm{d}t$ is the total integrated luminosity and ε_{t} is the global efficiency for double parton scattering events. Adding the statistical and systematic errors on N_{DPS} in quadrature, the value $\sigma_{\mathrm{DPS}} = 0.49 \pm 0.20$ nb is obtained, implying $\sigma_{\mathrm{DPS}} < 0.82$ nb at 95% CL. Using the simple formula relating σ_{DPS} and σ_{eff} this translates to $\sigma_{\mathrm{eff}} > 8.3$ mb at 95% CL.

7. Conclusions

A study of multi-jet events, using data collected during the 1988 and 1989 running periods, has shown that leading order QCD calculations describe the data well. Shapes of distributions and absolute normalizations are well reproduced within the statistical and systematic errors of the measurement. A search for additional production mechanisms of four-jet events has been carried out and, in the absence of an unambiguous signal, an upper limit on the production cross section for these processes has been placed.

Acknowledgement

We thank H. Kuijf and Z. Kunszt for helpful discussions and for providing us with their QCD calculations. We thank T. Sjöstrand for fruitful discussions and for providing us with the modified version of PYTHIA to model double parton scattering events. We gratefully acknowledge P. Darriulat for his contributions and guidance during the design and construction of the UA2 upgrade project. The technical staff of the institutes collaborating in UA2 have contributed substantially to the construction and operation of the experiment. We deeply thank them for their continuous support. The experiment would not have been possible without the very successful operation of the improved CERN p̄p Collider whose staff and coordinators we sincerely thank for their collective effort. Financial support from the Schweizerischen Nationalfonds zur Förderung der Wissenschaftlichen Forschung to the Bern group, from the UK Science and Engineering Research Council to the Cambridge group, from the Bundesministerium für Forschung und Technologie to the Dortmund and Heidelberg groups, from the Australian Research Council, the CRA Pty Ltd, and the Victorian Education Foundation to the Melbourne group, from the Institut National de Physique Nucléaire et de Physique des Particules to the Orsay group, from the Istituto Nazionale di Fisica Nucleare to the Milano, Pavia, Perugia and Pisa groups and from the Institut de Recherche Fondamentale (CEA) to the Saclay group are acknowledged.

References

[1] See e.g. the reviews P. Bagnaia and S.D. Ellis, Ann. Rev. Nucl. Part. Sci. 38 (1988) 659;
R.K. Ellis and W.G. Scott, in: Proton–antiproton collider physics, eds. G. Altarelli and L. DiLella (World Scientific, Singapore, 1989) p. 131.

[2] N. Paver and D. Treleani, Nuovo Cimento 70A (1982) 215;
B. Humpert, Phys. Lett. B 131 (1983) 461;
N. Paver and D. Treleani, Phys. Lett. B 146 (1984) 252;
B. Humpert and R. Odorico, Phys. Lett. B 154 (1985) 211.

[3] UA2 Collab., Proposal to improve the performance of the UA2 detector, CERN reports CERN/SPSC 84-30, 84-95 (1984), 85-3 (1985), unpublished;
C.N. Booth (UA2 Collab.), Proc. 6th Topical Workshop on Proton–antiproton collider physics (Aachen, 1986), eds. K. Eggert et al. (World Scientific, Singapore, 1987) p. 381.

[4] H. Fesenfeldt, Simulation of hadronic showers, Aachen preprint PITHA 85-02 (1985).

[5] G. Blaylock et al., Proc. Intern. Conf. on the Impact of digital microelectronics and microprocessors on particle physics, eds. M. Budinich et al. (World Scientific, Singapore, 1988) pp. 247, 254.

[6] UA2 Collab., K. Meier, Proc. 8th Topical Workshop on Proton–antiproton collider physics (Castiglione della Pescaia, 1989), eds. G. Bellettini et al. (World Scientific, Singapore, 1990) p. 120.

[7] UA2 Collab., J. Alitti et al., Z. Phys. C 47 (1990) 11.

[8] Z. Kunszt and W.J. Stirling, Phys. Lett. B 171 (1986) 307.

[9] F. Berends, W. Giele and H. Kuijf, Nucl. Phys. B 333 (1990) 120; Phys. Lett. B 232 (1990) 266;
H. Kuijf, private communications.

[10] Z. Kunszt and W.J. Stirling, Phys. Rev. D 37 (1988) 2439;
S.J. Parke and T.R. Taylor, Phys. Rev. Lett. 56 (1986) 2459.

[11] UA1 Collab., G. Arnison et al., Phys. Lett. B 136 (1984) 294;
UA2 Collab., P. Bagnaia et al., Phys. Lett. B 144 (1984) 283.

[12] D.W. Duke and J.F. Owens, Phys. Rev. D 30 (1984) 49.
[13] M. Glück, E. Hoffman and E. Reya, Z. Phys. C 13 (1982) 119.
[14] A.D. Martin, R.G. Roberts and W.J. Stirling, Phys. Rev. D 37 (1988) 1161.
[15] E. Eichten et al., Rev. Mod. Phys. 56 (1984) 579.
[16] R.D. Field and R.P. Feynman, Nucl. Phys. B 136 (1978) 1.
[17] UA4 Collab., M. Bozzo et al., Phys. Lett. B 147 (1984) 392.
[18] T. Sjöstrand and M. Zijl, Phys. Rev. D 36 (1987) 2019.
[19] AFS Collab., T. Åkesson et al., Z. Phys. C 34 (1987) 163.
[20] H.U. Bengtson and T. Sjöstrand, PYTHIA, Comput. Phys. Commun. 46 (1987) 43;
T. Sjöstrand, private communication.
[21] J.S. Patrick (CDF Collab.), Proc. 7th Topical Worshop on Proton–antiproton collider physics (Fermilab, 1988) eds. R. Raja et al. (World Scientific, Singapore, 1989) p. 217.