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MEASUREMENT OF VERY LARGE TRANSVERSE MOMENTUM JET
PRODUCTION AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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ABSTRACT

The production of very large transverse momentum hadron jets has been measured in the UA2 experiment at the CERN $\bar{p}p$ Collider for $\sqrt{s} = 540$ GeV using a highly segmented calorimeter. The range of previously available cross-sections for inclusive jet production is extended to $p_T = 150$ GeV and the two-jet invariant mass distribution to $m_{jj} = 280$ GeV with the largely increased data sample collected during the 1983 running period. The results are compared with the predictions of QCD models.

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1. INTRODUCTION

The recent unambiguous identification of jets in hadronic collisions [1-4] at the CERN $\bar{p}p$ Collider and at the ISR has revived the interest in this field after the first observation of large transverse momentum (p_T) processes in early ISR experiments [5]. The prediction that the hard scattering of hadron constituents should result in the production of two hadronic jets having the same large transverse momenta as the scattered partons [6,7] has been evidenced in a direct way at the CERN $\bar{p}p$ Collider with the observation of a dominant two-jet structure in events depositing very large transverse energy into the central calorimeters of the UA1 [3] or UA2 [1] experiments. In fact one of the most outstanding benefits of the very successful operation of the CERN $\bar{p}p$ Collider [8] at a centre of mass energy $\sqrt{s} = 540$ GeV is the possibility for detailed measurements of hadronic jet production and their fragmentation properties [9-11] in an energy domain where hard processes can be separated clearly from the soft hadronic interactions [12].

A comparison of hadron jets produced in electron-positron, lepton-hadron and hadron-hadron collisions, including recent results from the ISR, is given in Ref. [13].

New results on jet production from the UA2 experiment are reported in this Letter. The data sample has been significantly increased, by about a factor of 15 over the previously available statistics, due to the increased luminosity of the CERN $\bar{p}p$ Collider and due to the now completed azimuthal coverage ($\Delta\phi = 360^\circ$) of the UA2 central calorimeter. Because of the presence of a single-arm spectrometer [14] $\Delta\phi$ was only 300° for the data reported in [1,9]. The events with very large transverse energy depositions (ΣE_T up to 250 GeV in the pseudo-rapidity interval $-1 < \eta < 1$) are observed to be completely dominated by a two-jet structure. The cross-section measurements for inclusive jet production are extended to $p_T = 150$ GeV and the two-jet invariant mass distribution to $m_{jj} = 280$ GeV. In the last section of this Letter these measurements are compared to the predictions of QCD models.

2. APPARATUS

The UA2 detector has been described in detail elsewhere [15,16]. At the centre of the UA2 apparatus a vertex detector consisting of cylindrical proportional and drift chambers measures particle trajectories in a region without magnetic field. The vertex detector is surrounded by a highly segmented electromagnetic and hadronic calorimeter (the central calorimeter) which covers polar angles $40^\circ < \theta < 140^\circ$ ($-1 < \eta < 1$). The forward regions ($20^\circ < \theta < 37.5^\circ$ and $142.5^\circ < \theta < 160^\circ$) are each instrumented with twelve toroidal magnet sectors followed by drift chambers, multitube proportional chambers and electromagnetic calorimeters.

The present results have been obtained mainly with the central calorimeter. It is segmented into 240 cells, each covering 15° in ϕ and 10° in θ and built in a tower structure pointing to the centre of the interaction region. The cells are segmented longitudinally into a 17 radiation length thick electromagnetic compartment (lead-scintillator) followed by two hadronic compartments (iron-scintillator) of two absorption lengths each. Following an initial energy calibration of all cells in a 10 GeV electron, muon and pion beam from the CERN PS the calorimeter response has been tracked with a light flasher system, measurements of the direct-current induced by a Co^{60} radioactive source and by measuring the average energy flow into each cell for unbiased $\bar{p}p$ collisions. The systematic uncertainty in the energy calibration for the data discussed here is less than $\pm 1.5\%$ for the electromagnetic calorimeter and less than $\pm 3.5\%$ for the hadronic one.

The response of the calorimeter to electrons, single hadrons and multi-hadrons (produced in a target in front of the calorimeter) has been measured at the CERN PS and SPS machines using beams from 1 to 70 GeV. The energy resolution for electrons is measured to be $\sigma_E/E = 0.14/\sqrt{E}$ (E in GeV) whereas for hadrons it varies from 32% at 1 GeV to 11% at 70 GeV, approximately proportionally to $E^{-1/4}$.

