We present comparisons of high-$p_T$ photon and pion production in hadronic interactions with expectations from next-to-leading order perturbative QCD (NLO pQCD). We also comment on phenomenological models of $k_T$ smearing (which approximate effects of additional soft-gluon emission) and on the status of resummation calculations.

Direct-photon production in hadronic collisions at high transverse momenta ($p_T$) has long been viewed as an ideal testing ground for the formalism of pQCD. A reliable theoretical description of the direct-photon process is of special importance because of its sensitivity to the gluon distribution in a proton through the quark–gluon scattering subprocess ($gq \to \gamma q$). The gluon distribution, $G(x)$, is relatively well constrained for $x < 0.25$, but much less so at larger $x$. In principle, fixed-target direct-photon production can constrain $G(x)$ at large $x$, and such data have therefore been incorporated in fits to global parton distribution functions (PDF).

However, both the completeness of the NLO description of the direct-$\gamma$ process, as well as the consistency of results from different experiments, have been questioned. The inclusive production of hadrons provides a further means for testing predictions of the NLO pQCD formalism. Deviations have, in fact, been observed between measured inclusive direct-$\gamma$ and pion production cross sections and NLO pQCD calculations, and it has been suggested that part of this discrepancy can be ascribed to higher-order effects of initial-state soft-gluon radiation. However, it seems unlikely that theoretical developments alone will be able to accommodate the observed level of scatter in the ratio of data to theory for $\gamma$ and $\pi^0$ yields. These observations motivated us to consider measurements of the $\gamma/\pi^0$ ratio over a wide range of $\sqrt{s}$. Both experimental and theoretical uncertainties tend to cancel in such a ratio, and the ratio should also be less sensitive to incomplete treatment of gluon radiation. A sample of the ratio of direct-$\gamma$ to $\pi^0$ cross sections for both data and NLO pQCD is given in Fig. 1 for incident protons, as a function of $x_T = 2p_T/\sqrt{s}$, for $\sqrt{s} \approx 23 - 24$ GeV (left) and $\sqrt{s} = 31 - 39$ GeV (right). For all measurements in the left panel, theory is high compared to data; similar levels of agreement are observed at $\sqrt{s} = 19.4$ GeV. At larger $\sqrt{s}$, the NLO value for the ratio agrees better with experiment, as seen in Fig. 1 (right) for $\sqrt{s} = 31 - 39$ GeV. At even higher $\sqrt{s}$, theory lies slightly below the data. (The NLO calculations use a single scale of $\mu = p_T/2$, CTEQ4M PDFs and BKK fragmentation functions for pions.) A compilation of these results, shown for simplicity without their un-
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Figure 1: Left: Comparison of $\gamma/\pi^0$ rates as a function of $x_T$ for WA70, NA24, and UA6 at $\sqrt{s} \approx 23 - 24$ GeV. Overlayed are the results from NLO pQCD. Right: Same for R806 at $\sqrt{s} = 31$ GeV and E706 at $\sqrt{s} = 31.6$ and 38.8 GeV.

certainty, is presented in Fig. 2 (left). Here, the ratios of data to theory for the ratio of $\gamma$ to $\pi^0$ yields (e.g., in Fig. 1) were fitted as constant values at high $p_T$, and the results plotted as a function of $\sqrt{s}$. The figure suggests an energy dependence in the ratio of data to theory for the $\gamma/\pi^0$ production ratio. There are also substantial differences between the experiments at low $\sqrt{s}$ (where the observed $\gamma/\pi^0$ is smallest), which makes it difficult to quantify this trend. Recognizing the presence of these differences is especially important because thus far only the low energy photon experiments have been used in PDF fits to extract $G(x)$.

Recently, an intuitive, and often successful, phenomenological approach has been used to describe soft gluon radiation in high-$p_T$ inclusive production, parametrized in terms of an effective $k_T$ that provided additional transverse impulse to the outgoing partons. At fixed-target energies, the resulting corrections for direct-$\gamma$ and $\pi^0$ production can be large over the full range of $p_T$. The corrections depend on the values used for $\langle k_T \rangle$, with changes of 200 MeV/c making substantial difference. It is therefore difficult to obtain the precision needed for extracting global parton distributions. In addition, there are different ways to implement such models, which can produce quantitative differences in the $k_T$-correction factors.

Resummed pQCD calculations for single direct-$\gamma$ production are currently under development. Two recent threshold-resummed pQCD calculations for direct photons exhibit far less dependence on QCD scales than NLO theory, and provide an enhancement at high $p_T$. A method for simultaneous treatment of recoil and threshold corrections in inclusive single-$\gamma$ cross sections is also being developed. This approach accounts explicitly for the recoil from soft radiation in the hard scattering, and conserves both energy and transverse momentum for the resummed radiation. The possibility of substantial enhancements from higher-order pertur-
Figure 2: Left: The ratio of data for the $\gamma/\pi^0$ measurements to NLO theory, as a function of $\sqrt{s}$. Right: Comparison between the E706 direct-photon data at $\sqrt{s} = 31.6$ GeV and recent pQCD calculations. The dotted line represents the full NLO calculation, while the dashed and solid lines, respectively, incorporate purely threshold resummation and joint threshold and recoil resummation.

bative and power-law nonperturbative corrections relative to NLO are indicated at both moderate and high $p_T$ for fixed-target energies (Fig. 2 (right)), similar to the enhancements obtained with simple $k_T$-smearing. These recent developments in theory of direct-$\gamma$ processes provide cause for optimism that the long-standing difficulties in developing an adequate description of direct-$\gamma$ production can eventually be resolved, making possible a reliable extraction of $G(x)$ from such data.

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