Influence of Parton k_T on High-p_T Particle Production

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We report on recent work concerning the phenomenology of initial-state parton-k_T effects in direct-photon production and related processes in hadron collisions. High-mass direct-photon and π^0 pairs are used to explore the impact of parton-k_T on kinematic distributions. After a brief summary of a phenomenological k_T-smearing model, we present a study of recent results on fixed-target and collider direct-photon production. This approach provides a consistent description of the observed deviations of next-to-leading order QCD calculations relative to the inclusive direct-photon and π^0 data. We also comment on the implications of these results for the extraction of the gluon distribution of the nucleon.

I. INTRODUCTION

Direct-photon production has long been viewed as an ideal process for measuring the gluon distribution in the proton and has been calculated within perturbative QCD (pQCD) to next-to-leading order (NLO) [1]. The quark–gluon Compton scattering subprocess ($gq \to \gamma q$) provides a large contribution to inclusive direct-photon production. The gluon distribution is relatively well constrained for $x < 0.1$ by deep-inelastic scattering and Drell-Yan data, but less so at larger x. Direct-photon data can constrain the fits at large x, and consequently has been incorporated in several modern global parton distribution analyses.

A pattern of deviation between measured direct-photon cross sections and NLO calculations has been observed [2]. The suspected origin of the disagreements is the effect of initial-state soft-gluon radiation, referred to here as k_T-effects. Kinematic distributions of high-mass pairs of particles directly probe the transverse momentum of incident partons in hard-scattering events. Evidence of significant k_T has been observed in measurements of dimuon, diphoton, and dijet pairs [3]. A collection of measurements of the average transverse momentum of the pairs ($\langle p_T \rangle_{pair}$) is displayed in Fig. 1 (left) for a wide range of center-of-mass energies ($\sqrt{s}$). The values of $\langle p_T \rangle_{pair}$ are large, and increase with increasing $\sqrt{s}$. The values of $\langle k_T \rangle$ per parton (estimated as $\approx \langle p_T \rangle_{pair} / \sqrt{2}$) indicated by these Drell-Yan, diphoton, and dijet data, as well as the inclusive direct-photon and π^0 production data, are too large to be interpreted as "intrinsic" — i.e., due only to the finite size of the proton. From the observed data, one can infer that the average k_T per parton is order 1 GeV/c at fixed-target energies, increasing to 3-4 GeV/c at the Tevatron collider, while one would expect $\langle k_T \rangle$ values on the order of 0.3 to 0.5 GeV/c based solely on proton size.

II. COMPARISONS WITH E706

Fermilab E706 is a fixed-target experiment designed to measure the production of direct photons, neutral mesons, and associated particles at high p_T [4]. The apparatus included a charged particle spectrometer consisting of silicon microstrip detectors in the target region and multiwire proportional chambers and straw tube drift chambers downstream of a large aperture analysis magnet [5]. Photons were detected in a large, lead and liquid-argon, sampling electromagnetic calorimeter (EMLAC), located 9 m downstream of the target [6]. The EMLAC readout was split azimuthally into octants, each consisting of interleaved, finely segmented, radial and azimuthal views. The radial views were also used to form a fast, localized, high-p_T event selection trigger. Correlations between localized high-p_T electromagnetic depositions on opposite sides of the EMLAC were used to trigger on the production of high-mass pairs of neutral particles. The experiment accumulated data from a 515 GeV/c π^- beam, and from 530 GeV/c and 800 GeV/c proton beams incident upon beryllium, copper, and hydrogen targets.

A. High-Mass Pairs

The distributions of high-mass direct-photon pairs as functions of pair p_T (Q_T), azimuthal angle between the photons ($\Delta\phi$), and out-of-plane momentum ($p_{\rm OUT}$) are shown in Fig. 1 (right) for 515 GeV/c π^-Be interactions. Overlayed on the data are the results from both NLO [7] and resummed [8] pQCD calculations. The shape of the NLO calculation is inconsistent with the data distributions. The resummed calculation (RESBOS), which incorporates the effects of multiple soft-gluon emission, provides a reasonable match to the shape of the data. Also shown are the double direct-photon distributions from PYTHIA, which approximates k_T effects by a Gaussian smearing technique. PYTHIA provides a reasonable description of the data using a value for $\langle k_T \rangle$ consistent with the measurements displayed in Fig. 1.