Details of the construction, calibration and performance of the calorimeter are reported in Ref. [16].

3. DATA TAKING AND REDUCTION

The data presented in this Letter were recorded during the 1983 CERN $\bar{p}p$ Collider run with a trigger selecting $\bar{p}p$ collisions which deposited a large total transverse energy (ΣE_T) into the central calorimeter. The gains of the photomultipliers were adjusted such that their response is proportional to transverse energy, and their signals were linearly added. The sum was required to exceed a threshold, normally at about 40 GeV except for special low threshold data runs.

Background from sources other than $\bar{p}p$ collisions was suppressed at the trigger level by requiring a coincidence of the ΣE_T condition with two signals ("minimum bias" trigger) obtained from scintillator arrays covering an angular range $0.44^\circ < \theta < 2.84^\circ$ on both sides of the collision region [17]. The loss of genuine large ΣE_T $\bar{p}p$ events due to this requirement was measured in special runs where this condition was removed. For $\Sigma E_T > 40$ GeV the loss is consistent with zero and $< 5\%$ at 90% confidence level, independent of ΣE_T . Background from cosmic rays was found to be negligible.

A sample of "minimum bias" events was recorded simultaneously with the ΣE_T data to provide a measurement of the luminosity. Data with $\Sigma E_T > 40$ GeV were recorded for a total integrated luminosity $\int \mathcal{L} dt = 112 \text{ nb}^{-1}$. An uncertainty of $\pm 20\%$ was estimated for $\int \mathcal{L} dt$ from the observed fluctuations during different running conditions and from the overall uncertainty in the cross-section accepted by the "minimum bias" trigger [17].

The full data sample was used in the following analysis for $\Sigma E_T > 60$ GeV; smaller samples and special runs were used for lower thresholds [18].

The events collected with the ΣE_T trigger include a small ($< 10\%$) background contamination. Beam halo particles can either satisfy the triggering condition directly or appear as an accidental overlap with a "minimum bias" $\bar{p}p$ interaction. The background events exhibit a characteristic pattern in the detector different from that of large ΣE_T

$\bar{p}p$ events. They are rejected from the data sample if any of the following conditions is satisfied :

- i) if they are associated with an early signal in the small angle scintillator arrays ;
- ii) if they have an abnormally large total transverse energy fraction in the hadronic compartments (more than 60% in the second one or more than 95% in both together) ;
- iii) if they contain only one cluster (as defined below) with more than 90% of its energy in the hadronic compartments.

These requirements reduce the background contamination in the data sample to $< 5\%$ independent of ΣE_T . The loss of good events introduced by the cuts is negligible. This has been verified by applying the time-of-flight requirement on minimum bias events and by using test beam data for the energy deposition criteria.

4. TRANSVERSE ENERGY DISTRIBUTION

The response of the electromagnetic calorimeter compartments to energy deposited by photons (or electrons) differs from that of hadrons by typically 20%, depending on energy. We have adopted a constant set of weighting factors (1.18, 1.00, 1.06) for the three compartment energies (electromagnetic, first and second hadronic) that optimizes the resolution and linearity of the calorimeter response to high energy hadrons, as described in detail in Ref. [16].

The total hadronic energy in a cell of the calorimeter is measured as the weighted sum of the energies in the three compartments where each compartment contributing to the sum must exceed 150 MeV, well above pedestal fluctuations.

The observed ΣE_T distribution, normalized using the integrated luminosity, is presented in Fig. 1 for two pseudo-rapidity intervals ($-1 < \eta < 1$ and $-0.54 < \eta < 0.54$). The transverse energies are summed over all cells in the full azimuthal acceptance $\Delta\phi = 360^\circ$ under the approximation that the event vertex is located at the centre of the detector. The event vertex has been reconstructed for a sample of the events used for the cross-section measurement. Its distribution along the $\bar{p}p$ beam axis is well centered in the detector and has a r.m.s. spread of 10 cm. No acceptance correction has been applied to the data shown in Fig. 1. We estimate that the uncertainty in the energy scale of ΣE_T due to systematic effects (150 MeV minimum compartment energy requirement, calibration errors, neglecting event vertex position, etc.) is less than $\pm 10\%$.

The ΣE_T distributions of Fig. 1 show a clear departure from exponential when ΣE_T exceeds ~ 60 GeV. This corresponds to the transverse energy where the two-jet production cross-section begins to dominate over soft hadronic interactions, as explained below.

