Measurement of Forward Jets Produced in High-Transverse-Momentum Hadron-Proton Collisions

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A measurement of charged-particle production is reported for the forward region in events triggered by high–transverse-momentum ($p_\perp$) jets and single particles. The momentum distributions of forward-going particles are observed to scale in a simple $p_\perp$-dependent longitudinal variable. Forward-going (beam) jets are observed to be tilted away from the original direction by an amount which agrees with muon-pair data when interpreted in a parton (quantum-chromodynamics) model.

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The results reported here are from a Fermilab experiment; details of the apparatus and recent analysis results may be found in Refs 1–3. The experiment involved directing beams of 200- and 130-GeV hadrons onto a liquid hydrogen target and triggering on both high-$p_\perp$ single particles and jets of particles produced at 90° (with respect to the beam direction) in the center-of-mass system. In addition, a sample of minimum-bias events were recorded with no high-$p_\perp$ trigger requirements.[4] The resulting event structure was analyzed with a multiparticle spectrometer which had nearly 100% detection efficiency for charged particles produced in the forward hemisphere.[1,2] In this Letter, new results will be presented on the analysis of the forward (beam-jet) region, for which this experiment is particularly well suited.

Events in which high-$p_\perp$ particles are produced are characterized by a four-jet structure,[1,5] which in a parton model, arises from the hard scattering of pointlike constituents. The scattered partons form the trigger and away-side jets; the remnants of the beam and target form two additional jets. In this experiment we detect almost all of the charged component of the beam jet (roughly two-thirds of it), and its existence is clearly seen in these data.[1,2] In events with a high-$p_\perp$ trigger, the probability of producing a forward-going particle with Feynman x_F greater than 0.1 ($x_F = 2p_z/\sqrt{s}$, where p_z is the center-of-mass momentum in the beam direction and $\sqrt{s}$ is the total center-of-mass energy) is greatly reduced with increasing trigger $p_\perp$. This is shown in Fig. 1(a) where we plot the single charged-particle distribution function, $f(x_F)=x_F\sigma^{-1}d\sigma/dx_F$, for a proton beam. Since we wish to study the beam region, only particles in a forward cone of half-angle 45° are included in Fig. 1; this cut, of course, removes only very low-x particles. As suggested by analyses of CERN intersecting-storage-rings data,[6,7] one may define a new scaling variable whick takes the high-$p_\perp$ trigger into account. We define

$$x' = 2p_z/(\sqrt{s} - 2E_T), \qquad (1)$$

where E_T is the trigger-jet energy.[8] Figure 1(b) shows the x' distributions for several trigger-jet $p_\perp$ bins, including the minimum-bias sample which has no high-$p_\perp$ requirement. When plotted in this way, the data are observed to scale over

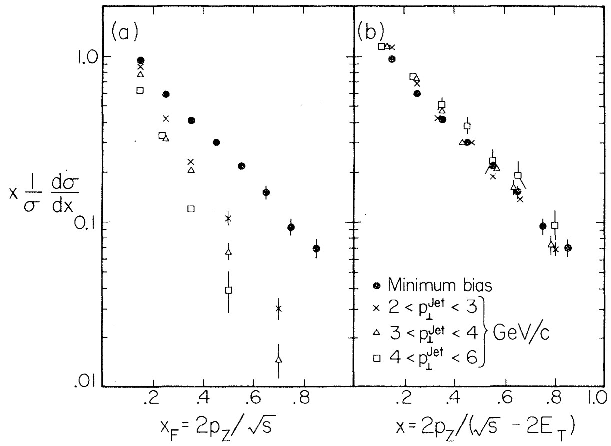

FIG. 1. Beam-jet fragmentation functions.

a wide range of trigger $p_\perp$, even when half of the energy is removed from the beam ($\sqrt{s}/2 = 9.7$ GeV for these plots). The significance of the scaling of the data to the form (1) is emphasized by using the more general expression

$$x_\alpha = 2p_z/(\sqrt{s} - \alpha E_T). \tag{2}$$

Fitting (2) to the data gives $\alpha = 1.8 \pm 0.2$.[9] The scaling of Fig. 1(b) was observed separately for positive- and negative-charged particles and also for π^- and π^+ beams (not shown).[9] Further the actual shape of the x distributions is independent of the beam particle (π^- beam giving positive secondaries is equal to p beam giving negatives and vice versa). There are small deviations from this rule for small-$p_\perp$ triggers but the beams fragment universally at high $p_\perp$. The universal fragmentation function in Fig. 1(b) is similar to that for a quark.[1]

It has already been pointed out,[10,11] that when one triggers on high-$p_\perp$ particles, there is a bias for selecting those events in which a parton is already headed in the trigger direction. Some of this trigger bias momentum is expected to appear in the beam and target jets[12]; some experimental evidence for this already exists.[6] We present data which clearly indicate that a large part of the trigger $p_\perp$ is balanced by forward-going beam (and therefore target) jets with a momentum component opposite the trigger.

