Evidence for Parton k_T Effects in High-p_T Particle Production

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Inclusive π^0 and direct-photon cross sections in the kinematic range $3.5 < p_T < 12$ GeV/c with central rapidities ($y_{\rm cm}$) are presented for 530 and 800 GeV/c proton beams and a 515 GeV/c π^- beam incident on Be targets. Current next-to-leading-order perturbative QCD calculations fail to adequately describe the data for conventional choices of scales. Kinematic distributions from these hard scattering events provide evidence that the interacting partons carry significant initial-state parton transverse momentum (k_T). Incorporating these k_T effects phenomenologically greatly improves the agreement between calculations and the measured cross sections. [S0031-9007(98)07206-8]

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In recent years, perturbative QCD (PQCD) has been tested in a variety of strong interaction processes at short distances, and increasing attention is now being directed towards areas that may be sensitive to shortcomings in the current theoretical description [1]. The high statistics samples of hard-scattering data accumulated by Fermilab fixed-target experiment E706 provide an opportunity to probe such issues. This paper presents comparisons of PQCD calculations to our data on the production of direct photons and π^0's with large transverse momenta (p_T). Direct-photon data have long been expected to provide an accurate determination of the distributions of gluons in hadrons, especially at large longitudinal momentum fraction (x), where information has proven difficult to obtain from other measurements. Inclusive meson production at large p_T probes a different mix of hard-scattering processes and provides insight into parton fragmentation. For conventional choices of parameters, our data are not described satisfactorily by next-to-leading-order (NLO) PQCD calculations [2]. Resolving the observed discrepancies is important for improving the understanding of both parton distribution functions (PDF) and parton fragmentation functions (FF).

Several interesting aspects of QCD contributions beyond leading order (LO) can be investigated experimentally through studies of processes sensitive to transverse motion of the partons prior to the hard scatter. This k_T is presumably due to effects of hadron size (primordial k_T) as well as initial-state gluon radiation. Measurements of Drell-Yan pair production [3] and direct diphoton production [4] have demonstrated the presence of substantial effective k_T (significantly larger than can be attributed to primordial k_T), and have revealed a center-of-mass energy ($\sqrt{s}$) dependence of $\langle k_T \rangle$. (In this paper, $\langle k_T \rangle$ denotes the average magnitude of the transverse momentum vector, $|\mathbf{k}_T|$, of *each* of the two colliding partons in the initial state.) A resummation of soft-gluon emissions has recently been used to reproduce the size of the effect observed in the WA70 direct diphoton data [5]. Other data also suggest $\langle k_T \rangle$ values larger than those expected from NLO PQCD calculations. Recent comparisons of p_T spectra from charm-particle hadroproduction to NLO PQCD results provide evidence that supplemental k_T may be required to properly describe the data [6]. Likewise, it has been suggested that the observed pattern of discrepancies between data from various direct-photon experiments and results from NLO PQCD calculations could be related to k_T effects [7].

E706 is designed to measure the production of direct photons, neutral mesons, and associated particles at high p_T. The apparatus features a large lead and liquid argon electromagnetic calorimeter and a charged particle

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spectrometer [8]. The experiment accumulated ≈ 10 events/pb of π^- beam data at 515 GeV/c, ≈ 9 events/pb of proton beam data at 530 GeV/c, and ≈ 11 events/pb of proton beam data at 800 GeV/c on Be, Cu, and H targets (primarily Be) [9]. A variety of event selection triggers sensitive to high-p_T electromagnetic showers was employed (using different prescale factors) to accumulate data over a broad range of p_T.

The steep p_T dependences of neutral meson and direct-photon production make the measured cross sections very sensitive to uncertainties in the energy calibration. Therefore, achieving a precise and accurate calibration of the electromagnetic calorimeter was essential. As a result of detailed studies of the data acquired, the uncertainty in the calibration of the energy response of the calorimeter was reduced to less than 0.5% [10].

