Photons and Diphotons from E706

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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-γ and π^0 pairs are used to explore the impact of parton-k_T. We present comparisons of a phenomenological k_T model to recent fixed-target and collider inclusive data. Our approach provides a consistent prescription for correcting observed deviations of NLO pQCD calculations from inclusive direct-γ and π^0 data. We also comment on the implications of these results for the extraction of the gluon distribution, $G(x)$.

Direct-γ production has long been viewed as an ideal process for measuring $G(x)$ in the proton as the Compton scattering subprocess ($gq \to \gamma q$) provides a large contribution to direct-γ production. $G(x)$ is relatively well constrained for $x < 0.1$ by DIS and DY data, but less so at larger x. Direct-γ data can constrain the PDFs at intermediate and large x.

A pattern of deviation has been noted [1] between measured direct-γ cross sections and NLO pQCD [2]. The suspected origin of the disagreement is initial-state soft-gluon radiation, which we refer to as k_T-effects. Distributions of high-mass pairs of particles probe the k_T of incident partons in hard-scattering events. Evidence of significant k_T has been observed in measurements of $\mu^+\mu^-$, $\gamma\gamma$, and dijets [3]. From these data, one can infer $\approx$ 1 GeV/c k_T/parton at fixed-target energies, which increases to 3-4 GeV/c at the Tevatron collider, while one would expect $k_T \approx 0.4$ GeV/c based solely on proton size.

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 [5] and a large, Pb–LAr, sampling electromagnetic calorimeter [6]. The experiment accumulated data for 515 GeV π^- and π^+ beams, and for 530 GeV and 800 GeV p beams, on Be, Cu, and H targets.

Distributions for high-mass direct-γ pairs as functions of pair transverse momentum (Q_T), azimuthal angle between the photons ($\Delta\phi$), and out-of-plane momentum ($p_{\rm OUT}$) are shown in Fig. 1. Overlayed on the data are both NLO [7] and resummed [8] pQCD calculations. The shape of the NLO calculation is inconsistent with the data. The resummed calculation (Resbos), which incorporates the effects of multiple soft-gluon emission, provides a reasonable match to the data shape. Also shown are $\gamma\gamma$ distributions from pythia [9], which approximates k_T effects through a Gaussian smearing technique.

Studies of high-mass π^0 pairs [4] and away-side fragmentation distributions also show evidence of substantial k_T, as do our comparisons of the high-p_T $D^\pm$ cross section to NLO pQCD [5]. All these results suggest $\langle k_T \rangle \approx 1$ GeV/c. Similar soft-gluon effects are expected in other hard-scattering processes, such as the inclusive production of jets or direct-photons [10,11].

Invariant cross sections for inclusive direct-γ and π^0 production are displayed in Fig. 2, with overlays from theory. Discrepancies between NLO pQCD and data are particularly striking. Efforts to provide k_T resummed pQCD calculations for single direct-γ production are underway [12], but since current NLO calculations do not account for the effects of multiple soft-gluon emission, we employed a phenomenological model to incorporate k_T effects in direct-γ and π^0 pQCD [4,3]. We use LO pQCD [13], which includes Gaussian k_T smearing, to estimate k_T-enhancements [3], and then apply these factors

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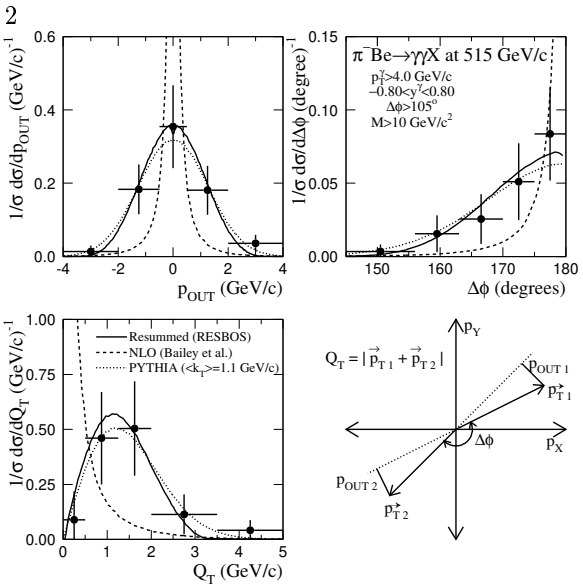