Analyses of high-mass π^0 pairs [4], as well as studies of the distribution of the fractional momentum carried by 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 [5]. All these results suggest a supplemental $\langle k_T \rangle$ of order 1 GeV/c. Similar soft-gluon effects may be expected in other hard-scattering processes, such as the inclusive production of jets or direct photons [9–11].

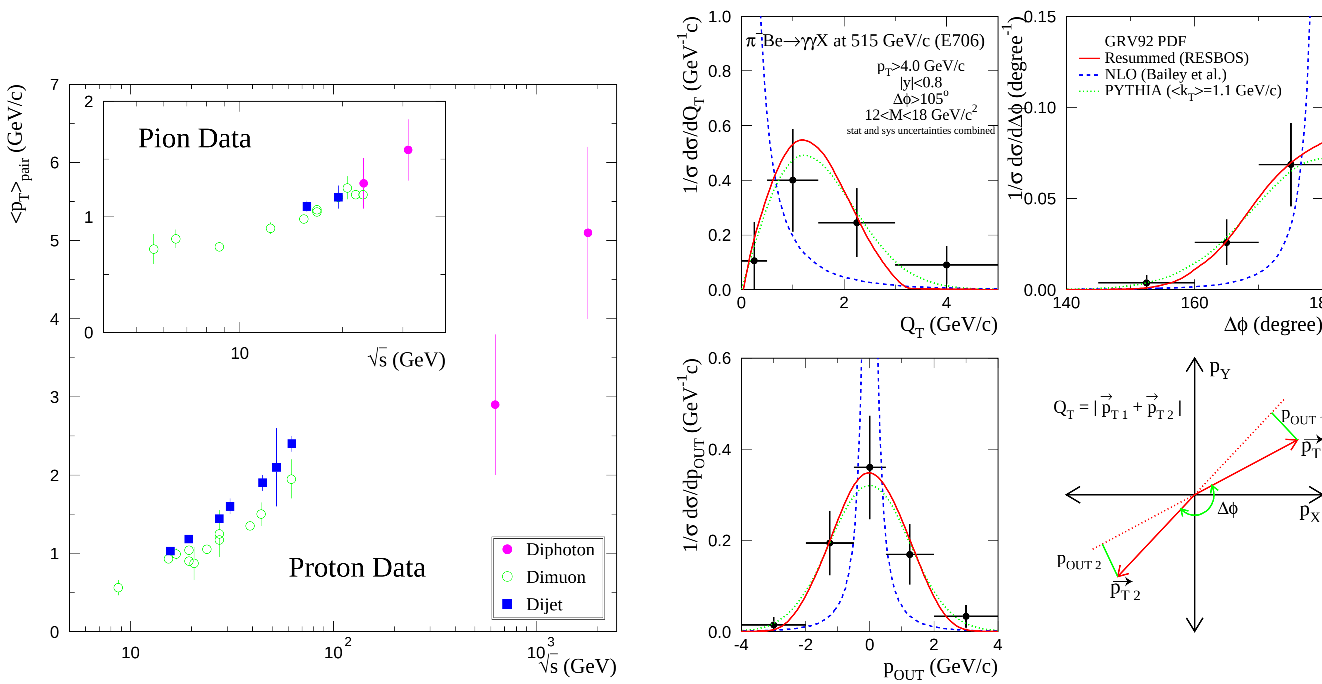

FIG. 1. Left: $\langle p_T \rangle$ of pairs of muons, photons, and jets produced in hadronic collisions by incident protons or pions versus $\sqrt{s}$ ($\langle p_T \rangle_{pair} \approx \sqrt{2}\,\langle k_T \rangle$).
Right: Kinematic distributions (preliminary) for high-mass direct-photon pairs produced in 515 GeV/c π^-Be interactions. Overlayed on the data are the results from NLO (dashed) and resummed (solid) calculations. PYTHIA results (dotted) with $\langle k_T \rangle = 1.1$ GeV/c are also shown. The various kinematic quantities are illustrated in the vector diagram.