The single-photon sample is composed of photons not identified as an element of a reconstructed two photon decay of a π^0 or η meson candidate. The direct-photon signal is extracted from the single-photon sample via statistical subtraction of the background contributions. These backgrounds are primarily due to photons from unreconstructed decays of neutral mesons. Failure to correctly identify a photon as originating from a π^0 or η decay occurs when the other photon from that decay converts in the target region, escapes the fiducial volume of the calorimeter, or is otherwise not reconstructed. Sources of direct-photon background have been modeled using the HERWIG event generator [11] and a detailed GEANT simulation [12] of the spectrometer response. These Monte Carlo generated events have been weighted to accurately represent our measured neutral meson production spectra.

The p_T dependences of inclusive π^0 and direct-photon cross sections are shown in Figs. 1, 2, and 3. The results of NLO PQCD calculations [using Binnewies-Kniehl-Kramer (BKK) FF [13] for the π^0] are compared with the data [14]. For simplicity, all QCD scales (renormalization, factorization, and, where appropriate, fragmentation) have been set equal. The broken curves in Fig. 1 represent the results of NLO PQCD calculations using conventional choices of scales (and GRV PDF [15]). The calculations are quite sensitive to the scales (an indication of the importance of still higher order contributions), but even for rather small scales, the NLO calculations fail to describe our data. Using other recent PDF [16,17] in the calculations also does not adequately account for the discrepancy between the NLO PQCD results and our data (broken curves in Fig. 2) [18]. Differences between LO [19] and NLO PQCD are likewise not large when compared to the difference between either of these calculations and the measured cross sections (Fig. 3). However, PQCD at NLO may not adequately account for soft-gluon radiation that imparts an effective transverse momentum to the incident partons.

Kinematic distributions for high-mass pairs of particles directly probe the transverse momentum of incident partons in hard-scattering events. The distribution of the angle between two π^0 mesons (each with

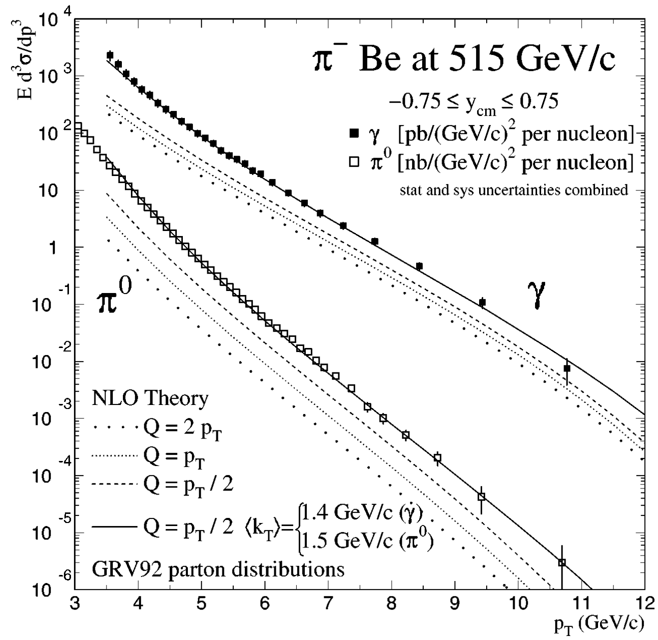

FIG. 1. The π^0 and direct-photon inclusive cross sections as functions of p_T for 515 GeV/c π^--nucleon interactions compared to NLO PQCD results for several choices of scales. The solid curves show the NLO PQCD results for $Q = p_T/2$ scales adjusted for supplemental $\langle k_T \rangle$. (Note that the units for the π^0 and γ results differ by a factor of 1000.)

