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# Observation of the Production of Jets of Particles at High Transverse Momentum and Comparison with Inclusive Single Particle Reactions*

by

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## ABSTRACT

Data are presented on production from 200 GeV/c hadrons incident on beryllium of both single particles and jets (groups of particles) with high $p_\perp$ (transverse momentum). The experiment was performed in a wide aperture multiparticle spectrometer at Fermilab. The jet and single particle cross sections have a similar shape from $p_\perp = 3$ to 5 GeV/c but the jet cross section is over two orders of magnitude larger. The distributions of charged particle momenta show striking similarities to those observed in lepton induced processes.

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Interest in high $p_\perp$ physics was originally stimulated by the observation of unexpectedly large yields of single particles for $p_\perp \geqslant 3$ GeV/c[1]. The motivation of our experiment is to shed light on the dynamics of these rare processes by studying both the particles produced in conjunction with a single high $p_\perp$ particle and the structure of events in which high $p_\perp$ is found as the sum of the transverse momenta of several particles. The data presented in this letter are the result of an initial run at Fermilab and details of the apparatus and additional data will be presented elsewhere[2].

The spectrometer is shown schematically in Fig. 1. Beam particles with momentum 200 GeV/c struck a beryllium target either 3 or 6 cm. thick. Charged particles emerging from the target at lab angles $\leqslant 150$ mr. and momenta $\geqslant 2$ GeV/c were analyzed by track chambers and the spectrometer magnet which was set to give a transverse momentum kick of .38 GeV/c. Behind the last track chamber were two calorimeters, each divided into four separate modules. The modules consisted of a front section comprised of six alternating layers of .25" scintillator and .56" lead, totaling about 15 radiation lengths or about 0.5 nuclear absorption lengths, and a rear section comprised of 15 layers of .25" scintillator and 2" iron, totaling about 4.5 absorption lengths. The lead ("electron") sections and iron ("hadron") sections were viewed by separate phototubes. In addition each module was viewed at the top and bottom. Pulse height analysis gave a measure of the energy and mean vertical position of the interactions.

Event triggers for the experiment were derived from the calorimeter module signals, weighted by their mean lab angle so that they were an approximate measure of transverse momentum. Two types of trigger were used, which we have called "single particle" and "jet." For the former, it was required that the sum of the transverse momentum in the electron and hadron sections of any individual module be greater than a preset trigger bias of 3 GeV/c. The jet trigger demanded that the total transverse momentum of all four modules of either calorimeter was above a preset level: data with thresholds of 3, 4 and 4.5 GeV/c were used in this analysis. In Fig. 1, the jet trigger $p_\perp$ is 5.31 GeV/c in the right side calorimeter.

The mean number of reconstructed tracks which come from the beryllium vertex and pass through the magnet is about ten for jets and one less for single particle triggers. Furthermore the chambers in front of the magnet measure, on the average, 4-5 additional charged particles per event which are outside the magnet acceptance. Individual spark chamber gap efficiencies are estimated at 90% up to multiplicities of 15 and the overall efficiency of track finding, away from the beam direction, is estimated to be 95 ± 5%. The number of spurious high transverse momentum tracks is shown to be small both by comparing calorimeter and track energies and also by the lack of a high momentum tail in our charged particle $p_\perp$ spectrum. The momentum resolution of the track chambers is $\Delta p/p^2 = .0007\ \mathrm{GeV}^{-1}$. For the calorimeters we measure an energy resolution $\Delta E/E$ of $.33/\sqrt{E}$ for electron and $1.03/\sqrt{E}$ for hadron modules (standard deviations, E in GeV).

The "single particle" trigger is straightforward to analyze. Taking events with a single particle track with $p_\perp > 2$ GeV/c, we find the acceptance corrected invariant cross section plotted in Fig. 2 using a sample of the events in which the track enters a fiducial region in the middle of the calorimeter. Our data can be directly compared to the more precise measurements of the Chicago-Princeton3) collaboration and there is good agreement above the calorimeter trigger threshold of 3 GeV/c.