B. Inclusive Production

Invariant cross sections for inclusive direct-photon and π^0 production are displayed in Figs. 2 and 3 with theory overlays. Discrepancies between the NLO theory and the data are particularly striking. Resummed pQCD calculations for single direct-photon production are anticipated [12–14]. Since current NLO theory calculations do not account for the effects of multiple soft-gluon emission, we employed a phenomenological model to incorporate k_T effects in pQCD calculations of direct-photon and π^0 production [4,3].

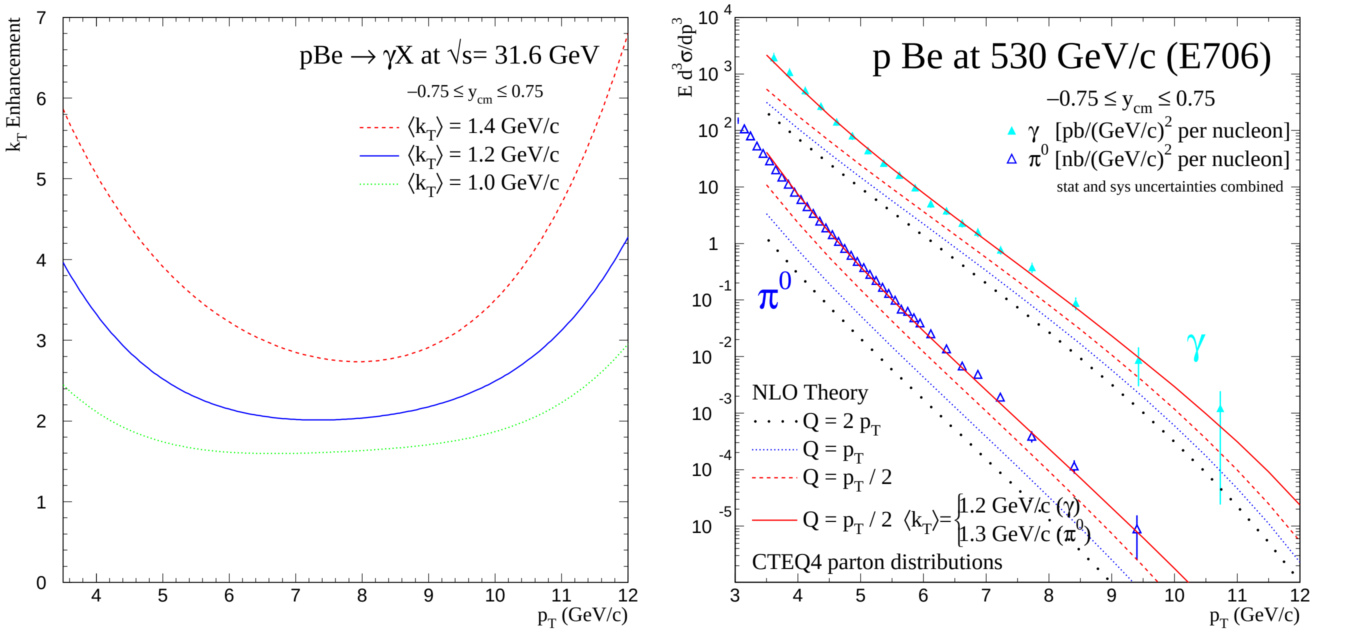

FIG. 2. Left: The variation of k_T enhancements, $K(p_T)$, relevant to the E706 direct-photon data in the figure to the right. Right: Invariant cross sections (per nucleon) for direct-photon and π^0 production in pBe interactions at 530 GeV/c. Cross sections are shown as a function of p_T averaged over the full rapidity range. Curves represent NLO QCD calculations for scale choices of $Q = 2p_T$ (wide dots), $Q = p_T$ (dotted), and $Q = p_T/2$ (dashed), and a k_T-enhanced NLO result with scale $Q = p_T/2$ (solid).

