MEASUREMENT OF THE INCLUSIVE JET CROSS-SECTION AT THE CERN $p\bar{p}$ COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen¹ - Amsterdam (NIKHEF)² - Annecy (LAPP)³ - Birmingham⁴ - CERN⁵ -
Harvard⁶ - Helsinki⁷ - Kiel⁸ - Imperial College, London⁹ - Queen Mary College, London¹⁰ -
MIT¹¹ - Padua¹² - Paris (Coll. de France)¹³ - Riverside¹⁴ - Rome¹⁵ - Rutherford Appleton Lab.¹⁶ -
Saclay (CEN)¹⁷ - Victoria¹⁸ - Vienna¹⁹ - Wisconsin²⁰ Collaboration

G. Arnison¹⁶, M.G. Albrow¹⁶, O.C. Allkofer⁸, A. Astbury¹⁸, B. Aubert³, C. Bacci¹⁵,
J.R. Batley¹⁰, G. Bauer⁶, A. Bettini¹², A. Bézaguét⁵, R.K. Bock⁵, K. Bos², E. Buckley¹⁰,
J. Bunn¹⁶, G. Busetto¹², P. Catz³, P. Cennini⁵, S. Centro¹², F. Ceradini¹⁵, G. Ciapetti¹⁵,
S. Cittolin⁵, D. Clarke¹⁰, D. Cline²⁰, C. Cochet¹⁷, J. Colas³, P. Colas¹⁷, M. Corden⁴, G. Cox⁴,
D. Dallman¹⁹, D. Dau⁸, M. DeBeer¹⁷, J.P. deBrion¹⁷, M. DeGiorgi¹², M. Della Negra^{3,5},
M. Demoulin⁵, B. Denby¹⁶, D. Denegri¹⁷, A. DiCiaccio¹⁵, L. Dobrzynski¹³, J. Dorenbosch²,
J.D. Dowell⁴, E. Duchovni⁵, R. Edgecock⁴, K. Eggert¹, E. Eisenhandler¹⁰, N. Ellis⁴, P. Erhard¹,
H. Faissner¹, M. Fincke Keeler¹⁸, P. Flynn¹⁶, G. Fontaine¹³, R. Frey¹⁴, R. Frühwirth¹⁹,
J. Garvey⁴, S. Geer⁶, C. Ghesquière¹³, P. Ghez³, F. Ghio¹⁵, P. Giacomelli⁵, W.R. Gibson¹⁰,
Y. Giraud-Héraud¹³, A. Givernaud¹⁷, A. Gonidec³, M. Goodman⁶, H. Grassmann¹,
G. Grayer¹⁶, W. Gurny¹⁴, W. Haynes¹⁶, S.J. Haywood⁴, H. Hoffmann⁵, D.J. Holthuisen²,
R.J. Homer⁴, A. Honma¹⁰, W. Jank⁵, M. Jimack⁴, G. Jorat⁵, P.I.P. Kalmus¹⁰, V. Karimäki⁷,
R. Keeler¹⁸, I. Kenyon⁴, A. Kernan¹⁴, W. Kienzle⁵, R. Kinnunen⁷, J. Kroll⁶, D. Krynn¹³,
P. Kyberd¹⁰, F. Lacava¹⁵, J.P. Laugier¹⁷, J.P. Lees³, R. Leuchs⁸, S. Levegrun⁸, A. Lévêque^{5,17},
M. Levi⁵, D. Linglin³, E. Locci¹⁷, K. Long⁵, T. Markiewicz²⁰, M. Markytan¹⁹, T. Martin¹³,
G. Maurin⁵, T. McMahon⁴, J.-P. Mendiburu¹³, A. Meneguzzo¹², O. Meyer⁵, T. Meyer⁵,
M.-N. Minard³, M. Mohammadi²⁰, K. Morgan¹⁴, M. Moricca^{5,15}, H. Moser¹, B. Mours³,
Th. Muller⁵, A. Nandi¹⁰, L. Naumann⁵, A. Norton⁵, L. Paoluzi¹⁵, D. Pascoli¹², F. Pauss⁵,
C. Perault³, G. Piano Mortari¹⁵, E. Pietarinen⁷, C. Pigot¹⁷, M. Pimiä⁷, D. Pitman¹⁴, A. Placci⁵,
J.-P. Porte⁵, E. Radermacher¹, J. Ransdell¹⁴, T. Redelberger¹, H. Reithler¹,
J.P. Revol¹¹, J. Richman⁵, M. Rijssenbeek⁵, J. Rohlf⁶, P. Rossi⁸, C. Roberts¹⁶, W. Ruhm⁵,
C. Rubbia⁵, G. Sajot¹³, G. Salvini¹⁵, J. Sass^{5,17}, B. Sadoulet⁵, D. Samyn⁵, A. Savoy-Navarro¹⁷,
D. Schinzel⁵, A. Schwartz⁶, W. Scott¹⁶, T.P. Shah¹⁶, I. Sheer¹⁴, I. Siotis⁹, D. Smith¹⁴,
R. Sobie¹⁸, P. Sphicas¹¹, J. Strauss¹⁹, J. Streets⁴, C. Stubenrauch¹⁷, D. Summers²⁰,
K. Sumorok⁶, F. Szoncso¹⁹, C. Tao¹³, I. ten Have², G. Thompson¹⁰, E. Tscheslog¹,
J. Tuominiemi⁷, B. van Eijk², P. Verecchia¹⁷, J.P. Vialle³, T.S. Virdee⁹, H. von der Schmitt⁵,
W. von Schlippe¹⁰, J. Vrana¹³, V. Vuillemin⁵, H.D. Wahl¹⁹, P. Watkins⁴, R. Wilke⁵, J. Wilson⁴,
I. Wingerter³, S.J. Wimpenny⁵, C.-E. Wulz¹⁹, T. Wyatt⁵, M. Yvert^{3,5}, I. Zacharov²,
N. Zaganidis¹⁷, L. Zanello¹⁵ and P. Zotto¹²

