Photon and Pion Production at High $p_T$

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Abstract. We present a study of high-$p_T$ photon and pion production in hadronic interactions, focusing on a comparison of the yields with expectations from next-to-leading order perturbative QCD (NLO pQCD). We examine the impact of phenomenological models of $k_T$ smearing (which approximate effects of additional soft-gluon emission) on absolute predictions for photon and pion production and their ratio.

Single and double direct-photon production in hadronic collisions at high transverse momenta ($p_T$) have 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 ($gq \rightarrow \gamma q$). The gluon distribution, $G(x)$, is relatively well constrained for $x < 0.1$, but much less so at larger $x$ [1]. In principle, fixed-target direct-photon production can constrain $G(x)$ at large $x$, and such data have therefore been incorporated in several modern global parton distribution function (PDF) analyses [2–4].

However, both the completeness of the NLO description of the direct-photon process, as well as the consistency of results from different experiments, have been questioned [4–11]. The inclusive production of hadrons provides a further means of testing the predictions of the NLO pQCD formalism. Deviations have been observed between measured inclusive direct-photon and pion cross sections and NLO pQCD calculations. Examples of such discrepancies are shown in Fig. 1 where ratios of data to theory are displayed as a function of $x_T = 2p_T/\sqrt{s}$ for photon and pion data. (Unless otherwise indicated, all NLO calculations [12–16] in this paper use a single scale of $\mu = p_T/2$, CTEQ4M PDFs [2], and BKK fragmentation functions for pions [17].) It has been suggested that part of the deviations from theory for both photons and pions can be ascribed to higher-order effects of initial-state soft-gluon radiation [6–8].

Given the scatter of the data shown in Figs. 1, it may be instructive to consider measurements of the $\gamma/\pi^0$ ratio over a wide range of $\sqrt{s}$ [18]. 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 compilation of comparisons between data and theory, shown for simplicity without their uncer-
The differences between many of the data sets and pQCD, seen in Fig. 1, may be due to the impact of the effective parton transverse momentum, $k_T$. In hadronic hard-scattering processes, there is generally a substantial amount of $k_T$ in the initial state resulting from gluon emission [8]. The presence of $k_T$ impacts the final state and has been observed in measurements of Drell-Yan, diphoton, and heavy quark production; the amount of $k_T$ expected from NLO calculations is not sufficient to describe the data. The effective values of $\langle k_T \rangle$/parton for these processes vary from $\approx 1$ GeV/$c$ at fixed target energies, as illustrated in Fig. 2 for diphoton distributions from E706 [19], to 3–4 GeV/$c$ at the Tevatron Collider — the growth is approximately logarithmic with center-of-mass energy [8]. The size of the $\langle k_T \rangle$ values, and their dependence on energy, argue against a purely "intrinsic" non-perturbative origin. Rather, the major part of this effect is generally attributed to soft-gluon emission. While the importance of including gluon emission through the resummation formalism has long been recognized and calculations have been available for some time for Drell-Yan [20], diphoton [21,22], and W/Z production [21], they have only recently been developed for inclusive direct-photon production [23–28].

In the absence of a rigorous theoretical treatment of the impact of gluon emission on high-$p_T$ inclusive production, a more intuitive phenomenological approach has proved successful [8]. The soft gluon radiation was parametrized in terms of an effective $\langle k_T \rangle$ that provided an additional transverse impulse to the outgoing...
partons. Because of the steeply falling cross section in $p_T$, such a $\langle k_T \rangle$ can shift the production of final-state particles from lower to higher values of $p_T$, effectively enhancing the cross section.

As described in [8], a leading-order (LO) pQCD calculation [29] has been used to generate K-factors (ratios of calculations for any given $\langle k_T \rangle$ to the result for $\langle k_T \rangle = 0$) for inclusive cross sections. These $p_T$-dependent factors have been then applied to the NLO pQCD calculations. The enhancements that would be expected for direct-photon production from parton-showering models [30,31] have also been investigated [18]. These programs do not provide sufficient smearing at fixed-target energies because shower development is constrained by cut-off parameters that ensure the perturbative nature of the process. Consequently, these calculations allow additional input $k_T$ for Gaussian smearing, and are often used that way in comparisons to data. The respective corrections have been obtained using default settings for other program parameters and an input $\langle k_T \rangle$ of 1.2 GeV/c for the smearing, relative to these same settings with $\langle k_T \rangle = 0$, and then applied to NLO pQCD calculations. The resulting comparisons to data from E706 [7] are displayed in Fig. 3 (similar results hold for pion production, not shown). The observed differences should be kept in mind when comparing these models to data for $k_T$-sensitive quantities.

Recently, there has been significant progress in more rigorous resummed pQCD calculations for single direct-photon production [23–28]. Substantial corrections to fixed-order QCD calculations are expected from soft-gluon emission, especially in regions of phase space where gluon emission is restricted kinematically. At large $x$, there is a suppression of gluon radiation due to the rapidly falling parton distributions and a complete description of the cross section in this region requires the resummation of “threshold” terms. Two recent threshold-resummed pQCD
FIGURE 3. Left: Comparison between the E706 direct-photon data at $\sqrt{s} = 31.6$ GeV [7] and the NLO pQCD calculation (solid), and the NLO theory enhanced by K-factors obtained using the LO calculation [29] (dashed), HERWIG [31] (dotted), and PYTHIA [30] (dash-dotted). Right: Same data compared to recent QCD calculations. The dotted line represents the full NLO calculation [14], while the dashed and solid lines, respectively, incorporate purely threshold resummation [23] and joint threshold and recoil resummation [28].

calculations for direct photons [23,24] exhibit far less dependence on QCD scales than found in NLO theory. These calculations agree with the NLO prediction for the scale $\mu \approx p_T/2$ at low $p_T$ (without inclusion of explicit $k_T$ or recoil effects), and show an enhancement in cross section at high $p_T$.

A method for simultaneous treatment of recoil and threshold corrections in inclusive single-photon cross sections is being developed [28] within the formalism of collinear factorization. This approach accounts explicitly for the recoil from soft radiation in the hard-scattering subprocess, and conserves both energy and transverse momentum for the resummed radiation. The possibility of substantial enhancements from higher-order perturbative and power-law nonperturbative corrections relative to NLO are indicated at both moderate and high $p_T$ for fixed-target energies, similar to the enhancements obtained with the simple $k_T$-smearing model discussed above. Figure 3 (right) displays the results of an example calculation [28] based on this approach compared with direct-photon measurements from E706.

While there is still no resummation calculation for inclusive pion production, the trend of recent developments in direct-photon processes has led to an increased appreciation of the importance of the effects of multiple gluon emission, and to the emergence of tools for incorporating these effects. These latest theoretical developments encourage optimism that the long-standing difficulties in developing an adequate description of these processes can eventually be resolved, making possible a global re-examination of parton distributions with an emphasis on the determination of the gluon distribution from the direct-photon data [32].
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