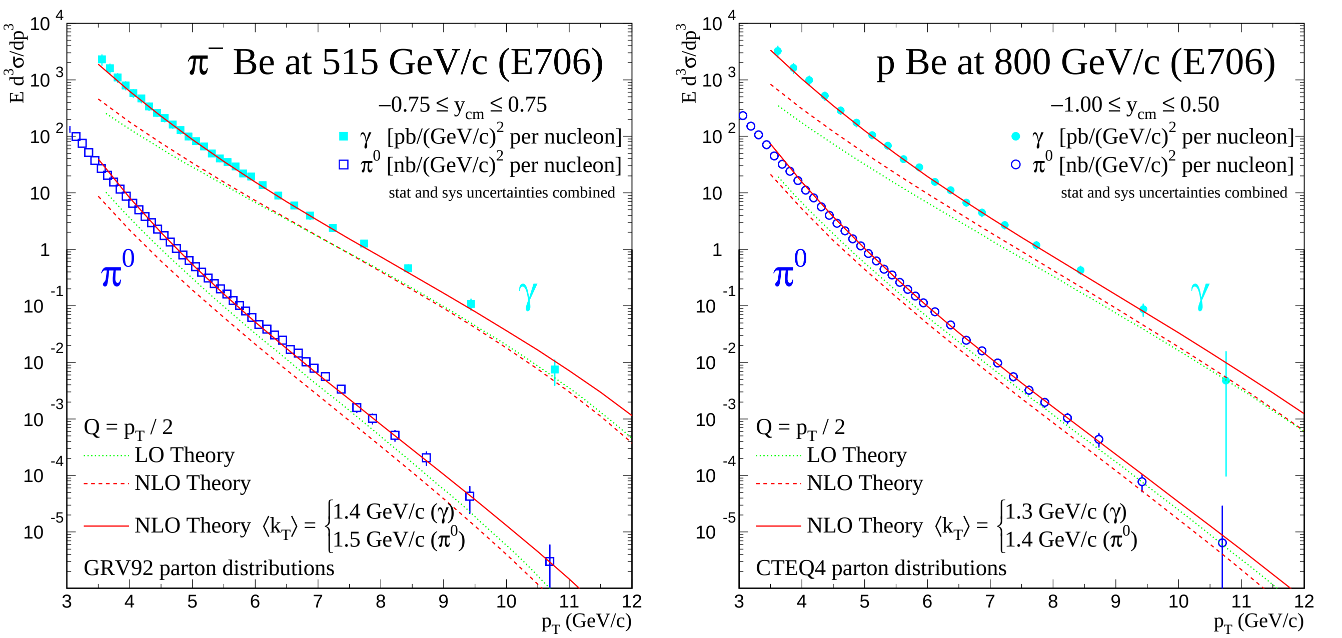

FIG. 3. Invariant cross sections (per nucleon) for direct-photon and π^0 production in π^-Be interactions at 515 GeV/c (left) and pBe interactions at 800 GeV/c (right). Cross sections are shown as a function of p_T averaged over the full rapidity range. Curves represent LO (dotted) and NLO (dashed) pQCD calculations and a k_T-enhanced NLO result (solid) for scale $Q = p_T/2$.

We use leading-order (LO) pQCD calculations [15] which include Gaussian k_T smearing to create K-factors (Fig. 2), and then apply these K-factors to the NLO calculations. We recognize that this procedure involves a risk of double-counting since some of the k_T-enhancement may already be contained in the NLO calculation. However, we expect such double-counting effects to be small. The k_T-enhancements (using values consistent with the high-mass pair data) are successful in describing both the shape and normalization of both the direct-photon and π^0 cross sections (Figs. 2 and 3).

III. COMPARISONS WITH OTHER EXPERIMENTS

We can use this phenomenological k_T model to compare with cross sections from other experiments. The consequences of k_T smearing are expected to depend on $\sqrt{s}$ (Fig. 1). At the Tevatron collider [16], where p_T is large compared to k_T, the above model of soft-gluon radiation leads to a relatively small modification of the NLO cross section. Only the lowest end of the p_T spectrum is significantly modified (Fig. 4). CDF has measured an average transverse momentum of photon pairs of $\langle p_T \rangle_{pair} = 5.1 \pm 1.1$ GeV$/c$ at $\sqrt{s} = 1.8$ TeV [17]. Employing this value, the phenomenological model adequately describes the excess of data over NLO theory at low-p_T for both CDF and D0. The agreement between the phenomenological model and the collider direct-photon data can also be seen in preliminary CDF data at $\sqrt{s} = 630$ GeV (Fig. 4 (right)).

