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

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Data are presented on production by 200-GeV/c hadrons incident on beryllium of both single particles and jets (groups of particles) with high p_T (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 $p_T = 3$ 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.

Interest in high-p_T physics was originally stimulated by the observation of unexpectedly large yields of single particles for $p_T \gtrsim 3$ 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_T particle and the structure of events in which high p_T 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 a momentum of 200 GeV/c struck a beryllium target either 3 or 6 cm thick. Charged particles emerging from the target at lab angles $\lesssim 150$ mrad and momenta $\gtrsim 2$ GeV/c were analyzed by track chambers and the spectrometer magnet which was set to give a transverse momentum kick of 0.38 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 0.25 in. of scintillator and 0.56 in. of lead, totaling about 15 radiation lengths or about 0.5 nuclear absorption length, and a rear section comprised of fifteen layers of 0.25 in. of scintillator and 2 in. of 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 momenta 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
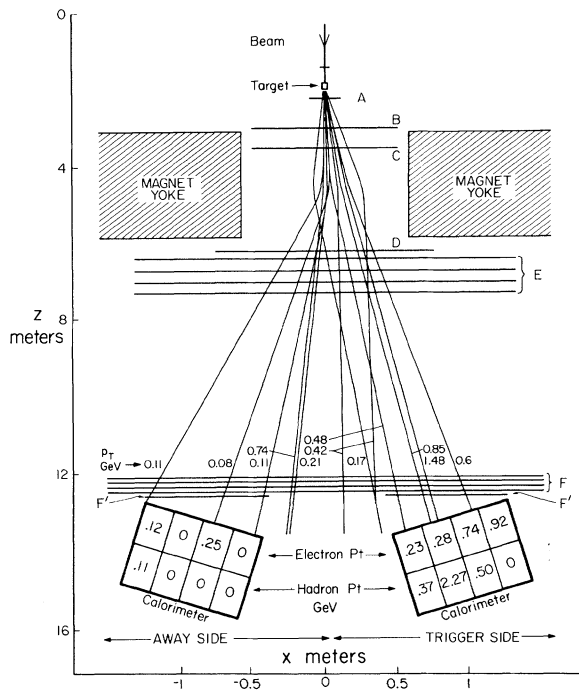
FIG. 1. Plan view of the spectrometer, with tracks from a typical event. *A–D* and *F'* indicate proportional planes, while *E* and *F* are spark chambers

FIG. 2. The single-particle and jet cross sections averaged over the c.m. system rapidty (y) region of 0.1 to 0.44. The jet definition is all particles into the cal-orimeter, while the plotted data are an average of equal amounts of π^- and proton beam. The jet cross sections for the separate beam types π^- and p are equal to within 20% for $4 < p_\perp^{\mathrm{JET}} < 5$ GeV/c. The single-particle data correspond to a proton beam only and the Chicago-Princeton results (Ref. 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.

the total transverse momentum of all four modules of either calorimeter be 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_T is 5.31 GeV/c in the right-hand-side calorime-ter.

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 cham-bers in front of the magnet measure, on the aver-age, four to five additional charged particles per event which are outside the magnet acceptance. Individual spark-chamber–gap efficiencies are estimated at 90% up to multiplicities of fifteen 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_T spectrum. The momentum resolution of the track chambers is $\Delta p/p^2 = 0.0007$ (GeV/c)$^{-1}$. For the calorimeters we measure an energy resolution $\Delta E/E$ of $0.33/\sqrt{E}$ for electron modules and $1.03/\sqrt{E}$ for hadron modules (stan-
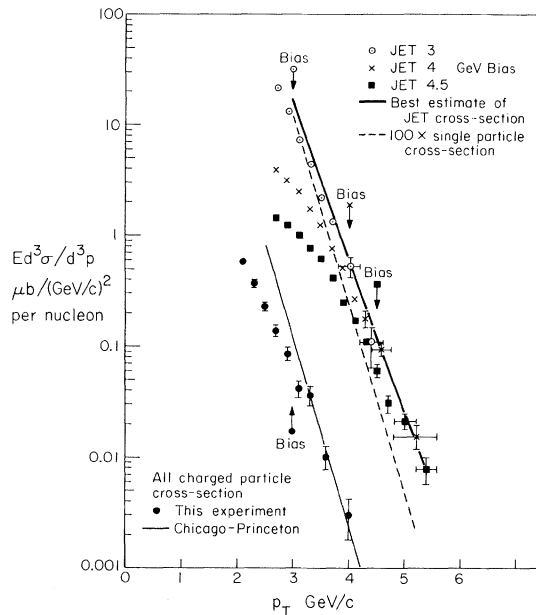
dard deviations, E in GeV).

The single-particle trigger is straightforward to analyze. Taking events with a single-particle track with $p_T > 2$ 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 cal-orimeter. Our data can be directly compared to the more precise measurements of the Chicago-Princeton[3] collaboration and there is good agree-ment 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_T divide into three categories: (i) *charged parti-cles* (typical multiplicity three) measured by the track chambers and comprising 57% of the jet mo-mentum[4]; (ii) *photons* (presumably from π^0, η, 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 sig-
nals module by module; the resultant resolution
in energy is poor because of the subtraction and
modest calorimeter resolution. This third cate-
gory includes neutrons, $K_L{}^0$, and nonvertex tracks
($K_s{}^0$, Λ, and reconstruction losses) and we find
that it carries between 6 and 24% of the jet p_T
with 13% as our best estimate. The jet cross sec-
tion 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 $\pm 30\%$ (p_T
$= 3$ GeV/c) to $\pm 50\%$ ($p_T = 5$ GeV/c) not indicated in
Fig. 2.