Figure 1. Distributions of high-mass direct-photon pairs from E706. Overlays are the results from NLO (dashed) and resummed (solid) calculations. PYTHIA results (dotted) with $\langle k_T \rangle = 1.1$ GeV/c are also shown.

to the NLO calculations. Our phenomenological k_T-enhanced NLO calculations (using k_T values consistent with the high-mass pair data) are successful in describing the shape and normalization of the direct-γ and π^0 cross sections (Fig. 2).

We have used this phenomenological k_T model to compare with cross sections from other experiments. The consequences of k_T smearing are expected to depend on $\sqrt{s}$. At the Tevatron collider [14], where $p_T >> k_T$, 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 affected (Fig. 3). CDF has measured $\langle p_T \rangle_{pair} = 5.1 \pm 1.1$ GeV/c for $\gamma\gamma$ production at $\sqrt{s} = 1.8$ TeV [15]. Employing this value, our phenomenological model describes adequately the excess of data over NLO theory at low-p_T for both CDF and D0.

Comparisons are also shown for the lower energy WA70 [16] and UA6 [17] data (Fig. 4). WA70 measured $\langle k_T \rangle = 0.9 \pm 0.1 \pm 0.2$ GeV/c using their $\gamma\gamma$ sample [18]. We use this $\langle k_T \rangle$ as the central value for calculating k_T-enhancements in both experiments (Fig. 4). The k_T-enhanced model is in good agreement with the π^0 and with the UA6 and π^- beam WA70 direct-γ cross sections.

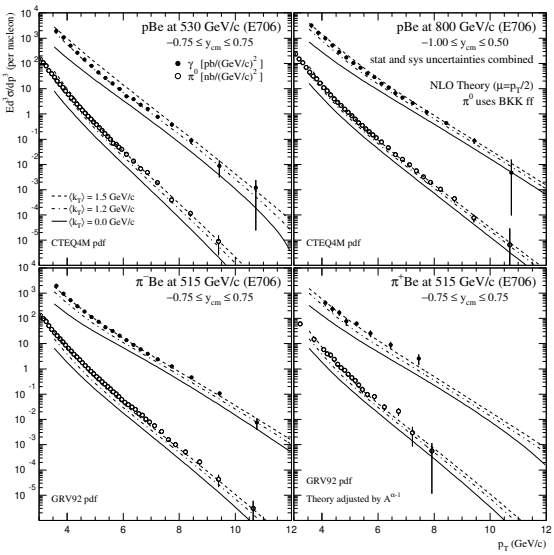

Figure 2. Invariant cross sections for direct-γ and π^0 production from E706. Curves represent NLO pQCD with and without k_T-enhancements.

It is generally accepted that the uncertainty on $G(x)$ at large x is still quite large. Thus, it is important to incorporate further constraints on the gluon, especially from direct-γ data. To investigate the impact of k_T effects on the determination of $G(x)$, we included the E706 direct-γ cross sections for incident protons, along with DIS and DY data used in determining the CTEQ4M PDFs, in a new global fit. The CTEQ fitting package was employed to obtain these results [19], using NLO pQCD for direct-γ cross sections, adjusted by the k_T-enhancement factors. The WA70, UA6, CDF, and D0 direct-γ and all inclusive jet data were excluded from this fit. The resulting $G(x)$, shown in Fig. 5, is similar to that from CTEQ4M, as expected, since the k_T-enhanced NLO calculations using CTEQ4M provide a reasonable description of the E706 data (Fig. 2). At large x the MRST gluon distribution [20] (Fig. 5) is significantly lower than that of CTEQ4M. While the MRST fit employs k_T enhancements, it attempts to accommodate the WA70 incident proton direct-γ data, which do not exhibit an obvious k_T effect.