We define the beam jet in the center-of-mass system as the collection of all particles in a forward cone of half-angle 45°. We define θ as the angle between the original beam direction and the momentum projected on the plane defined by beam and trigger jet. Figure 2 shows beam-jet

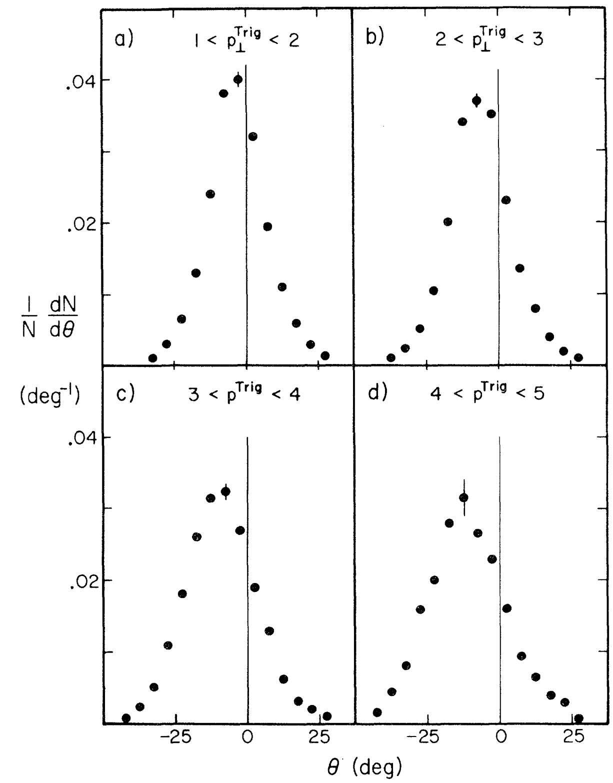

FIG. 2. Beam-jet angle (in trigger plane) for different values of trigger-jet $p_\perp$(GeV/c).

angular distributions for a π^- beam and four different trigger-jet $p_\perp$'s. A mild cut on total observed beam-jet energy (E_b) of $E_b > 1$ GeV is made for these plots. The data show a significant tilting of the beam jet away from the trigger direction whose magnitude increases with increasing trigger $p_\perp$. Similar angular distributions were obtained for a proton beam as seen in the mean values of Table I. The slight broadening of the distributions with increasing trigger $p_\perp$ is expected because the higher-$p_\perp$ triggers have less energy in the beam region and so a poorer statistical determination of the beam direction.

Several tests were made to check the results shown in Fig. 2. In earlier work (1), we showed that our data could be fitted well with a four-jet model. This Monte Carlo showed that the 45°-cone beam-jet definition is adequate for determining the beam-jet direction. The difference between the true beam-jet angle and the determined angle, θ, was less than 1° in the Monte Carlo (over the entire trigger-$p_\perp$ range of this experiment) and the standard deviation of the distribution was about 8°.[13] Reducing the beam cone size to 25° showed a beam-jet tilt similar to Fig. 2,

TABLE I. Single-particle and total beam-jet tilts as a function of trigger transverse momentum.

Trigger $p_\perp$ (GeV/c)	Beam-jet tilt (deg)	$\langle p_x \rangle$ per particle (all x_F) (MeV/c)	$\langle p_x \rangle$ per particle ($x_F > 0.2$) (MeV/c)
		p beam	
1–2	-2.5 ± 0.15	-41 ± 2	-157 ± 10
2–3	-5.7 ± 0.15	-87 ± 2	-312 ± 12
3–4	-7.5 ± 0.2	-105 ± 3	-392 ± 21
4–5	-8.7 ± 0.5	-120 ± 7	-430 ± 57
5–6	-10.4 ± 1.6	-125 ± 18	-290 ± 110
		π^- beam	
1–2	-2.9 ± 0.1	-50 ± 2	-175 ± 9
2–3	-6.3 ± 0.15	-106 ± 2	-354 ± 11
3–4	-8.9 ± 0.2	-129 ± 3	-495 ± 17
4–5	-10.7 ± 0.4	-152 ± 6	-641 ± 46
5–6	-12.7 ± 1.0	-160 ± 14	-549 ± 150

but with poorer resolution. Limiting the beam-jet definition to high-x particles also gave the same beam-jet tilt. No average tilt was observed normal to the trigger plane. For the reasons given above, we believe that the data show a clear tilting of the forward jet and in the model of Ref. 12 at least, this tilting is not due to fragments from the away-side jet entering the beam region.

