THE JET CROSS-SECTION IN pp INTERACTIONS AT $\sqrt{s} = 45$ GeV AND ITS $\sqrt{s}$ DEPENDENCE*The Axial Field Spectrometer Collaboration*(Brookhaven¹-Cambridge²-CERN³-Copenhagen⁴-Lund⁵-
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ABSTRACT

The differential cross-section for production of jets in pp interactions at $y = 0$ and p_T from 6-12 GeV/c has been measured at $\sqrt{s} = 45$ GeV at the CERN Intersecting Storage Rings and compared with a previous measurement at $\sqrt{s} = 63$ GeV. The data were obtained using a 2.1 sr hadron calorimeter which was triggered on transverse energy. The energy dependence of the jet cross-sections is well described by $(1-x_T)^m \cdot p_T^{-n}$, with $m = 10.6 \pm 1.0$ and $n = 5.3 \pm 0.2$. The results are in good agreement with predictions obtained from a QCD-motivated model.

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Recent calorimeter-triggered experiments [1-3] at $\sqrt{s} = 63$ GeV and 540 GeV have observed an important contribution from jet production at sufficiently large transverse energy. Specifically, the final-state particles are found to be emitted in a solid angle significantly smaller than the acceptance of the triggering calorimeters. Such events are interpreted in terms of hard scattering of the hadron constituents, and provide a relatively unbiased way of studying deep-inelastic hadron-hadron scattering [4]. However, similar experiments at lower $\sqrt{s}$ [5] did not find jet production to be dominant, even at the highest accessible E_T . This can be explained in terms of contamination of the jets by beam fragmentation [6] and significant smearing of the hard scattering by gluon bremsstrahlung [7].

The energy ($\sqrt{s}$) dependence of the jet production cross-section is clearly of interest, and in this paper we report on measurements at $\sqrt{s} = 45$ GeV which complement our recent 63 GeV data [1,2]. The 45 GeV data were taken with the same apparatus and processed with the same off-line analysis chain as the 63 GeV data, which enables us to minimize the experimental systematic uncertainties. In addition, we relate our measurements to the jet cross-section from $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV.

The results were obtained using the Axial Field Spectrometer (AFS), which was triggered on large transverse energy E_T , deposited in a 2.1 sr uranium/copper scintillator calorimeter consisting of 192 towers (see fig. 1). The calorimeter, trigger, and tracking system of the AFS have been described elsewhere [1,8]. For this analysis, only the roof calorimeter was used in the trigger. The energy resolution is $16\%/\sqrt{E}$ for electromagnetic showers and 30% at 1 GeV ($37\%/\sqrt{E}$ above 2 GeV) for hadronic showers. The estimated uncertainty in our absolute energy scale for isolated showers is 4%. For the analysis, a fiducial volume of 1.7 sr covering $\pm 36^\circ$ (32°) in azimuth for electromagnetic (hadronic) showers and ± 0.93 in rapidity (y) was used.

The trigger was formed by the addition of the pulse heights detected in the calorimeter, with each signal suitably weighted to transform to transverse energy (E_T) in the centre-of-mass system. In addition we required a minimum multiplicity

of 2 hits in the 44-element hodoscope (IH) surrounding the interaction region. Upstream and downstream counters (BB), covering $2^\circ < \theta < 6^\circ$ in polar angle, were used to monitor the luminosity. The integrated luminosity for the $\sqrt{s} = 45$ GeV data was $1.23 \times 10^{35} \text{ cm}^{-2}$, and the average luminosity during data-taking was $6.3 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.

The data obtained were processed through our standard tracking and vertex reconstruction programs for charged particles in the central detector. We removed background from beam-gas events, cosmic-ray events, and pile-up, using the same procedure as in ref. 1, with an additional requirement on timing of the local energy deposit in the calorimeter. This new requirement, when imposed on the 63 GeV data [1], removed 3% of the events with $E_T > 12.5$ GeV. When imposed on the present data it removed 7% of the events with $E_T > 10.5$ GeV and less than 1% of the events at lower E_T . At the highest E_T , all these cuts removed 35% of the raw data, and we estimate a residual background contamination of less than 5%.