5. TWO-JET DOMINANCE

In order to investigate the pattern of energy distribution in the events a straightforward clustering algorithm has been adopted which takes advantage of the fine granularity of the calorimeter segmentation [1,9]. All cells which share a common side and have a cell energy $E_{\text{cell}} > 400$ MeV are joined into a cluster. Clusters having two or more local maxima separated by a valley deeper than 5 GeV are split. In each event the clusters are ranked in order of decreasing transverse energies denoted by $E_T^1 > E_T^2 > E_T^3 \dots$. The clusters contain typically 3 cells for $E_T = 2$ GeV and 10 cells for $E_T = 40$ GeV.

The fractions $h_1 = E_T^1 / \Sigma E_T$ and $h_2 = (E_T^1 + E_T^2) / \Sigma E_T$ describe the transverse energy accounted for in each event by the cluster (respectively the two clusters) with the largest transverse energy. An event containing only two jets of equal transverse energy would have

$h_1 = 0.5$ and $h_2 = 1$ in an ideal detector. The mean values of h_1 and h_2 are shown in Fig. 2a as a function of ΣE_T . Their behaviour illustrates the emergence of a dominant two-jet structure at large ΣE_T , as previously reported [1,9]. The effect becomes even more pronounced at the largest values of ΣE_T reached in this experiment. The dependence on ΣE_T of the mean values of the ratio $r_{21} = E_T^2/E_T^1$ and $r_{32} = E_T^3/E_T^2$ are displayed in Fig. 2b. They show the same effect : as ΣE_T increases, r_{21} approaches about 0.9 whereas r_{32} decreases below 0.1. A very large fraction of the total transverse energy of large ΣE_T events is shared on average by two clusters only.

The two clusters are approximately back-to-back in the transverse plane as reported previously in Refs. [1,9] where also typical event configurations are displayed, and where the study of the properties of large E_T clusters has led to their identification as hadronic jets.

6. INCLUSIVE JET PRODUCTION CROSS-SECTIONS

For a measurement of the inclusive jet production cross-sections

$$\bar{p}p \rightarrow \text{jet} + \text{anything} \quad (1)$$

$$\bar{p}p \rightarrow \text{jet}_1 + \text{jet}_2 + \text{anything} \quad (2)$$

events are selected containing at least one cluster with E_T exceeding the ΣE_T threshold for reaction (1) and with $E_T^1 + E_T^2$ larger than the ΣE_T threshold (and $E_T^1, E_T^2 > 10$ GeV) for reaction (2), after inclusion of nearby clusters as explained below. The jet direction and transverse energy are measured from the centroid and energy of the associated clusters with respect to the event vertex.

The individual clusters are taken to be massless [7] in the following procedure, equating therefore $p_T = E_T$. Actually, by attributing a zero-mass momentum vector ($p = E$) to each cell which participates to a cluster one observes a mean invariant "cluster mass" of 9 GeV for clusters having $E_T > 30$ GeV. This value results from the combined

effects of shower and cell sizes and of actual jet masses, and is in agreement with a Monte Carlo simulation [19] described below. For jets having $p_T > 30$ GeV this calculation predicts a mean ratio $|\vec{p}_T|/E_T = 0.86$, where $|\vec{p}_T|$ and E_T are summed over all generated final state particles.

In order to partly account for final state gluon radiation effects, as reported and discussed in Ref. [9], the jet momenta are defined by adding to the measured momentum vector of the selected cluster those of all clusters having $E_T > 3$ GeV and separated by an angle ω from the selected cluster momentum vector such that $\cos\omega > 0.2$. About 20% of the jets with $p_T > 30$ GeV include at least one such nearby cluster with $E_T > 3$ GeV. Note that in this case the jet acquires a mass and p_T differs from E_T . The inclusion of these nearby clusters increases the observed transverse momentum distribution (p_T) for jets by about 15%, roughly independent of p_T .