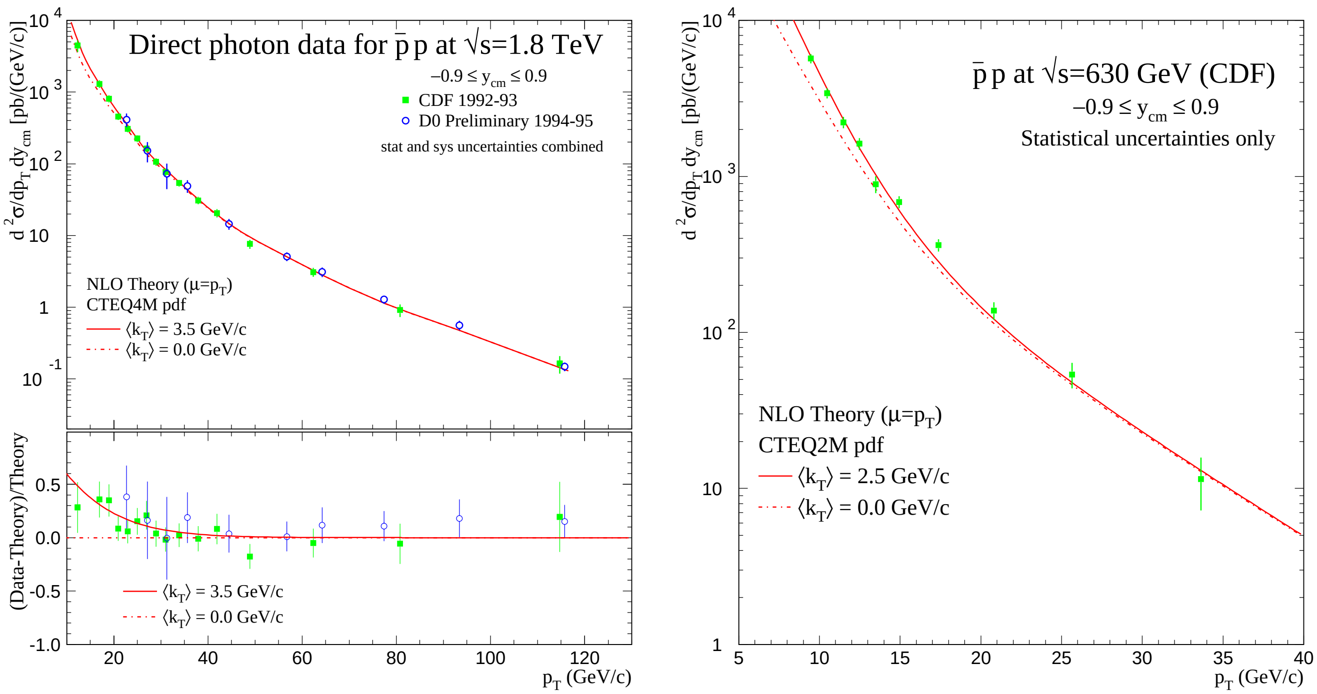

FIG. 4. Left: Isolated direct-photon cross sections from CDF and D0 at $\sqrt{s} = 1.8$ TeV. Overlayed on the data are the results of the NLO calculations with (solid) and without (dashed) k_T enhancements for $\langle k_T \rangle = 3.5$ GeV$/c$.
Right: Preliminary, isolated direct-photon cross section for CDF at $\sqrt{s} = 630$ GeV. Overlayed on the data are the results of the NLO calculations with (solid) and without (dashed) k_T enhancements for $\langle k_T \rangle = 2.5$ GeV$/c$.

Comparisons are also shown for the lower energy WA70 [18] (Fig. 5) and UA6 [19] data (Fig. 6). Both WA70 and UA6 have measured direct-photon and π^0 production with good statistics, and their direct-photon data have been included in recent global parton distribution fits. The center-of-mass energies for these two experiments ($\sqrt{s} \approx 24$ GeV) are lower than those for E706. Correspondingly, $\langle k_T \rangle$ values for these experiments are expected to be slightly smaller than the values used for E706. WA70 measured $\langle k_T \rangle = 0.9 \pm 0.1 \pm 0.2$ GeV$/c$ using their diphoton sample [20]. We therefore use this $\langle k_T \rangle$ as the central value for the k_T-enhancement factors for both experiments and vary the $\langle k_T \rangle$

by ±0.2 GeV/c (Figs. 5 and 6). Over the narrower p_T range of the WA70 and UA6 measurements, the effect of k_T is essentially to produce a shift in normalization. The k_T-enhanced theory compares well with the π^0 cross sections and with the UA6 and π^- beam WA70 direct-photon cross sections.

