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Measurement of the Di-jet Cross Section in 400 GeV pp Collisions

E-609 Collaboration

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Abstract

The invariant cross section for production of jet pairs in 400 GeV/c pp interactions has been measured as a function of p_T in the p_T range 4 to 9 GeV/c. The results are in good agreement with predictions of perturbative QCD models.

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A principal goal of the study of jet production in hadronic interactions is measurement of the dijet cross section, which is expected to reflect directly the underlying parton-parton scattering. Only recently has clear evidence for jet production in hadronic interactions emerged; such evidence is visually striking at the 540 GeV center of mass energy of the CERN collider[1,2] and is also clear at the highest ISR energies.[3]

It is important to have measurements of jet cross sections, for comparison with theory, over a wide energy range. At FNAL/SPS fixed target energies the observation of jets is more complicated [4,5] than at CERN $\bar{p}p$ collider energies. As we have previously shown,[6] however, jets can be clearly detected at these lower energies. Here we present a measurement of the dijet cross section as a function of p_T in pp interactions at $\sqrt{s}$ = 27.4 GeV. Limitations of space preclude giving a detailed exposition of all the issues involved in measuring the cross section. We present here an outline of the method used to extract the cross section and discuss the results. A detailed description of the analysis will be given in a comprehensive article.[7]

The data were acquired with the E-609 apparatus at Fermilab, which has been described previously.[6] The 400 GeV/c proton beam was incident on a liquid hydrogen target. The heart of the apparatus consisted of a large aperture, full azimuth, segmented calorimeter.[8] The calorimeter was composed of 132 towers that roughly pointed to the target, each consisting of a lead-scintillator module and 3 iron-scintiallator modules. The calorimeter array covered from 30 degrees to 120 degrees in CM polar angle.

The apparatus was triggered by requiring a minimum amount of transverse energy (E_T) in some region of the calorimeter array. Several types of such E_T triggers were used, but the results presented here are from a somewhat different trigger that we call the two-high trigger. This trigger required that the E_T of any two towers anywhere in the array each be greater than about 1.5 GeV, a value chosen to be high enough to reject non-jetlike events and low enough to avoid collecting only jets that fragment mainly into a single high-p_T particle. This trigger makes use of the entire calorimeter, is geometrically unbiased, and is efficient for high-p_T jets.

The pattern of energy deposition in the calorimeter array was unfolded to determine the momenta of particles striking the calorimeter. The p_T scale was determined by steering hadron beams into the calorimeter and is known to ±7%.

The determination of the jet cross section requires several steps. One must first identify the jet events in the data and determine how many of them are real and how many due to fluctuations in non-jet events. Then the efficiency for triggering the apparatus must be determined. These steps were optimized with the help of a Monte Carlo model that has been described briefly previously[9] and will be discussed in detail in a work now in preparation.[10] This program generates complete events consisting of two high-p_T jets and beam and target jets. The events are generated according to the first order QCD cross section, with the momentum transfers $\hat{t}$ and $\hat{u}$ in the scattering process allowed to be as small as 1.0 $(\mathrm{GeV}/c)^2$.

The jet fragmentation is accomplished according to the prescription of Field and Feynman.[11] The particles are propagated to the calorimeter and a complete simulation of the calorimeter response is made. The program does well in reproducing several features of real data, most notably the non-jetlike nature of events selected using the global E_T trigger.

Jets were identified in the experimental data by means of a jet-finding algorithm which iteratively searched for concentrations of p_T within a cone of fixed half angle in the center of mass. The half angle of the cone was chosen to be 55 degrees in order to achieve agreement between the number of jets generated in the Monte Carlo model and the number found by the algorithm when applied to Monte Carlo events. The chosen value represents a balance between loss of p_T from jet fragments lying outside of the cone and gain of p_T from beam and target jet fragments included in the cone. A fiducial range of 60 degrees to 100 degrees in CM polar angle was used.

The jet finding algorithm is not restricted as to how many jets it is allowed to find. We take for the jet-p_T of the event the average p_T of the two highest p_T jets. In about one-third of the events a third, low p_T, jet is found. Figure 1(a) shows the difference of the p_T's of the two highest p_T jets for data events with average jet-p_T greater than 4 GeV/c. The algorithm makes no requirement on the azimuthal angles of the jets. Figure 1(b) shows the difference in azimuth between the two highest p_T jets in the data. These results show that the events found by the algorithm have the properties expected of dijet events, coplanarity and p_T balance.