The evaluation of the cross-sections for reactions (1) and (2) from these events requires the measurement of the integrated luminosity for the normalization and the determination of the detector acceptance including the effects of the energy smearing on the steeply falling p_T spectra. A Monte Carlo simulation of the detector is used to calculate the acceptance. The Monte Carlo events are processed through the same analysis chain as the data. The simulation reproduces the details of the event configuration and of the detector response, using the same weighting factors for the three calorimeter compartment energies as for the data. In particular, the distribution of cluster size and both hadronic fragmentation and shower development are adequately described [9]. The comparison of the transverse momentum (p_T) and the two-jet invariant mass (m_{jj}) distributions of the reconstructed Monte Carlo events with those of the initial partons used as input provides the acceptance functions $\varepsilon(p_T)$ and $\varepsilon(m_{jj})$ by which the observed cross-sections must be divided to obtain the corrected jet and two-jet cross-sections. The function $\varepsilon(p_T)$ varies from about 0.8 to 1.0 over the range $30 < p_T < 150$ GeV and $\varepsilon(m_{jj})$ from about 0.5 to 0.8 over the range $50 < m_{jj} < 250$ GeV. The uncertainty due to the model dependence of the acceptance calculation has been studied by using

different independent models [9,19], by changing the details of the jet fragmentation and by varying relevant analysis parameters, such as the accepted rapidity range, the parameters of the clustering algorithm, weighting factors for the calorimeter compartment energies etc... The systematic uncertainty on ϵ is estimated to be $\pm 35\%$.

The cross-section for inclusive jet production $d^2\sigma/dp_T d\eta$ at $\eta = 0$ is shown in Fig. 3a and listed in Table 1a as a function of the jet transverse momentum p_T . The cross-section for two-jet production $d\sigma/dm_{jj}$ with both jets in the interval $-0.85 < \eta < 0.85$, is displayed in Fig. 3b and Table 1b as a function of the invariant two-jet mass m_{jj} . The quoted errors include the statistical errors and an energy-dependent systematic uncertainty on the acceptance functions. Further uncertainties have to be considered in addition to the systematic error on the acceptance ($\pm 35\%$). The normalization is affected by the $\pm 20\%$ systematic uncertainty in the knowledge of the integrated luminosity, and the systematic error on the calorimeter energy calibration is contributing another $\pm 20\%$. The overall systematic uncertainty on the cross-sections for the reactions (1) and (2) is estimated to be $\pm 45\%$ after adding the three contributions in quadrature.

Also shown in Figs. 3a and 3b are the cross-sections obtained previously by the same experiment [9] with a much smaller data sample (from the 1982 running period). For these data an additional systematic error of $\pm 40\%$ has been quoted. The two measurements are in very good agreement. One should note though that the systematic uncertainties of the two results have largely common origins and the two evaluations are not independent. The inclusive jet production cross-section reported by the UA1 experiment [3,10] is also shown in Fig. 3a. The systematic uncertainty for this measurement is given in [10] as a factor 1.65. Even though the UA1 data points are about a factor 1.5 to 2 below the present measurement, both experiments are consistent in the region of overlap within systematic errors.

No obvious signal from the decay of the intermediate vector bosons $W^\pm$, Z^0 into jets is visible in Fig. 3b. A detailed search for structures in their mass region is beyond the scope of this Letter.

7. COMPARISON WITH QCD CALCULATIONS

The measurements of the inclusive jet production cross-sections, reactions (1) and (2), can be compared directly with QCD predictions. In principle such comparisons do not require any assumption on the fragmentation mechanism: to the extent that jets are correctly identified they correspond directly to the hard scattered partons [7]. The observations [1,3,9,10] of the predicted increase of the yield of jets having $p_T > 20$ GeV at the CERN $\bar{p}p$ Collider with respect to top ISR energy (by about four orders of magnitude [20]) is a remarkable success of the QCD parton picture.

Several QCD calculations have since been reported. In the following the data are compared with those of Refs. [21-23]. Two major uncertainties affect the theoretical predictions [24] : scale ambiguities (choice of Q^2) in the leading logarithm calculations and, related to it, the choice of the Λ parameter in the strong coupling constant $\alpha_s(Q^2)$, and the parametrization used for the parton densities (structure functions) in the incoming p and $\bar{p}$. Furthermore higher order (in α_s) contributions to the jet production cross-sections are not fully included. The influence of these theoretical ambiguities has been studied, for example, in Refs. [21-23]. The calculations ignore fragmentation effects and assume massless partons.

A comparison between data and a range of these predictions is indicated in Figs. 4a and 4b as a shaded band [25]. The solid curve in Fig. 4a corresponds to the prediction of Ref. [20] and coincides practically with the results of Refs. [21,22], not separately shown, for the theoretical assumptions listed in [26]. The latter results are also displayed in Fig. 4b as a solid curve. The data are at a level comparable to the QCD predictions.