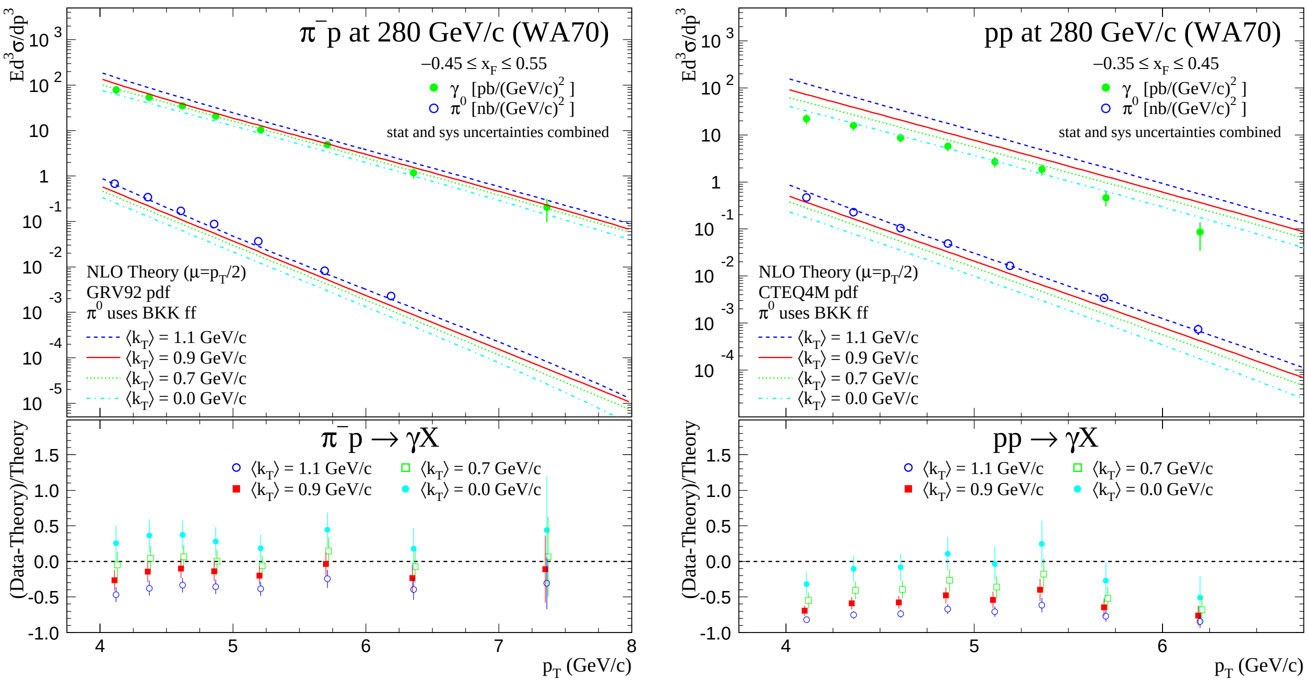

FIG. 5. Invariant cross sections for direct-photon and π^0 production from WA70. Overlayed on the data are the results of the NLO calculation with k_T enhancements for several values of $\langle k_T \rangle$. A linear comparison is shown for the direct-photon data.