Figure 3 shows, as a function of trigger $p_\perp$, the net momentum carried by the (sum of all) charged particles in the beam jet in the direction of the trigger (x direction). Data are presented for both π^- and proton beams, single particle and jet triggers, and two center-of-mass energies. Again, we make a cut of $E_b > 1$ GeV. The p_x shifts per charged particle are given in Table I. The data of Table I show that making the cut $x_F > 0.2$ enhances the p_x shift per particle. This is because higher-x_F particles carry a greater fraction of the (tilted) beam-jet energy. The data clearly show that $|\langle p_x \rangle_{\text{beam jet}}|$ increases with increasing trigger $p_\perp$ and is the same for jet and single-particle triggers.[14] The equality of the beam-jet tilts for single-particle and jet triggers is further evidence that the dynamics of the two processes are identical, and that the measured large jet to single-particle ratio is not due to either beam-jet background[1] or to an anomalous contribution of parton $k_\perp$ to jet production. There is no observed s dependence of $\langle p_x \rangle_{\text{beam jet}}$. Values of $\langle p_x \rangle_{\text{beam jet}}$ are similar for proton and pion beams, but there is definitely more p_x shift for the pion beam. An analogous effect is seen in data on high-$p_\perp$ muon-pair production; $\langle p_\perp^2 \rangle_{\mu^+\mu^-}$ is greater for pion beams than for proton beams.[15]

The model of Ref. 12 predicts that for a 5-GeV trigger, one should observe an average tilt of 7° in the beam jet if the beam remains recoiled coherently after the scatter.[1] This corresponds to an average beam-jet p_x of -550 MeV/c. For a 5-GeV/c trigger jet, the data show an average beam-jet p_x of -400 MeV/c for the charged-particle component, and this corresponds to a total beam-jet p_x of -400 MeV/c divided by $\frac{2}{3}$, or -600 MeV/c.[16] Thus, in this context, the data qualitatively confirm the large magnitude of the parton transverse momentum determined from the muon-pair data which determined the parameters of Ref. 12. One may think of the parton transverse momentum as arising from two (possibly physi-

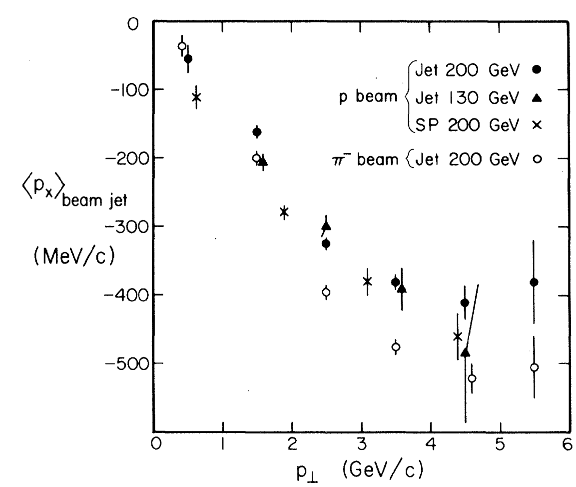

FIG. 3. Beam-jet momentum carried by charged particles in the trigger direction. Single-particle $p_\perp$'s are divided by 0.8 (Ref. 15).

cally inseparable) parts[12]: (a) an intrinsic component due to parton confinement, and (b) gluon bremsstrahlung. The coherent beam jet observed in our data is characteristic of a large intrinsic component (a) and one might naively expect that the process (b) would not lead to a beam-jet tilt but rather to an extra gluon jet of soft particles on the away side. However, a precise calculation of the process (b) has not been done, and so more definite conclusions await further theoretical calculations.

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[12]R. P. Feynman, R. D. Field, and G. C. Fox, Phys. Rev. D 18, 3320 (1978).

[13]Alternative beam definitions did not improve this resolution. We note, however, that in a standard model of parton fragmentation [R. D. Field and R. P. Feynman, Nucl. Phys. B136, 1 (1978)], 10° is a typical angle that the leading particle makes with the parton direction.

[14]We divide the single particle $p_\perp$ by 0.8 for comparison to jets, because there is evidence that high-$p_\perp$ single particles arise from partons which had, on the average, about 15% more momentum (see Ref. 1).

[15]J. K. Yoh *et al.*, Phys. Rev. Lett. 41, 684 (1978); K. J. Anderson *et al.*, Phys. Rev. Lett. 42, 944 (1979).

[16]For the case of the proton beam, the target jet is symmetric to the trigger jet and so the net average transverse-momentum bias observed with a 5-GeV/c trigger is about 1.2 GeV/c.