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 models[5-7] which pos-
tulate that large-p_T hadrons come from the frag-
mentation of quarks produced in an elementary
hard collision between constituent quarks in the
initial hadrons. Note that there are no clear res-
onance signals in our jet data and the large jet
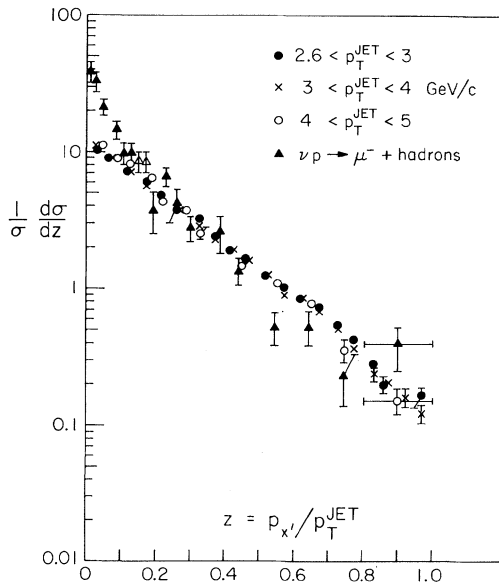cross section is not simply due to a sum of low-
mass resonances.

Motivated by the constituent models, we define
the jet plane as that plane formed by the jet mo-
mentum vector and the direction of the incident
hadrons and plot in Fig. 3 the transverse momen-
tum fraction $z = p_{x'}/p_T{}^{\mathrm{JET}}$, where $p_T{}^{\mathrm{JET}}$ is the
transverse momentum of the jet and $p_{x'}$ is the
component of the transverse momentum of indi-
vidual charged particles in the jet plane. There
is a striking similarity between our z distribu-
tions and those for lepton-induced processes.[7,8]
Furthermore our data show evidence for the co-
planar structure of events suggested by constitu-
ent models. For the charged particles (both jet
and nonjet members) in these events we find a
sharp exponential dependence with a mean of 0.20
GeV/c for the component of the transverse mo-
mentum out of the jet plane. Also the two-dimen-
sional 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
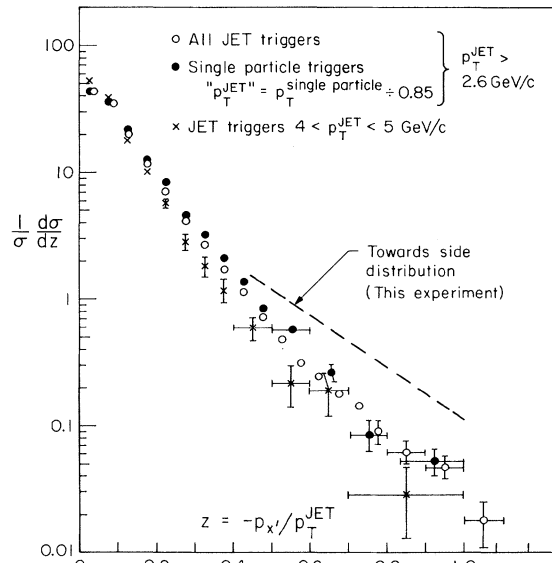particles balance the transverse momentum of

FIG. 3. The distribution in transverse momentum
fraction z for three jet $p_\perp$ ranges compared with neu-
trino scattering (Refs. 7 and 8). The comparison fails
below $z \sim 0.2$ as the neutrino data have significant con-
tributions from the fragmentation of the target proton.

FIG. 4. Distributions in momentum fraction z for
particles on the away side. The shifting of scale for
single particles is motivated by the quark model (Refs.
7 and 9) which suggests that single particles carry from
80 to 90% of the momentum of the high-$p_\perp$ quark (jet).
The data are integrated over the *whole* away side and
include a correction for spectrometer acceptance which
is valid for the higher-momentum particles, $z \gtrsim 0.25$.

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 of ~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 give strong support to the idea that the same constituents (quarks presumably) are probed by both high-p_T hadron and lepton collisions. We are currently continuing our analysis on the completed experiment which has 10 times the data presented here, taken with a liquid-hydrogen target and incident proton and meson beams.

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[2]C. Bromberg *et al.*, "Production of Jets and Single-Particles at High p_T in 200-GeV Hadron Beryllium Collisions" (to be published).

[3]J. W. Cronin *et al.*, Phys. Rev. D **11**, 3105 (1975). Figure 2 shows more recent data [D. Antreasyan *et al.*, Phys. Rev. Lett. **38**, 115 (1977), and private communication of new results with a Be target].

[4]The percentage of jet p_T carried by the three components varies slightly with the jet p_T and more significantly with the hadronic neutral estimate used. The quoted percentages correspond to the cut $4 < p_T^{JET} < 5$ GeV/c and a 13% hadronic neutral contribution.

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Measurement of the Proton Structure Function from Muon Scattering*

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Results on the proton structure function, νW_2 are presented for $0.3 < q^2 < 50$ GeV^2 and $5 < \nu < 130$ GeV. They are compared to earlier data and displayed to demonstrate violations of scaling. Values are reported for the energy-momentum sum rule and for $R \equiv \sigma_L/\sigma_T$ over a limited kinematic region.

In this Letter we report values of the structure function νW_2 of the proton obtained by measuring the inelastic scattering of muons from hydrogen at the Fermi National Accelerator Laboratory. The data were taken with the muon-scattering facility constructed by this group.