Not all events found by the jet-finder are necessarily jets; some may be background due to random fluctuations of non-jet events. We have used several methods to estimate the magnitude of this background as a function of jet-p_T. Two model-independent methods were used.[6,7] The first involves randomizing the directions of the particles in real events subject to the constraint that the overall transverse momentum unbalance of the event be preserved. The jet finder is then applied to the randomized events and the number of events found at each p_T compared to the original data. Column 2 of Table I shows the background fraction as found by this method. For jet-p_T's greater than 5 GeV/c an increasing number of the events are real jets. This method gives only an upper limit for the background, since some coalesced particle showers in the actual events will give apparent particle energies which are incorrectly high. We applied the same analysis to Monte Carlo events. The Monte Carlo results, shown in column 3 of Table I, indicate that indeed the background is overestimated.

The second model-independent method involves generating random events with the same single particle p_T distribution, angular distributions, and p_T balance as real events in the appropriate global E_T range, and examining the number of jets found in the sample. The results for jet-p_T's greater than 4 GeV/c are shown in column 4 of Table I. They indicate no background above 6 GeV/c and little background above 5 GeV/c.

A third method, model dependent, which was the method we actually used to correct the data for non-jet background, is simply to compare the number of jets found in our Monte Carlo model with the number originally generated. For

low p_T jets the jet finder finds more jets than were generated; the excess comes from low p_T jets in combination with fragments from the beam and target jets. The results of this method are shown in column 5 of Table I. Figure 2 shows the planarity distribution of the real data for various bins of jet-p_T. Planarity should peak near 1 for jet events. Figure 2 is consistent with backgrounds of order 50% in the 3 to 4 GeV/c bin decreasing to essentially no background above 5 to 6 GeV/c.

The di-jet trigger efficiency calculated from the Monte Carlo model increases monotonically from 10% at 4 GeV/c to 90% at 8 GeV/c. Reasonable variations in the Monte Carlo parameters or in the shower spreading parameters in the calorimeter, or use of an alternative Monte Carlo, ISAJET,[12] produce only modest changes in the efficiency-vs-p_T curve.[7]

Our experimental results for the invariant cross section $d\sigma/dp_T^2 dy_1 dy_2$ at $y_1 = y_2 = 0.18$ (80 degrees in the CM) are shown in Figure 3. The inner error bars are statistical and the outer error bars include the systematic errors. The systematic errors on the 3.5 GeV/c point are very large. Excluding the 3.5 GeV/c point a fit of the data to the form Ae^{-Bp_T} yields $A = (2.7 \pm 1.0)\ 10^{-28}$ and $B = 1.74 \pm 0.06$.

We know of no previous measurements of the dijet cross section with which we can directly compare our results. (There have been however several published results on the single jet cross section,[1,2,3] and also a determination of the angular dependence of dijet production.[13]) In Figure 3 we show comparisons with several theoretical curves calculated[7] using the

parton model and first order QCD. The cross section is proportional to the product of projectile and target structure functions and the sub-process differential cross sections, summed over all parton types.[14] The values of x_1, x_2 and $\hat{t}$ at which the structure functions and scattering cross sections are evaluated are derived from p_T, y_1 and y_2. For Q^2 we chose the form $(\hat{s}\hat{t}\hat{u})^{1/3}$, but other choices make little difference. The choice of structure functions remains, especially the gluon structure function which is the least well known. The curves in Figure 3 show several choices of structure functions.[15,16,17]

In general the agreement of the data with these theoretical calculations is quite good. This is especially true in view of the 7% uncertainty in the p_T scale. It should be relatively straightforward to compare our experimental results with more refined theoretical models.

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Figure Captions

Figure 1(a) The absolute value of the difference in p_T between the two highest p_T jets found in the event for data events with average jet-p_T greater than 4 GeV/c. (b) the difference in azimuth between the two jets.

Figure 2. Planarity distributions of the data for six bins of jet-p_T, indicated by the numbers on the plots.

Figure 3. The invariant cross section for dijets versus p_T. The inner error bars are statistical and the outer error bars include systematics. The curves show theoretical predictions of first order QCD. The different curves use different sets of proton structure functions. The solid curve is based on Ref. 15. The dotted curve uses the "counting rule" form and the dashed curve the "dynamical QCD" form of Ref. 16. The dot-dashed and dot-dot-dashed curves are based on the two sets of structure functions of Ref. 17.