The novel feature of our experiment is the "jet" trigger defined above. The contributions to jet $p_\perp$ divide into three categories: (i) charged particles (typical multiplicity three) measured by the track chambers and comprising 57% of the jet momentum4); (ii) photons (presumably from $\pi^o$, $\eta$, etc. decay) measured in the "electron" calorimeter and making up 30% of the jet momentum; and (iii) neutral hadrons or apparent neutrals. These latter are deduced by subtracting the charged track energies from the hadron calorimeter signals module by module; the resultant resolution in energy is poor because of the subtraction and modest calorimeter resolution. This third category includes neutrons, $K_L^o$ and non-vertex tracks ($K_s^o$, $\Lambda$ and reconstruction losses) and we find it carries between 6 and 24% of the jet $p_\perp$ with 13% as our best estimate. The jet cross section presented in Fig. 2 has been corrected for geometric acceptance but not for the trigger bias of the calorimeter. However comparison of the three trigger thresholds shown in Fig. 2 allows us to extract an unbiased jet cross section shown as the broad solid line. The uncertainty in the hadronic neutral component discussed above, leads to a cross section uncertainty of ±30% ($p_\perp = 3$ GeV/c) to ±50% ($p_\perp = 5$ GeV/c) not indicated in Fig. 2. The simplest analysis of the jet $p_\perp$ which uses the raw calorimeter pulse heights, gives a jet cross section which has a similar shape to that plotted but lies a factor of three higher in normalization.

Independent of the uncertainty in the hadronic neutral estimate, the striking feature of Fig. 2 is the very large (over two orders of magnitude) ratio of jet to single particle cross section. This result had been predicted in models5,6,7) which postulate that large $p_\perp$ hadrons come from the fragmentation of quarks produced in an elementary hard collision between constituent quarks in the initial hadrons. Note that there are no clear resonance signals in our jet data and the large jet cross section is not simply due to a sum of low mass resonances.

Motivated by the constituent models, we define the "jet plane" as that plane formed by the jet momentum vector and the direction of the incident hadrons and plot in Fig. 3 the transverse momentum fraction $z = p_{x'}/p_\perp^{JET}$, where $p_\perp^{JET}$ is the transverse momentum of the jet and $p_{x'}$, is the component of the transverse momentum of individual charged particles in the jet plane. There is a striking similarity between our z distributions and those for lepton induced processes7,8). Furthermore our data shows evidence for the coplanar structure of events suggested by constituent models. For the charged particles (both jet and non-jet members) in these events we find a sharp exponential dependence with a mean of 0.20 GeV/c for the component of the transverse momentum out of the jet plane. Also the two dimensional momentum perpendicular to the jet axis is strongly cut off for the jet members. In Ref. 2, we explore fully these points and the relation of our experimental jet definition to theory.

Finally Fig. 4 shows the momentum distribution of charged particles on the away side (cf. Fig. 1). The first striking feature is that these away side particles balance the transverse momentum of single particle and jet triggers in a similar way. This is expected in the quark picture[7,9] but seems difficult to understand in the constituent interchange model[10]. Again the away and trigger (towards) side z distributions have similar shapes but differ by a factor ~ 2.5 in magnitude at large z. In constituent models, this difference is a direct reflection of the transverse momentum of quarks inside hadrons[9].

Our data gives strong support to the idea that the same constituents (quarks presumably) are probed by both high $p_\perp$ hadron and lepton collisions. We are currently continuing our analysis on the completed experiment which has ten times the data presented here, taken with a liquid hydrogen target and incident proton and meson beams.

We are grateful for the assistance given to us by the staffs of the Accelerator Division, the Meson Department, and the Research Services Department at Fermilab.

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## References and Footnotes

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## Figure Captions

**Fig. 1** Plan view of the spectrometer, with the transverse dimensions magnified by a factor of 4. The tracks from a typical event are also shown. A, B, C, D, and F' indicate proportional planes, while E and F are spark chambers. A 22 cell gas Čerenkov counter between the E and F stations is omitted for clarity.

**Fig. 2.** The single particle and jet cross sections averaged over the cms rapidity y region .1 to .44. The jet definition as all particles into the calorimeter is described in the text while the plotted data is an average of equal amounts of $\pi^-$ and proton beam. The jet cross sections for the separate beam types $\pi^-$, p are equal to within 20% for $4 < p_\perp^{JET} < 5$ GeV/c. The single particle data corresponds to a proton beam only and the Chicago-Princeton results[3)] were taken at a lab angle of 77 mrad ($y \approx 0.25$) and have been summed over all charged particles for comparison with **our data.**

**Fig. 3** The distribution in transverse momentum fraction z for individual charged particles is shown for three jet $p_\perp$ ranges. It is compared with the analogous distribution from neutrino scattering[7,8)]. The uncertainty in hadronic neutral component leads to a systematic uncertainty not shown in figure which is at most 20% and takes this extreme value for $z \geqslant 0.6$ and $4 < p_\perp^{JET} < 5$ GeV/c.