$p_T > 3$ GeV/c) in the transverse plane ($\Delta\phi$) is shown in Fig. 4 for 515 GeV/c π^--nucleon collisions. The results of LO PQCD calculations [20], in which each of the incident partons has a Gaussian transverse momentum

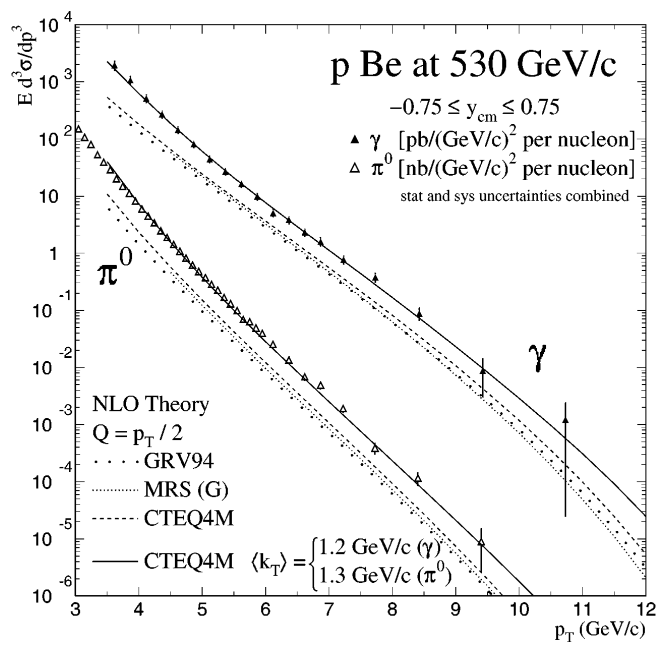

FIG. 2. The π^0 and direct-photon inclusive cross sections as functions of p_T for 530 GeV/c proton-nucleon interactions compared to NLO PQCD results for several choices of PDF. The solid curves show the NLO result (using the CTEQ4M PDF) adjusted for supplemental $\langle k_T \rangle$. (Note that the units for the π^0 and γ results differ by a factor of 1000.)

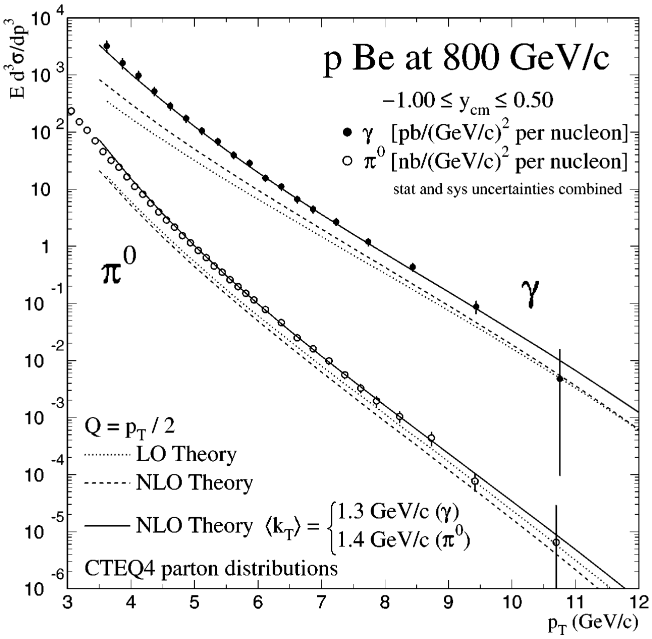

FIG. 3. The π^0 and direct-photon inclusive cross sections as functions of p_T for 800 GeV/c proton-nucleon interactions compared to LO and NLO PQCD results. The solid curves show NLO results adjusted for supplemental $\langle k_T \rangle$. (Note that the units for the π^0 and γ results differ by a factor of 1000.)