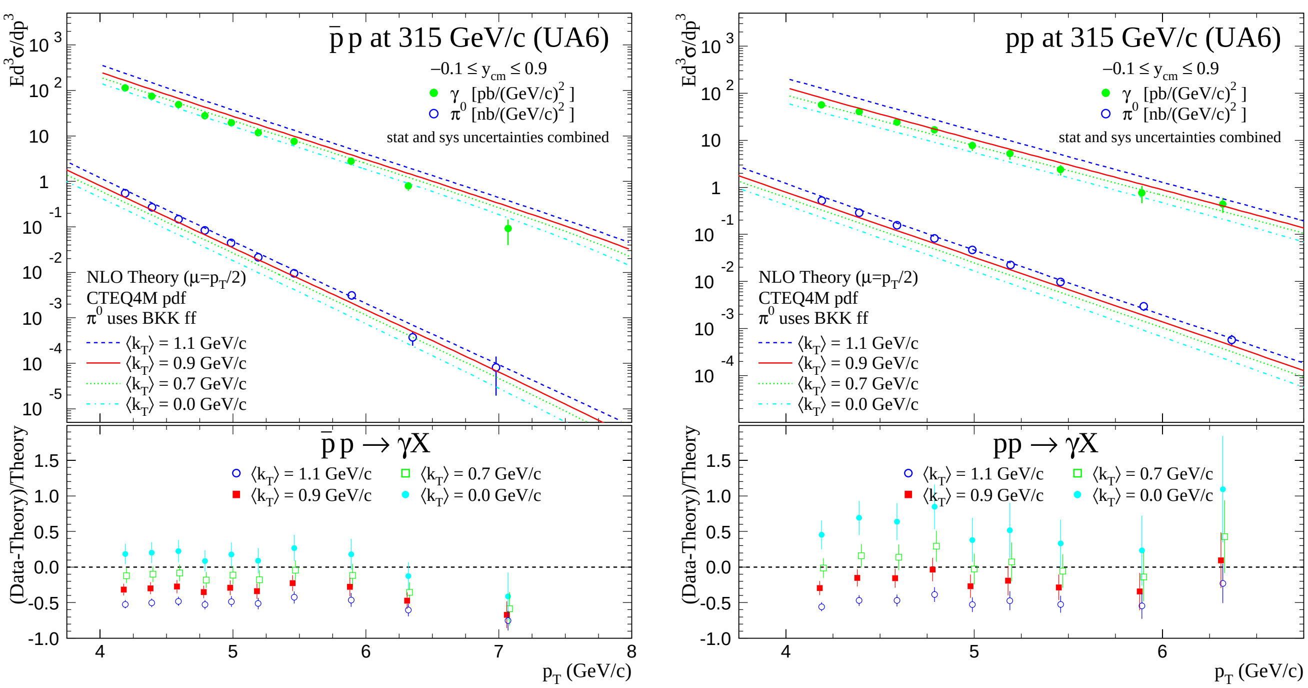

FIG. 6. Invariant cross sections for direct-photon and π^0 production from UA6. Overlayed on the data are the results of the NLO calculation with k_T enhancements for several values of $\langle k_T \rangle$. A linear comparison is shown for the direct-photon data.

IV. GLUON DISTRIBUTION

It is generally accepted that the uncertainty on the gluon distribution at large x is still quite large [21]. Thus, it is important to incorporate further constraints on the gluon, especially from direct-photon data. To investigate the impact of k_T effects on determinations of the gluon distribution, we have included the E706 direct-photon cross sections for incident protons, along with deep-inelastic scattering and Drell-Yan data that were used in determining the CTEQ4M PDFs, in a global fit to the parton distribution functions. The CTEQ fitting package was employed to obtain these results [22], using the NLO pQCD calculations for direct-photon cross sections, adjusted by the k_T-enhancement factors. The WA70, UA6, CDF, and D0 direct-photon and jet data were excluded from this particular fit. The resulting gluon distribution, shown in Fig. 7, is similar to CTEQ4M, as expected, since the k_T-enhanced NLO calculations using CTEQ4M provide a reasonable description of the E706 data (Figs. 2 and 3).