**Fig. 4** Distributions in momentum fraction z for particles on the away side for both jet and single particle triggers. The shifting of scale for single particles is motivated by the quark model[7,9)] which suggests single particles carry from 80 → 90% of the momentum of the high $p_\perp$ quark (jet). The data is integrated over the whole away side and includes a correction for spectrometer acceptance which is valid for the higher momentum particles, $z \geqslant 0.25$.

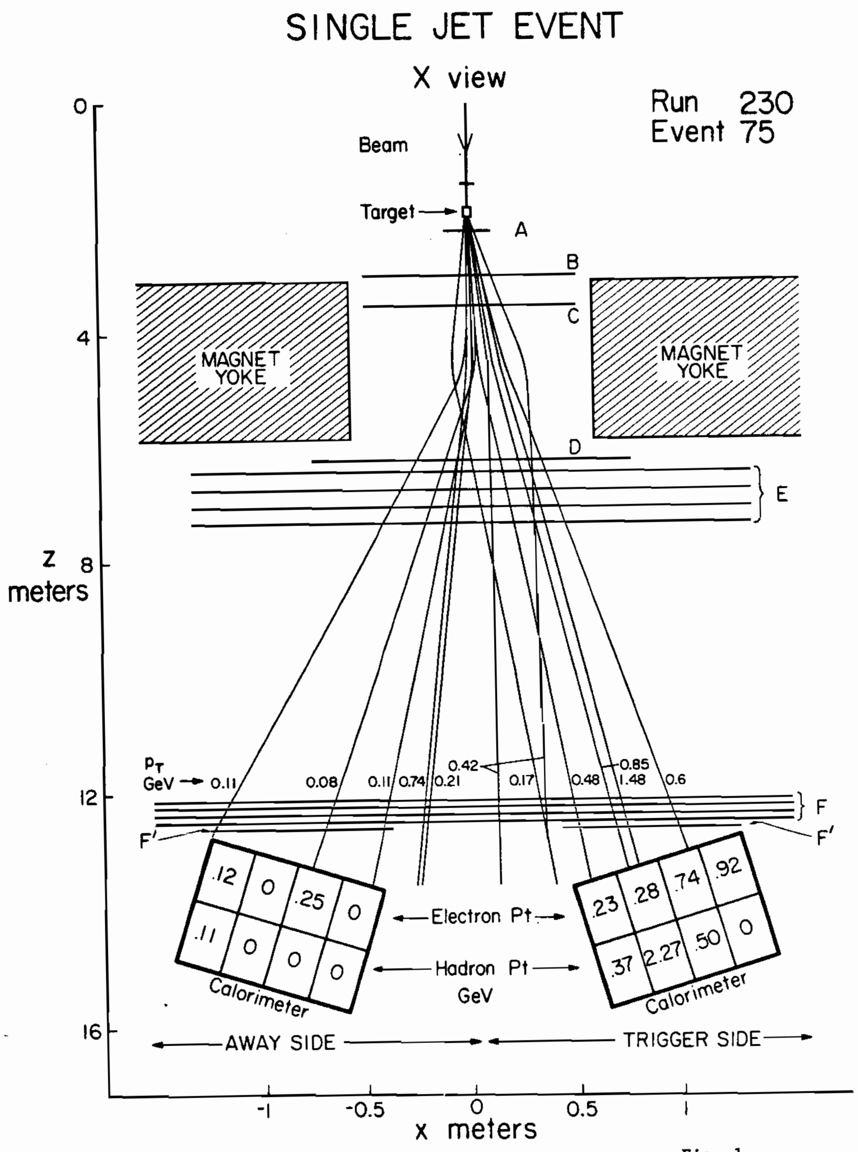
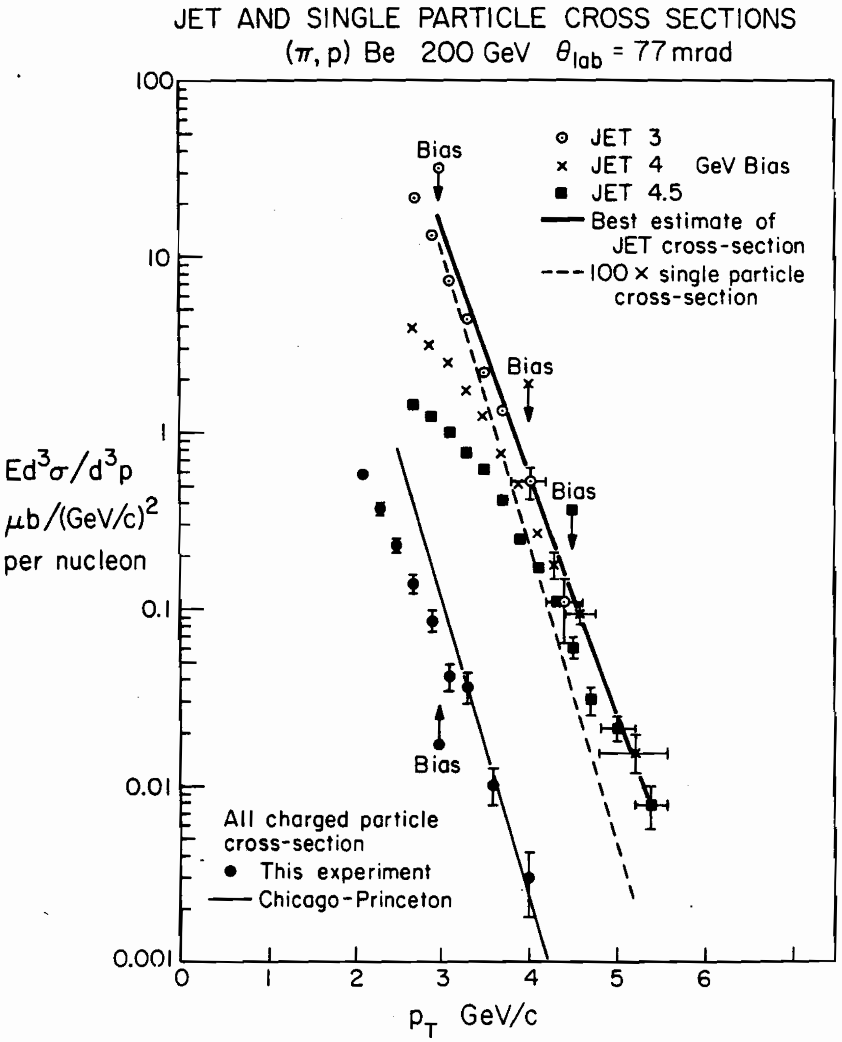
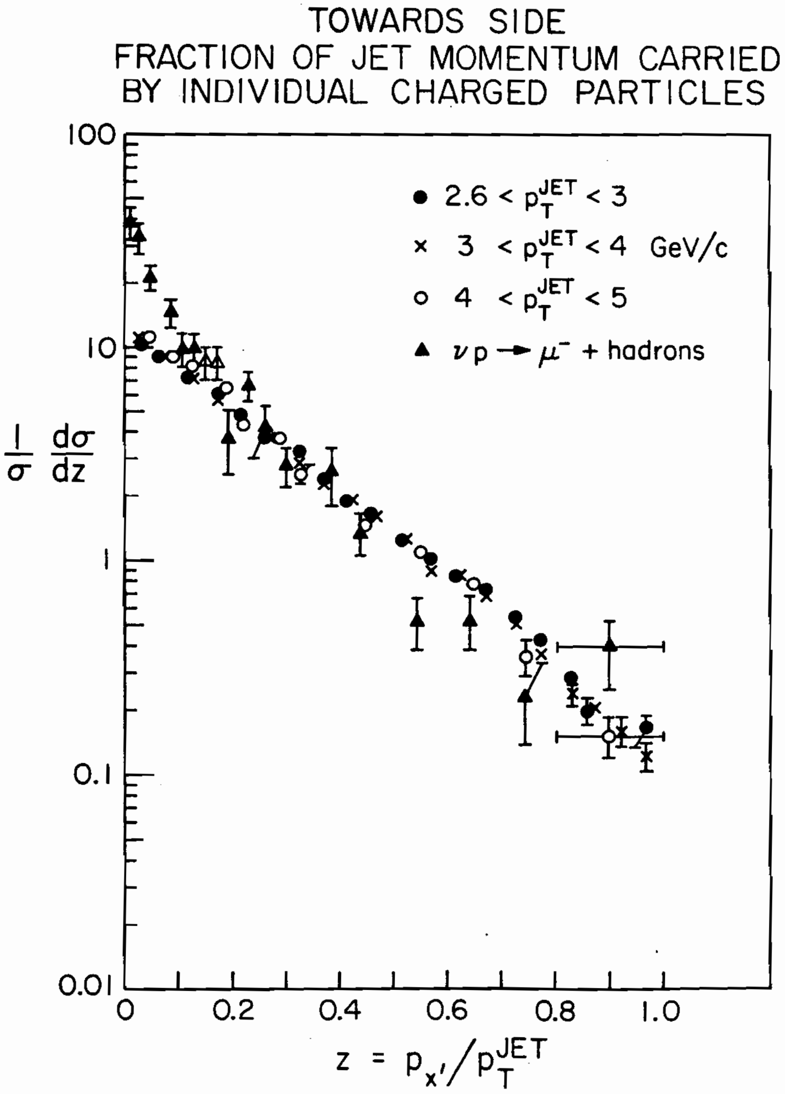