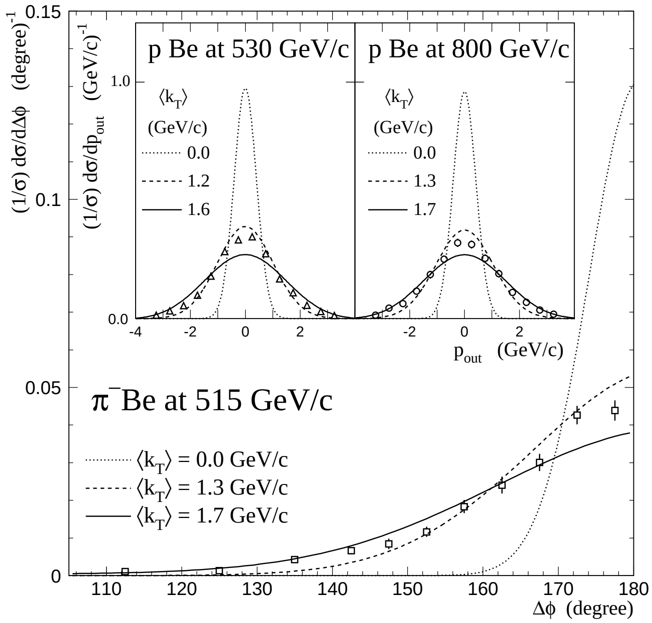

FIG. 4. The $\Delta\phi$ distribution for high-mass π^0 pairs produced in 515 GeV/c π^--nucleon interactions compared to LO PQCD results using various $\langle k_T \rangle$ values and GRV92 PDF. The inset shows the p_{out} distributions for high-mass π^0 pairs produced in proton-nucleon interactions at 530 and 800 GeV/c compared to results of LO PQCD calculations using CTEQ4L PDF. All calculations use BKK FF.

distribution with $\langle k_T \rangle = 1.3$ GeV/c (dashed curve) and $\langle k_T \rangle = 1.7$ GeV/c (solid curve), are also shown [19]; here, and in the inset, the values were chosen to bracket the data. While fragmentation alone contributes significantly to the width of the calculated $\Delta\phi$ distribution (dotted curve, $\langle k_T \rangle = 0$), adding supplemental $\langle k_T \rangle > 1$ GeV/c provides a much better description of the data.

Another kinematic variable that is sensitive to k_T is the out-of-plane momentum, p_{out} (the component of the momentum of one high-p_T particle, perpendicular to the plane defined by the incident beam direction and the direction of the other high-p_T particle). The inset within Fig. 4 displays p_{out} distributions for π^0 pairs, compared to LO results with and without k_T. These distributions ($\Delta\phi$ and p_{out}) show clear evidence for the presence of significant k_T (>1 GeV/c) in the hard-scattering interactions. The corresponding distributions for our other data samples also support this conclusion [21].

Our preliminary analyses of the $\gamma\pi^0$ and $\gamma\gamma$ kinematic distributions, as well as studies of the distribution of the fractional momentum carried by individual charged particles in jets recoiling against isolated photons, also show evidence of substantial k_T, as do our comparisons of the measured high-p_T charged-D cross section to NLO PQCD results [8]. All these results suggest a supplemental $\langle k_T \rangle$ of order 1 GeV/c.

Since the inclusive spectra fall rapidly with increasing p_T, the introduction of k_T smearing has a significant effect on predicted cross sections. To approximate the effect of supplemental k_T smearing on the inclusive NLO PQCD calculations for direct-photon (and π^0) production, we calculated k_T factors (as functions of p_T) for different values of $\langle k_T \rangle$, by computing ratios of results from LO PQCD calculations [19] for different $\langle k_T \rangle$ values compared to results without k_T [22]. These same k_T factors were then applied to the results of NLO PQCD calculations [23]. As indicated by the solid curves in Figs. 1, 2, and 3, reasonable representations of both the direct-photon and π^0 results are obtained using $\langle k_T \rangle$ values >1 GeV/c [24]. The kinematic distributions exhibit a pattern consistent with $\langle k_T \rangle$ increasing with $\sqrt{s}$, a trend reflected in the $\langle k_T \rangle$ factors employed in the theory curves (solid curves) shown in the inclusive cross section plots [25].