ABSTRACT

The inclusive jet cross-section has been measured in the UA1 experiment at the CERN $p\bar{p}$ Collider at centre-of-mass energies $\sqrt{s} = 546$ GeV and $\sqrt{s} = 630$ GeV. The cross-sections are found to be consistent with QCD predictions. The observed change in the cross-section with the centre-of-mass energy $\sqrt{s}$ is accounted for in terms of x_T scaling.

1. INTRODUCTION

The emergence of jets with large transverse energy was one of the first results from the CERN $p\bar{p}$ Collider [1]. At the energies of the Collider ($\sqrt{s} = 546$ and 630 GeV), jets are clearly distinguished from the background. Thus jet production properties can be studied with little dependence on the fragmentation, as the emitted jets can be associated directly with the scattered partons. Recently, jet production properties have been investigated by measurements of the inclusive cross-section [2, 3] and of the two-jet angular distribution [4]. These results have been shown to strongly support the QCD description of the hard scattering of partons in $p\bar{p}$ collisions.

In this letter, we present the inclusive jet cross-sections recently measured at $\sqrt{s} = 546$ and 630 GeV with the UA1 detector. The energy dependence of the inclusive cross-section is examined, and comparisons with current theoretical predictions are made.

2. APPARATUS AND DATA TAKING

The UA1 detector and the data-taking conditions are essentially unchanged from those reported in our previous publications, and we refer the reader to ref. [3] for more details. The data sample is comprised of all jet triggers from the 1983 Collider run at $\sqrt{s} = 546$ GeV and from the 1984 Collider run at $\sqrt{s} = 630$ GeV. At the trigger level, a jet is defined as a localized transverse energy E_T deposition anywhere in the central calorimetry (pseudorapidity $|\eta| < 3$). For the 1983 run, the data were based on an inclusive single-jet trigger, while for the 1984 run, the data were based partially on a low- E_T threshold, two-jet trigger, but primarily on a high- E_T inclusive single-jet trigger. The luminosities and relevant thresholds of the various data samples are presented in table 1.