Fig. 1


JET AND SINGLE PARTICLE CROSS SECTIONS

$(\pi, p)$ Be 200 GeV $\theta_{lab} = 77$ mrad

Fig. 2


TOWARDS SIDE

FRACTION OF JET MOMENTUM CARRIED BY INDIVIDUAL CHARGED PARTICLES

Fig. 3

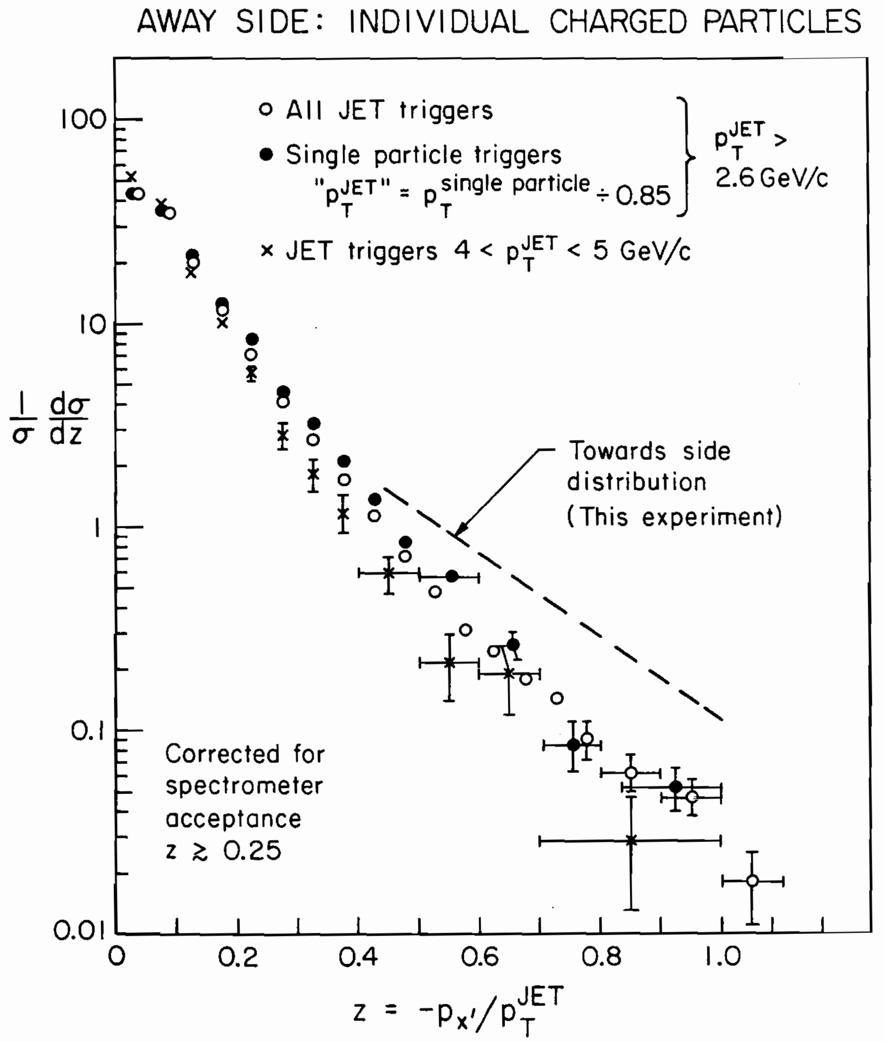

AWAY SIDE: INDIVIDUAL CHARGED PARTICLES
○ All JET triggers
● Single particle triggers
"$p_T^{JET}$" = $p_T^{single\ particle} \div 0.85$
$p_T^{JET} >$ 2.6 GeV/c
× JET triggers 4 < $p_T^{JET}$ < 5 GeV/c
Towards side distribution (This experiment)
Corrected for spectrometer acceptance z ≳ 0.25
$\frac{1}{\sigma}\frac{d\sigma}{dz}$
100
10
1
0.1
0.01
0
0.2
0.4
0.6
0.8
1.0
z = $-p_{x'}/p_T^{JET}$

Fig. 4