For the analysis of the calorimeter information, we used a pattern recognition program to reconstruct individual showers, with a spatial resolution of 1 cm for electromagnetic showers and 3-10 cm (depending on the incident angle) for hadronic ones. The transverse energy E_T was calculated by summing the transverse energy of the individual showers. Only events with more than 85% of their E_T in the fiducial volume were used. The E_T spectra for the two centre-of-mass energies are shown in fig. 2. The spectra are uncorrected for resolution, effects of energy leakage, and different calorimeter response to hadronic and electromagnetic showers. The errors shown are statistical only.

The data were divided into bins of E_T to study the spatial distribution of energy in the calorimeter wall. For each event a vector sum $\vec{E}'$ was formed by summing the highest energy clusters, making up $\geq 80\%$ of the E_T in the wall. Events were accepted if, in the laboratory frame, $\vec{E}'$ pointed to within $\pm 25^\circ$ in azimuth, and $\pm 30^\circ$ in polar angle, of the centre of the wall. Over 80% of the events satisfy these requirements. For these selected events, all the clusters in the wall were then used to calculate a quantity analogous to thrust T :

$$T = \sum \hat{E}' \cdot \vec{E}_i / \sum |\vec{E}_i| ,$$

where sums were carried out over all clusters; $\hat{E}'$ is the unit vector along $\vec{E}'$, and $\vec{E}_i$ are the individual cluster energy vectors; T is not explicitly maximized by variation of the $\hat{E}'$ direction and can take on values between 0.7 and 1.0. A pencil-like jet has $T \approx 1$, and highly isotropic events have $\langle T \rangle \approx 0.86$. The minimum value of T , $T = 0.7$, corresponds to an event with maximally separated showers within the calorimeter wall.

In fig. 3 we show $\langle T \rangle$ as a function of E_T for both $\sqrt{s} = 45$ and 63 GeV. For the lower E_T bins the average thrust is consistent with that expected for isotropic events ($\langle T \rangle \approx 0.86$); however, there is a clear rise in $\langle T \rangle$ as E_T increases. In fig. 4 we show the thrust distributions for a few E_T bins for both values of $\sqrt{s}$. The shape of the thrust distributions at the two energies are quite different at the highest values of E_T . Both data sets clearly deviate from what is expected for isotropic events by building up a high-thrust component. However, at $\sqrt{s} = 45$ GeV, this component does not dominate to the same degree as it does at $\sqrt{s} = 63$ GeV.

In order to obtain a jet cross-section, the fraction of events consistent with a hard-scattering constituent model is extracted from the shapes of the thrust distributions. This technique worked well for the $\sqrt{s} = 63$ GeV data, where clear evidence for the two components was observed in the thrust distribution. This is less evident in the $\sqrt{s} = 45$ GeV data, but for the purpose of comparison we use the same technique. Events with and without a hard-scattering constituent are generated using ISAJET [9], passed through a full simulation of the calorimeter response [10,11], and processed through our normal analysis chain.

ISAJET produces events using standard QCD perturbation theory in the leading log approximation. The events are composed of two high- p_T jets and two beam-jets fragmenting according to the Feynman-Field model [12]. The jet production and fragmentation are decoupled. The parton structure functions used are those of Baier et al. [13]. In the fragmentation process of high- p_T partons, a hard gluon may be emitted.

In the fit we assume that the thrust distributions have two components. The first component (jet) is described by hard-scattering constituents. The second component (non-jet) has a more isotropic event shape with a thrust distribution essentially the same as that observed for the events in the low E_T bins. In this paper we do not attempt to investigate further the detailed nature of the events attributed to the non-jet component.

Using these two components we fit the thrust distribution to obtain the relative jet-to-non-jet contribution in each E_T bin. As stated earlier, the results show a higher percentage of jet events for a given E_T bin at $\sqrt{s} = 63$ GeV. As $\sqrt{s}$ decreases and if this trend continues, the separation of the jet fraction from the rest of the events, using this or a similar method, will become more difficult [6].

Using the ISAJET Monte Carlo events and the detector simulation described above, we were able to relate the initial jet p_T to the E_T detected in the calorimeter. This together with the fit results enables us to transform the observed E_T spectrum into the p_T spectrum of the produced jet. The resulting inclusive jet production cross-section at $y = 0$ is shown in fig. 5 together with the results obtained at $\sqrt{s} = 63$ GeV [1] (see also Table 1). The inner errors reflect the statistical error of the fit and correction procedure. The outer errors include systematics, uncertainties in luminosity ($\pm 4\%$), model dependence of the Monte Carlo and representation of the detector (3.5% to 2%), and uncertainties in the energy scale (5% to 3.5%). An exponential fit, $\exp(-bp_T)$ at $\sqrt{s} = 45$ GeV gives a value for $b = 1.35 \pm 0.14$ GeV $^{-1}$, which is steeper than the observed slope 1.02 ± 0.09 GeV $^{-1}$ at $\sqrt{s} = 63$ GeV. The dotted lines in fig. 4 are the ISAJET predictions for the jet cross-section. The agreement in both shape and absolute normalization is good.