As an illustration of the sensitivity of our data to the gluon distribution, Fig. 5 compares our direct-photon cross sections to NLO PQCD calculations using CTEQ4M and CTEQ4HJ PDF [17]. Once soft-gluon effects are satisfactorily taken into account, either approximately as in this paper or in a more theoretically rigorous manner, our data can be used to help discriminate between PDF that otherwise provide acceptable descriptions of the data sets used in Ref. [17].

In conclusion, we have measured the inclusive production of high-p_T neutral mesons and direct photons by 530 and 800 GeV/c proton and 515 GeV/c π^- beams. Current NLO PQCD calculations (which exhibit substantial dependences on QCD scales) fail to account for the measured cross sections using conventional choices of scales. Significant k_T effects (>1 GeV/c) have been observed in kinematic distributions of high-mass pairs $\pi^0\pi^0$, $\gamma\pi^0$, and $\gamma\gamma$. A simple implementation of supplemental

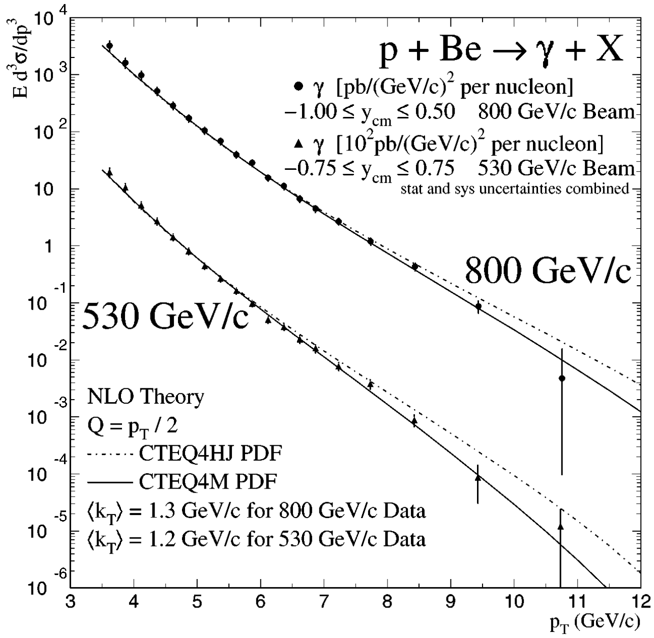

FIG. 5. Direct-photon inclusive cross sections as functions of p_T for 530 and 800 GeV/c proton-nucleon interactions compared to results of NLO PQCD calculations using CTEQ4HJ (dot-dashed curve) and CTEQ4M (solid curve) PDF. Factors for supplemental $\langle k_T \rangle$ are included. (Note that the units for the 530 and 800 GeV/c results differ by a factor of 100.)

parton k_T in PQCD calculations, using k_T values consistent with observations, provides a reasonable description of the inclusive cross sections. Our high statistics direct-photon data samples are directly sensitive to the gluon distribution at large x values. An improved theoretical understanding of soft-gluon effects in inclusive direct-photon production will facilitate the global determination of the gluon distribution function.

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[22] A possible variation of $\langle k_T \rangle$ with p_T, expected in PQCD, has been neglected in this analysis.

[23] Since the parton-level calculations with full treatment of kinematics already exist, it is convenient (but not essential) to use LO PQCD estimates of the k_T factors; one obtains similar results by numerically convoluting parametrizations of the inclusive cross sections with Gaussian smearing factors.

[24] The $\langle k_T \rangle$ used in the figures are representative values, not the results of fits to data. The $\langle k_T \rangle$ values that provide a corresponding level of agreement between LO direct-photon calculations (not shown) and our inclusive cross sections are somewhat larger ($\approx$10%) than the corresponding values for the NLO comparisons.

[25] At the same incident momenta, the $\langle k_T \rangle$ values observed in Drell-Yan data for π^- beams are larger than those observed using proton beams [3].