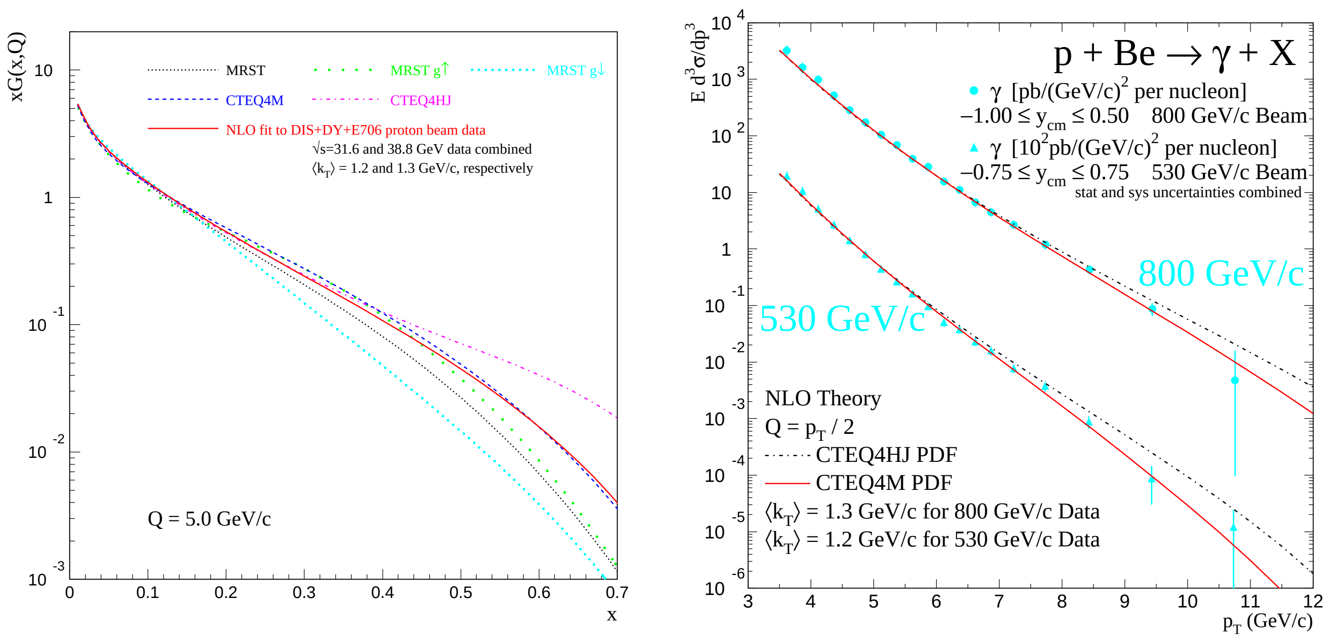

FIG. 7. Left: A comparison of the CTEQ4M, MRST, and CTEQ4HJ gluons, and the gluon distribution derived from fits that use E706 data. The $g\uparrow$ and $g\downarrow$ gluon densities correspond to the maximum variation in $\langle k_T \rangle$ that MRST allowed in their fits.
Right: The invariant direct-photon cross-section from the E706 proton beam data overlayed with k_T-enhanced NLO calculations using CTEQ4M (solid) and CTEQ4HJ (dash-dot) PDFs.

The MRST gluon distribution [23] (also shown in Fig. 7) is significantly lower than CTEQ4M at large x. While the MRST fit employs k_T enhancements (obtained using a different, analytical integration, technique), it attempts to accommodate the WA70 incident-proton direct-photon data, which does not exhibit an obvious k_T effect [24] (Fig. 5). In contrast, the CTEQ4HJ gluon distribution [22], designed to improve the description of the high-p_T jet data from CDF, is much larger than CTEQ4M in the same x range. (A comparison between the E706 direct-photon data and the calculations using CTEQ4M and CTEQ4HJ PDFs is shown in the right-side of Fig. 7 to illustrate the sensitivity of the direct-photon data to the gluon distribution.) This spread of solutions for the gluon distribution is uncomfortably large, and additional theoretical work is warranted to properly incorporate the available direct-photon data in the PDF fits.

V. CONCLUSION

Discrepancies between NLO pQCD calculations and direct-photon cross sections have been observed; they are particularly striking in the high statistics data from E706. The suspected origin of the disagreements is from the effects of initial-state soft-gluon radiation. A resummed pQCD calculation, which incorporates the effects of multiple soft-gluon emission, is sufficient to describe the shapes of kinematic distributions of high-mass direct-photon pairs. Pending completion of resummed calculations for inclusive direct-photon production, we employed a phenomenological model to incorporate k_T effects in pQCD calculations of direct-photon and π^0 production. Using $\langle k_T \rangle$ values consistent with the high-mass pair data, we find that the k_T-enhanced theory compares well with the π^0 cross sections and with the CDF, D0, E706, UA6, and π^- beam WA70 direct-photon cross sections. Further theoretical work in this area would be valuable for reducing the uncertainties on the gluon distribution at medium to high x.

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