It has been suggested that a possible substructure of quarks and leptons would manifest itself as a new contact interaction visible at large momentum transfers [27]. The cross-sections for reactions (1) and (2) are expected to deviate at large p_T or m_{jj} from the QCD behaviour depending on the energy scale ξ which characterizes the strength of

this new interaction (and the physical size of the composite states). For example, for $\xi = 200$ GeV, the cross-section of reaction (1) is expected to be one order of magnitude larger than the QCD prediction ($\xi = \infty$) at $p_T > 100$ GeV (Fig. 4a). A determination of ξ from the data is in principle possible but the uncertainties attached to the QCD calculations limit its accuracy. By comparing the measured cross-section for reaction (1) to the QCD calculations of Ref. [21,26] we find a fair agreement ($\chi^2 = 45$ for 29 degrees of freedom) if we multiply the QCD cross-sections by a p_T independent scale factor of 1.9. The remaining deviation can be expressed in terms of a lower limit on ξ by using the calculation of Ref. [28]. This method, which is model dependent, gives $\xi > 275$ GeV (95% CL).

In conclusion it has been further evidenced that two-jet production is the dominant hadronic process at large transverse energies at the CERN $\bar{p}p$ Collider. The jet production cross-sections are adequately described by QCD models.

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TABLE 1

a) Inclusive cross-section for
 $\bar{p}p \rightarrow \text{jet} + \text{anything}$ at $\sqrt{s} = 540$ GeV.

b) Inclusive cross-section for
 $\bar{p}p \rightarrow \text{jet}_1 + \text{jet}_2 + \text{anything}$
 at $\sqrt{s} = 540$ GeV, with both jets in the
 pseudo-rapidity range $-0.85 < \eta < 0.85$

p_T (GeV)	$d^2\sigma/dp_T d\eta$ at $\eta=0$ (nb GeV $^{-1}$)		m_{jj} (GeV)	$d\sigma/dm_{jj}$ (nb GeV $^{-1}$)	$ \eta_{\text{jet}} < 0.85$
31	54.2	± 14.2	46	94.	$\pm 12.$
33	39.1	10.1	50	66.	10.
35	25.0	6.7	54	47.	8.
37	15.8	4.5	58	23.	3.
39	15.7	4.4	62	15.	2.
41	8.1	1.6	66	10.2	1.1
43	6.2	1.2	70	7.6	.9
45	5.4	1.0	74	5.5	.5
47	3.1	.6	78	3.9	.4
49	1.8	.4	82	3.0	.3
51	1.9	.4	86	2.3	.2
53	1.7	.3	90	1.7	.2
55	.83	.19	94	1.26	.14
57	.92	.21	98	.97	.11
59	.51	.14	102	.78	.09
61	.51	.07	106	.59	.07
63	.40	.06	110	.49	.06
65	.27	.04	114	.37	.05
67	.22	.03	118	.27	.04
69	.16	.03	123	.20	.03
72	.14	.02	131	.134	.020
76	.102	.015	139	.083	.014
80	.036	.008	147	.067	.012
84	.037	.008	155	.043	.009
88	.019	.005	167	.018	.003
94	.013	.003	187	.0066	.0021
104	.0084	.0023	207	.0052	.0018
114	.0027	.0012	227	.0011	.0008
124	.0022	.0011	247	.0017	.0010
138	.0005	.0004	267	.0017	.0010

The listed errors include the statistical and the p_T or m_{jj} - dependent systematic uncertainties. The additional overall systematic error is $\pm 45\%$.

FIGURE CAPTIONS

1. Observed total transverse energy ΣE_T distributions for two pseudo-rapidity η intervals.
2. a) The fractions h_1 and h_2 of the total transverse energy ΣE_T contained in the cluster, and the two clusters respectively, having the largest ΣE_T are displayed versus ΣE_T .
b) Dependence on ΣE_T of the ratios $r_{21} = E_T^2/E_T^1$ and $r_{32} = E_T^3/E_T^2$ (see text).
3. a) Inclusive jet production cross-section. The additional systematic uncertainty is $\pm 45\%$. Previous measurements are from Refs. [3,9,10].
b) Two-jet production cross-section with both jets in the pseudo-rapidity range $-0.85 < \eta < 0.85$. The additional systematic uncertainty is $\pm 45\%$. The previous measurement is from Ref. [9].
4. a) Comparison of the inclusive jet production cross-section with QCD calculations (see text).
b) Comparison of the two-jet production cross-section with both jets in the pseudo-rapidity range $-0.85 < \eta < 0.85$ with QCD calculations (see text).
The additional systematic uncertainty on the data is $\pm 45\%$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4