Table Caption

Table I. Fraction of non-jet background as a function of p_T from various methods described in the text.

Table I

Estimates of non-jet background fraction

jet-p_T GeV/c	randomized data	randomized Monte-Carlo	single-particle Monte-Carlo	Monte-Carlo
3-4	1.17 ± 0.03	0.58 ± 0.21	---	0.53 ± 0.07
4-5	1.08 ± 0.03	0.75 ± 0.12	0.27 ± 0.03	0.48 ± 0.05
5-6	0.91 ± 0.04	0.40 ± 0.11	0.12 ± 0.03	0.34 ± 0.17
6-7	0.54 ± 0.05	0.61 ± 0.14	0	0
7-8	0.39 ± 0.08	0.28 ± 0.15	0	0
8-9	0.17 ± 0.09	0.17 ± 0.05	0	0

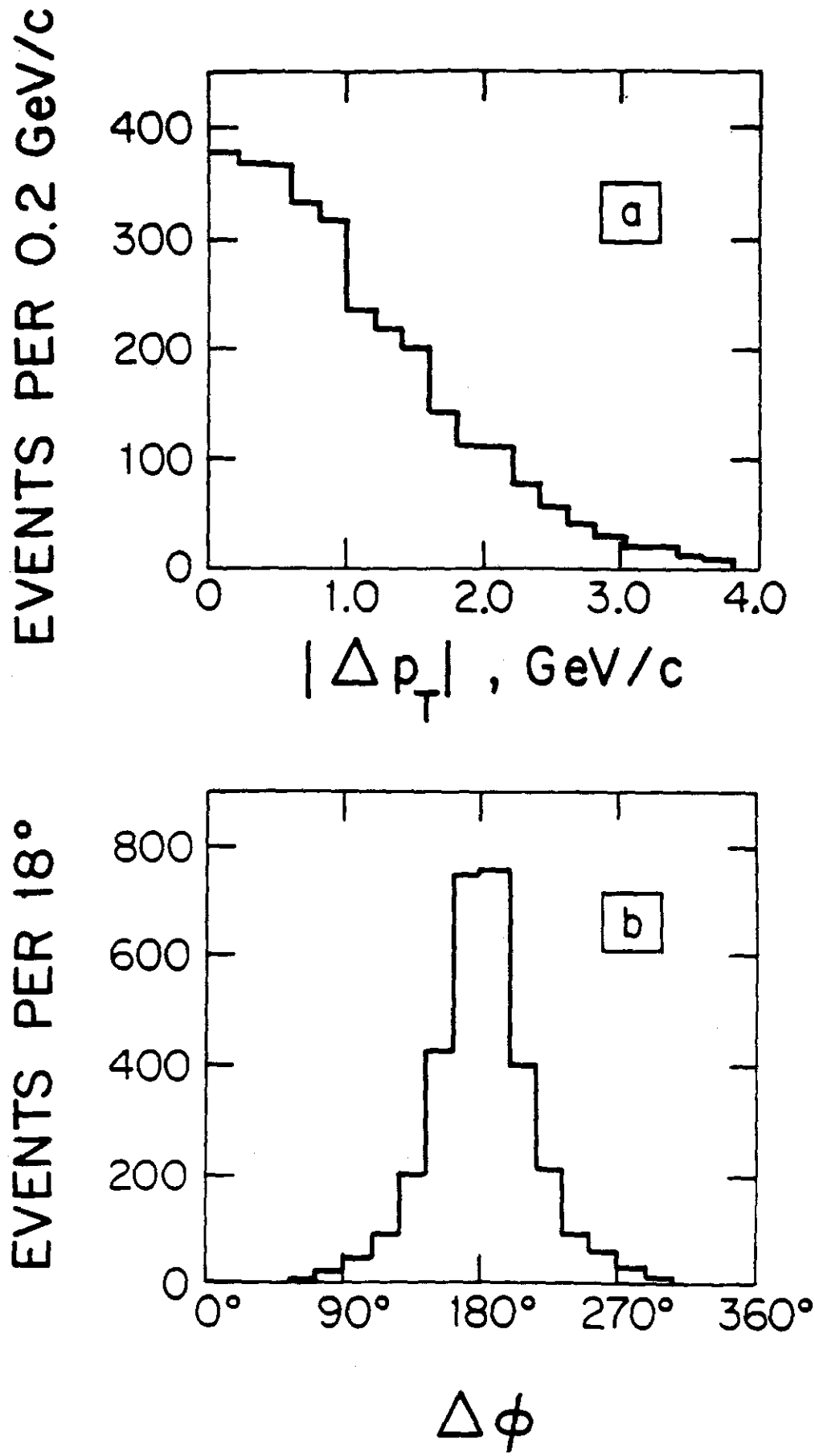
EVENTS PER 0.2 GeV/c
400
300
200
100
0
a
0
1.0
2.0
3.0
4.0
|Δp_T| , GeV/c
EVENTS PER 18°
800
600
400
200
0
b
0°
90°
180°
270°
360°
Δφ