A jet is defined by the UA1 jet algorithm [3], which combines calorimeter hits within a cone of radius 1 unit in η, ϕ space around the highest transverse-energy hits (ϕ is the azimuthal angle in radians). The energy and momentum of each jet are computed by taking the respective scalar and vector sums over the associated calorimeter cells. Charged-track information is not used for finding jets or for defining their energy. Corrections have to be applied off-line to the data for the effect of radiation damage to the calorimetry. The light yield coming from the electromagnetic calorimeter cells decreased by 6% during the 1983 run and 11% during the 1984 run periods. We have corrected this ageing by a factor proportional to the integrated luminosity received; however, we cannot exclude the possibility that ageing has partially occurred at one, or several, discrete times during the running periods.

The data were found to contain a small fraction of background events from beam-gas interactions and events involving two interactions in the same SPS bunch crossing. These are removed from the sample by imposing requirements on the total energy ($E_{\text{tot}} < 600$ GeV for the 1983 data and $E_{\text{tot}} < 700$ GeV for the 1984 data), and on the magnitude of the missing energy vector ($E_T^{\text{miss}} < 2.5\sigma$, where $\sigma = 0.7 \sqrt{\Sigma|E_T|}$). An additional veto against beam halo overlapping with real events was applied by rejecting jets where more than 80% of the energy is deposited in the hadronic part of the calorimeter.

A correction was applied to the measured energy and momentum of each jet, as a function of the pseudorapidity and azimuth of the jet, on the basis of a Monte Carlo analysis, to account for the effect of uninstrumented material and containment losses [4, 5]. Finally, a fiducial cut in azimuthal angle ϕ was used to exclude jets within 30° of the vertical direction, where there is a low trigger efficiency and a large uncertainty in the reconstructed jet energy.

3. RESULTS

The inclusive jet cross-section $d\sigma/dp_T d\eta$ averaged over the pseudorapidity interval $|\eta| < 0.7$ has been calculated from the observed number of jets and normalized to the integrated

luminosity. As the raw event rate has to be corrected for the effects of detector resolution, Monte Carlo studies of the detector were made to determine the jet resolution. By folding the Monte Carlo jet p_T resolution with a steeply falling p_T spectrum from a QCD calculation (described later), a smearing correction factor was obtained. Typical multiplicative corrections range from 0.8 at low p_T (30 GeV) to 0.7 at high p_T (130 GeV). The correction factors are quite similar at $\sqrt{s} = 546$ and 630 GeV. The luminosity was calculated from the rate observed in a pair of scintillator hodoscopes covering the range 12–56 mrad.

The results for the inclusive jet cross-section are presented in table 2 and shown in fig. 1. The errors shown include statistical errors and an energy-dependent uncertainty on the smearing correction. The overall systematic uncertainty in the cross-section is estimated to be $\pm 70\%$. This includes an error of $\pm 50\%$ due to the uncertainty in acceptance functions and jet energy corrections. In addition, there is a $\pm 40\%$ error in the cross-section due to the uncertainty in the calorimeter calibration. The error on the correction of the ageing effects on the calorimeter is estimated to be $\pm 10\%$ and the uncertainty in the luminosity is approximately $\pm 15\%$. The differential cross-section at $\sqrt{s} = 546$ GeV is slightly higher than that obtained in the 1982 Collider run [3]. We attribute the difference to our improved calculations of jet-energy resolution and jet-energy corrections. The present data are in good agreement with similar results at $\sqrt{s} = 546$ and 630 GeV from the UA2 Collaboration [2].

Figure 1 clearly shows the increase in the single-jet inclusive cross-section as $\sqrt{s}$ increases from $\sqrt{s} = 546$ to 630 GeV. Qualitatively, we observe that the difference between the two cross-sections appears to increase with the p_T of the jets. We can compare the inclusive jet cross-section with QCD calculations evaluated at $\eta = 0$ [6]. The curves shown in fig. 1 were calculated from a leading order in α_s , two-parton scattering QCD calculation using the structure functions of Eichten et al. [7]. The scale is defined to be $Q^2 = p_T^2$ and the Λ parameter in the strong coupling constant $\alpha_s(Q^2)$ is $\Lambda = 0.2$ GeV. The QCD calculation gives a good description of the p_T dependence of the data. The best fit to the data requires that the theoretical curves be multiplied by a factor of 1.5, which is within the systematic errors and the accuracy of the calculation. In fig. 1, both curves have been scaled upward by a factor of 1.5. Uncertainties in the Q^2 scale, the QCD scale parameter, the choice of the structure functions, and higher-order corrections, do not allow a greater accuracy than a factor of 2 in the QCD calculations [8].