To parametrize the cross-section as a function of energy, we have fitted our data to a function of the form $A(1-x_T)^m \cdot p_T^{-n}$ (where $x_T = 2p_T/\sqrt{s}$) which has previously been used to fit single-particle high- p_T cross-sections. The results of the fit give values of $A = (1.6 \pm 1.0) \times 10^{-26}$, $m = 10.6 \pm 1.0$, and $n = 5.3 \pm 0.2$,

where only the statistical errors are included. Since one expects that at low- x_T the pp and $p\bar{p}$ jet cross-sections will be essentially the same, we also compare our results with the $p\bar{p}$ data at $\sqrt{s} = 540$ GeV [3]. In fig. 6 we show the three measurements of the jet cross-section as a function of x_T multiplied by p_T^n , where $n = 5.3$. The dotted line in fig. 6 shows the π^0 cross-section [14] multiplied by p_T^n ($n = 8$). It can be seen that the shape of the resulting x_T dependence is similar for both jet and π^0 cross-sections. A possible interpretation is that the $f(x_T)$ describes the convolution of the proton constituent structure functions, which is expected to be similar for jet and single-particle production, whilst the difference in the p_T power can be attributed to the fragmentation.

In this paper we have reported on the jet cross-section at $\sqrt{s} = 45$ GeV. The jet differential cross-section is lower and steeper at $\sqrt{s} = 45$ GeV than at $\sqrt{s} = 63$ GeV. The observed fraction of events at a given E_T , which are clearly dominated by jet production, is lower at $\sqrt{s} = 45$ GeV than at $\sqrt{s} = 63$ GeV. If this trend continues, the identification and separation of the jet component at lower $\sqrt{s}$ will become increasingly difficult. At both energies, the shape and the magnitude of the measured cross-section are well described by a QCD-motivated model.

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Table 1

Cross-sections for single inclusive jet production.
Errors include both statistics and systematic effects.

$\sqrt{s} = 45 \text{ GeV}$		$\sqrt{s} = 63 \text{ GeV}$	
$p_T \text{ (GeV/c)}$	$E \, d\sigma/dp^3 \text{ (cm}^2/\text{GeV}^2)$	$p_T \text{ (GeV/c)}$	$E \, d\sigma/dp^3 \text{ (cm}^2/\text{GeV}^2)$
6.4	$(3.04 \pm 1.45) \times 10^{-32}$	6.66	$(7.02 \pm 2.35) \times 10^{-32}$
7.6	$(3.86 \pm 0.85) \times 10^{-33}$	7.96	$(1.07 \pm 0.45) \times 10^{-32}$
8.7	$(7.62 \pm 2.58) \times 10^{-34}$	9.16	$(3.61 \pm 0.69) \times 10^{-33}$
9.4	$(3.90 \pm 1.17) \times 10^{-34}$	10.46	$(8.84 \pm 1.80) \times 10^{-34}$
11.0	$(4.68 \pm 2.47) \times 10^{-35}$	11.46	$(2.42 \pm 0.47) \times 10^{-34}$
		12.85	$(9.00 \pm 1.33) \times 10^{-35}$

Figure captions

- Fig. 1 : Experimental set-up.
- Fig. 2 : The uncorrected transverse energy spectrum; error bars are statistical only.
- Fig. 3 : Mean thrust versus E_T .
- Fig. 4 : The fraction of events per 0.02 units of thrust for bins in E_T for $\sqrt{s} = 45$ GeV (a-d) and for $\sqrt{s} = 63$ GeV (e-h). Shaded region represents the contribution of the jet component; the solid curve shows the total fit.
- Fig. 5 : Invariant jet cross-section at $y = 0$ versus p_T . Outer errors include systematic effects. The dotted lines are theoretical predictions [9].
- Fig. 6 : The invariant jet cross-section multiplied by $p_T^{5.3}$ versus x_T , including the data of ref. 3. Also shown is the π^0 cross-section at $\sqrt{s} = 63$ GeV [14] multiplied by p_T^8 .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6