FIGURE 1

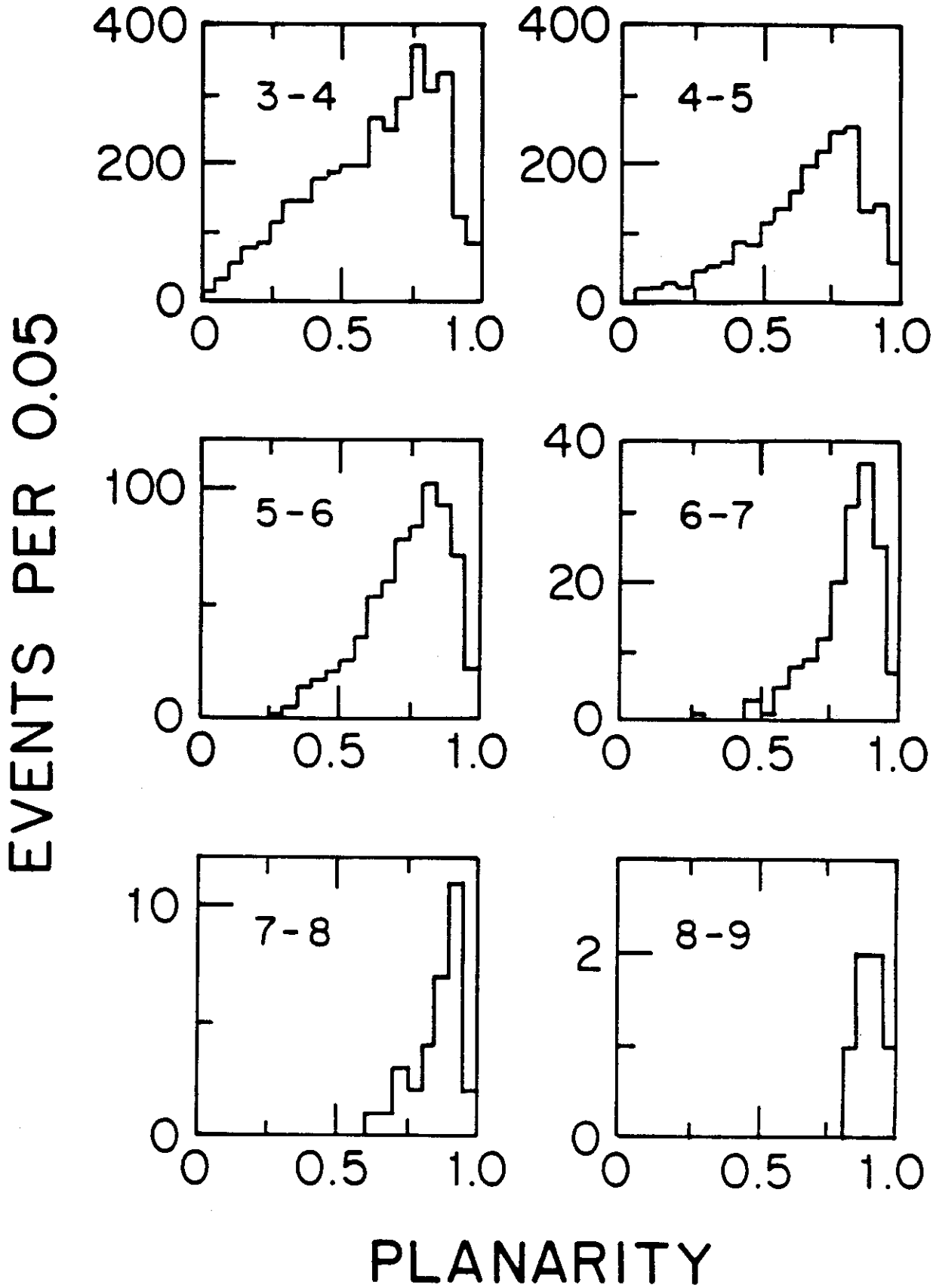
EVENTS PER 0.05
PLANARITY
3-4
4-5
5-6
6-7
7-8
8-9
400
200
0
100
40
20
10
2
0.5
1.0