The ratio of the cross-sections at $\sqrt{s} = 546$ and 630 GeV is shown in fig. 2. Although most systematic errors cancel in the ratio, the uncertainty in the ageing correction in each of the 1983 and 1984 data-taking periods yields a systematic error of $\pm 15\%$. The curve presented is the ratio of the QCD calculations shown in fig. 1 which, within the systematic error, it gives a satisfactory description of the data.

The increase in the cross-section between the two centre-of-mass energies can be accounted for in terms of x_T scaling. Figure 3 shows the dimensionless quantity $p_T^4 E d\sigma/dp^3$ plotted versus $x_T = 2p_T/\sqrt{s}$ for the two different beam energies. On this plot the two sets of data overlap, demonstrating that the observed increase in the cross-section with $\sqrt{s}$ is entirely consistent with perfect scaling. A much larger lever-arm in energy, e.g. $\sqrt{s} = 2000$ GeV (broken curve), would be needed to be sensitive to non-scaling QCD effects, although such effects have been observed previously in ISR experiments [9].

Recently there have been theoretical speculations that quarks and leptons have composite structures, and that they are bound states of more fundamental constituents called preons. Following the model of Eichten et al. [7], the energy scale of compositeness is defined as Λ_c . In this model, values of Λ_c different from infinity (i.e. consistent with ordinary QCD), produce an excess of events in the high- p_T regions of the inclusive jet cross-section. To determine the value of Λ_c , we have renormalized the QCD calculations to the low- p_T region. In all instances, the $\Lambda_c = \infty$

solution gave a good fit to the data. Taking into account theoretical and experimental uncertainties, the lower limit becomes $\Lambda_c > 400$ GeV at the 95% confidence level. This result compares well with the recent limit published by the UA2 Collaboration of $\Lambda_c > 370$ GeV [2]. Recently, limits for the scale of compositeness have been determined from the two-jet angular distribution [10]. The results of that analysis are similar to the limits from the inclusive jet cross-section.

In conclusion, we have presented the inclusive jet cross-section for $p\bar{p}$ collisions at $\sqrt{s} = 546$ and 630 GeV. The cross-sections are found to be well described by QCD calculations. The observed energy dependence of the cross-section is consistent with QCD, and no significant scaling violations are found in the scaled cross-section. The lower limit on Λ_c , the energy scale of quark compositeness, is found to be $\Lambda_c > 400$ GeV (95% C.L.).

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REFERENCES

- [1] M. Banner et al. (UA2 Collab.), Phys. Lett. **118B** (1982) 203.
G. Arnison et al. (UA1 Collab.), Phys. Lett. **123B** (1983) 115.
- [2] P. Bagnaia et al. (UA2 Collab.), Phys. Lett. **138B** (1984) 430.
J. Appel et al. (UA2 Collab.), Phys. Lett. **160B** (1985) 349.
- [3] G. Arnison et al. (UA1 Collab.), Phys. Lett. **132B** (1983) 214.
- [4] G. Arnison et al. (UA1 Collab.), Phys. Lett. **136B** (1984) 294.
- [5] E.J. Buckley and W. Kozanecki, UA1 Technical Note, TN-85-08 (1985).
- [6] J. Stirling, private communication.
- [7] E. Eichten et al., Rev. Mod. Phys. **56** (1984) 579.
- [8] G. Altarelli, preprint CERN TH-3733 (1983).
- [9] T. Åkesson et al. (AFS Collab.), Phys. Lett. **123B** (1983) 133.
- [10] G. Arnison et al. (UA1 Collab.) to be published.