The spread of solutions for $G(x)$ is uncomfortably large, and additional theoretical work is warranted to properly incorporate the available direct-γ data in the PDF fits in order to reduce $G(x)$ uncertainties at medium to high x.

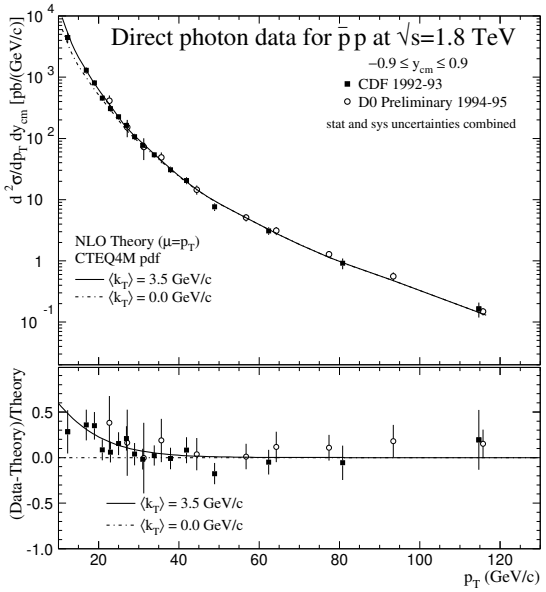

Figure 3. Isolated direct-γ cross sections from CDF and D0. NLO pQCD with k_T-enhancement is consistent with the data.

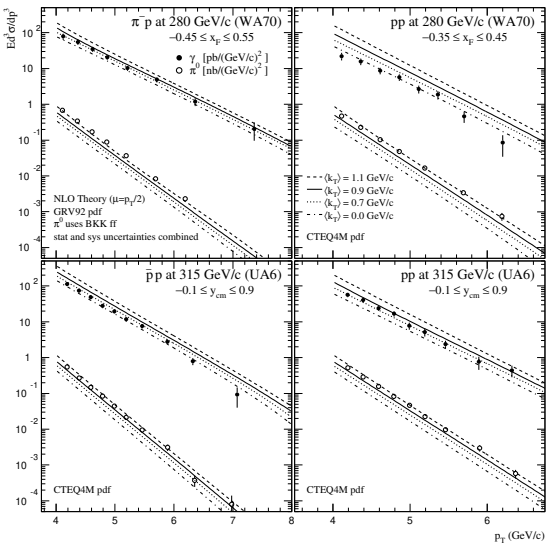

Figure 4. Invariant cross sections for direct-γ and π^0 production from WA70 (top) and UA6 (bottom). NLO calculations with and without k_T enhancements are overlayed on the data.

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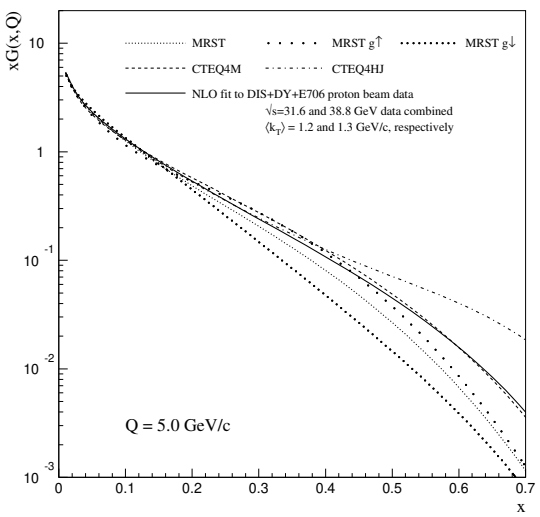

Figure 5. A comparison of the CTEQ4M, MRST, and CTEQ4HJ gluons, and $G(x)$ derived from fits that use E706 data. The $g\uparrow$ and $g\downarrow$ gluon densities correspond to the maximum variation in $\langle k_T \rangle$ that MRST allowed in their fits.