FIGURE 2

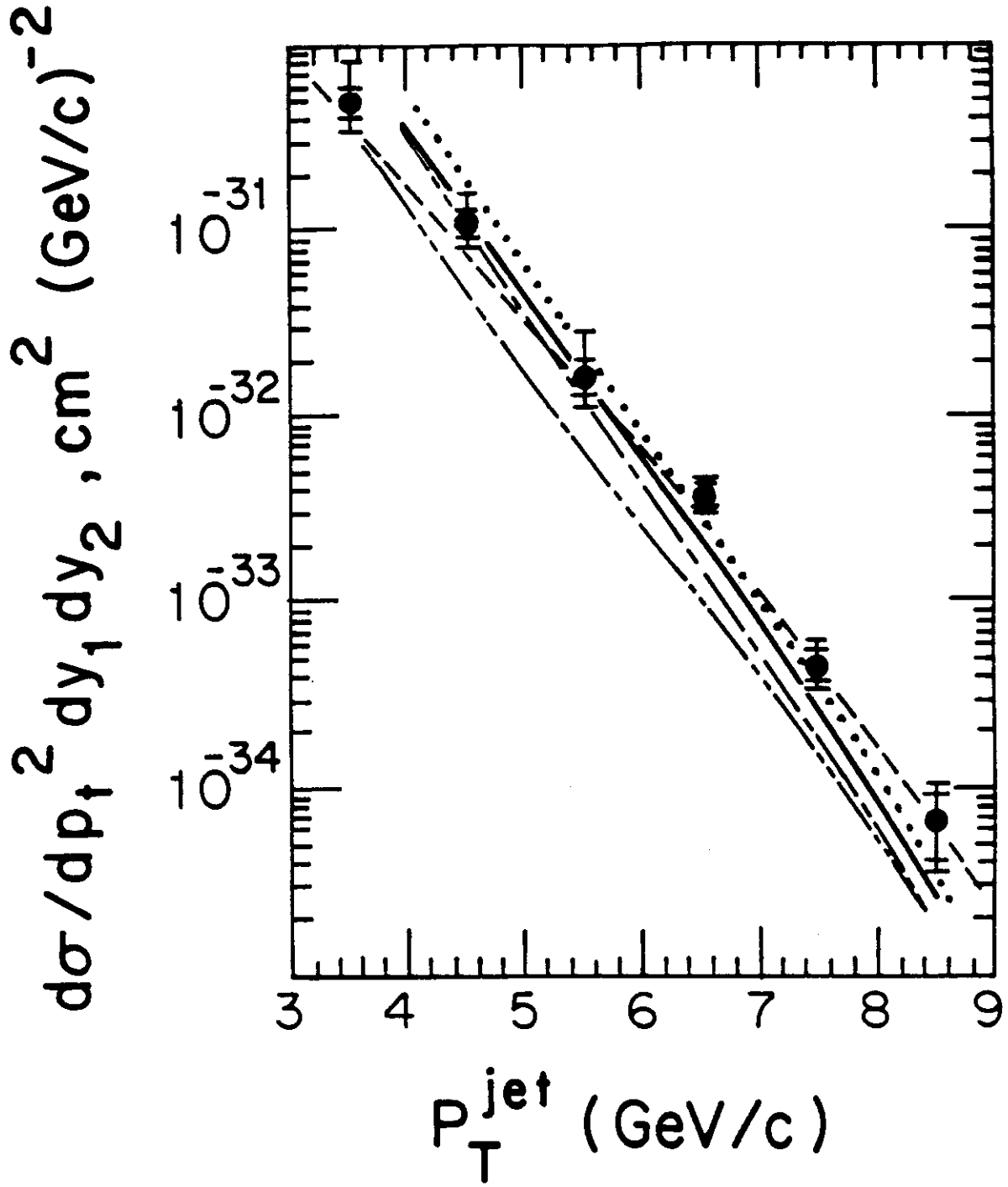
$d\sigma/dp_t^2\,dy_1\,dy_2$, cm^2 $(GeV/c)^{-2}$
10^{-31}
10^{-32}
10^{-33}
10^{-34}
3
4
5
6
7
8
9
P_T^{jet} (GeV/c)

FIGURE 3