Table 1

Summary of data sets

Run	Integrated luminosity (nb ⁻¹)	Trigger	Off-line threshold	Jet detection efficiency $\geq 90\%$
1983 $\sqrt{s} = 546$ GeV	6	1 jet $E_T \geq 15$ GeV	None	$p_T \geq 24$ GeV
	106	1 jet $E_T \geq 25$ or 30 GeV	1 jet $p_T \geq 30$ GeV	$p_T \geq 40$ GeV
1984 $\sqrt{s} = 630$ GeV	18	2 jets $E_T \geq 15$ GeV each	None	$p_T \geq 32$ GeV
	258	1 jet $E_T \geq 25$ or 30 GeV	1 jet $p_T \geq 40$ GeV	$p_T \geq 48$ GeV

Table 2

Inclusive jet cross-sections

p_T (GeV)	$d\sigma/dp_T d\eta$ (nb/GeV), $ \eta < 0.7$			
	$\sqrt{s} = 546$ GeV		$\sqrt{s} = 630$ GeV	
25	274	± 57		
27	192	± 40		
29	119	± 25		
31	75	± 15		
33	49	± 10	47	± 11
35	30.5	± 6.4	35.9	± 8.1
37	21.5	± 4.6	27.9	± 4.0
39	11.8	± 2.1	19.6	± 2.9
41	9.8	± 1.4	15.2	± 2.2
43	7.5	± 1.1	11.7	± 1.7
45	5.62	± 0.81	8.7	± 1.3
47	4.57	± 0.66	7.1	± 1.1
49	3.44	± 0.50	5.52	± 0.79
51	2.49	± 0.37	4.53	± 0.65
53	2.01	± 0.30	3.45	± 0.49
55	1.36	± 0.21	2.70	± 0.28
57	1.12	± 0.17	1.96	± 0.20
59	0.82	± 0.13	1.47	± 0.16
61	0.60	± 0.10	1.14	± 0.12
63	0.404	± 0.069	0.87	± 0.09
65	0.342	± 0.061	0.625	± 0.070
67	0.300	± 0.054	0.556	± 0.063
69	0.173	± 0.035	0.403	± 0.047
71	0.138	± 0.030	0.348	± 0.042
73	0.114	± 0.026	0.284	± 0.036
75	0.091	± 0.023	0.264	± 0.033
78	0.062	± 0.014	0.142	± 0.018
82	0.032	± 0.009	0.106	± 0.014
86	0.0224	± 0.0072	0.070	± 0.010
92	0.0120	± 0.0037	0.0351	± 0.0051
100	0.0063	± 0.0025	0.0196	± 0.0034
112	0.0039	± 0.0014	0.0055	± 0.0012
130	0.00032	± 0.00032	0.00158	± 0.00050
150	0.00032	± 0.00032	0.00040	± 0.00023

Figure captions

- Fig. 1** The inclusive jet cross-section for the pseudorapidity interval $|\eta| < 0.7$, as a function of the jet transverse momentum. The open dots correspond to the data at $\sqrt{s} = 546$ GeV and the solid dots to those at $\sqrt{s} = 630$ GeV. The systematic errors on both cross-sections is $\pm 70\%$. The curves are QCD calculations and are renormalized upward by 50%.
- Fig. 2** The ratio of the inclusive cross-section at $\sqrt{s} = 630$ GeV to the cross-section at $\sqrt{s} = 546$ GeV. The systematic error on the ratio is approximately $\pm 15\%$. The curve is a ratio of the QCD calculations at $\sqrt{s} = 630$ and 546 GeV.
- Fig. 3** The scaled jet cross-section as a function of the scaling variable $x_T = 2p_T/\sqrt{s}$. The curves are QCD predictions at $\sqrt{s} = 630$ GeV (solid curve) and $\sqrt{s} = 2000$ GeV (dashed curve). The predicted cross-section at $\sqrt{s} = 546$ GeV is very similar to that at $\sqrt{s} = 630$ GeV.

Fig. 1

Fig. 3

Fig. 2