Direct Photon Production at High p_T in π^-Be and pBe Collisions at 500 GeV/c

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We report new measurements of inclusive direct photon production at high transverse momenta (p_T) for π^- and p interactions on Be at 500 Gev/c. The yields as a function of p_T and rapidity (y) are in good agreement with expectations from next-to-leading-log QCD calculations employing recently extracted quark and gluon structure functions.

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The importance of studying direct photon production arises from the elementary nature of the photon and its well-understood electromagnetic coupling. Any hard-scattering process that emits a gluon from a quark vertex can also give rise to a photon, albeit with a cross section reduced by the ratio of the electromagnetic to strong-coupling constants. Such directly produced photons can emerge as free particles, carrying all the p_T that was imparted to them in the primary collision, whereas gluons must neutralize their color charge by fragmenting into jets of hadrons of reduced p_T. At the constituent level, only two leading-order processes contribute to direct photon production: In p-nucleon collisions, the Compton reaction $qg \rightarrow q\gamma$ is expected to dominate, while in π^--nucleon collisions, even at moderate values of p_T (≥ 6 GeV/c), the annihilation reaction $\bar{q}q \rightarrow g\gamma$ should be equally important. These features make direct photon production an excellent tool for investigating QCD phenomenology.

We report here on new measurements of direct photon production for π^- and p interactions on Be at 500 GeV/c, and compare these results with next-to-leading-log (NLL) QCD calculations. The data are from Fermilab experiment E706, which also provided measurements of high-p_T inclusive π^0 production, as described in a separate paper [1].

The primary background in a fixed-target direct photon experiment arises from two sources: muons in the beam halo and two-photon decays of π^0 and η mesons. Muons can occasionally produce showers in the electromagnetic calorimeter (EMLAC); when such showers occur in random coincidence with interactions in the target, and, especially when these showers are at large distances relative to the beam axis, they can produce high-p_T electromagnetic triggers. Most such events are rejected at the trigger level using two walls of veto counters located upstream of the target. In addition, timing and entrance angle information on EMLAC showers are used off-line to eliminate any residual muon-induced background. Interactions in which π^0 or η mesons decay such that one of the two photons either misses the EMLAC or else falls below its effective energy threshold (characteristic of decays involving highly asymmetric photon energies) simulate genuine direct photon events, and must therefore be corrected for on a statistical basis. Since γ/π^0 production ratios at moderate values of p_T are typically much less than unity, extracting the true direct photon signal requires an excellent understanding of an experiment's π^0 (and η) detection capabilities. Our understanding of the EMLAC is illustrated in our paper on inclusive π^0 production [1] by the observed energy asymmetry of photon pairs in the π^0 mass region, which is a particularly impor-

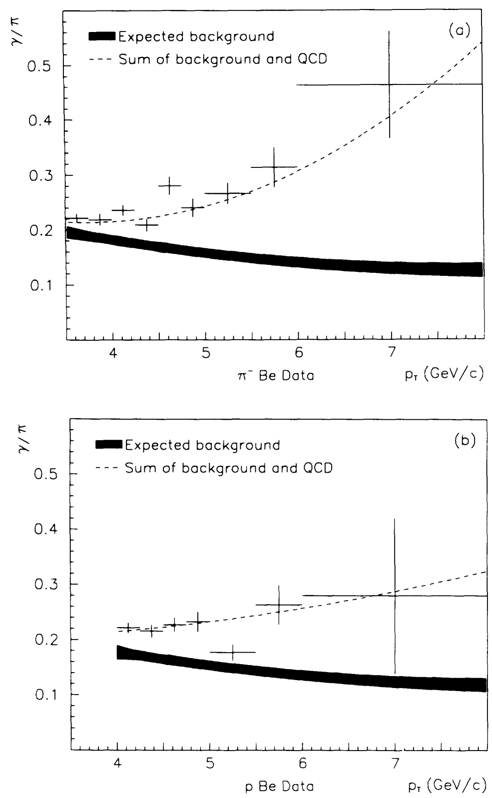

FIG. 1. The observed γ/π^0 ratios at 500 GeV/c. The lower bands are Monte Carlo estimates of the contributions from meson decays, with widths representing the uncertainty of these estimates. The curves are sums of the contributions from meson decays and leading-log calculations of the true γ/π^0 ratios (see text), (a) for π^-Be collisions and (b) for pBe collisions. The error bars on the points represent only statistical uncertainties.

tant comparison since the roll-off in this distribution at high values of asymmetry is a direct measure of the amount of π^0 feed-down into the direct photon sample. We have compared our Monte Carlo simulation with the measured data in a variety of other ways (e.g., mass and energy distributions), and have observed comparable levels of agreement.

Figures 1(a) and 1(b) display the observed γ/π^0 production ratios for π^-Be and pBe interactions, respectively. Photons contributing to $\gamma\gamma$ pairs in the π^0 or η regions (with energy asymmetries less than 0.75) are excluded from the direct photon sample; however, no isolation cuts are imposed. The lower bands are Monte Carlo estimates of the residual contributions to these ratios from photons originating from meson decays; about 80% of this background is due to π^0 decays and the rest is dominantly due to η mesons [2]. The upper curves correspond to the sums of the median background estimates and the expected γ/π^0 ratios calculated from leading-log QCD. The calculations are by Owens, using a recently extracted set of nucleon structure functions [3]. The

TABLE I. Invariant cross sections per nucleon for inclusive direct photon production in π^-Be and pBe collisions at 500 GeV/c, averaged over $|y| \le 0.7$ and the indicated p_T bands. (The pBe data were acquired using a higher p_T-trigger threshold.) The first uncertainty is statistical, the second systematic; there are also independent systematic uncertainties of $\pm 0.9\%$ in the absolute p_T scale, and $\pm 2\%$ in the mean value of the incident momentum (see Ref. [1]).

p_T (GeV/c)	$\pi^- + \mathrm{Be} \to \gamma + X$ (pb/GeV^2)	$p + \mathrm{Be} \to \gamma + X$ (pb/GeV^2)
3.5–3.75	$540 \pm 140 \pm 200$	⋯
3.75–4.0	$299 \pm 89 \pm 83$	⋯
4.0–4.25	$252 \pm 40 \pm 60$	$168 \pm 30 \pm 42$
4.25–4.5	$86 \pm 26 \pm 23$	$91 \pm 20 \pm 21$
4.5–4.75	$124 \pm 16 \pm 24$	$60 \pm 11 \pm 14$
4.75–5.0	$53 \pm 10 \pm 10$	$33 \pm 7 \pm 7$
5.0–5.5	$32 \pm 5 \pm 6$	$5.6 \pm 2.8 \pm 1.8$
5.5–6.0	$15 \pm 3 \pm 3$	$6.2 \pm 1.6 \pm 1.2$
6.0–7.0	$5.4 \pm 0.9 \pm 0.9$	$1.3 \pm 0.4 \pm 0.2$
7.0–8.0	$0.5 \pm 0.2 \pm 0.1$	$0.06 \pm 0.08 \pm 0.01$
8.0–10.0	$0.16 \pm 0.08 \pm 0.03$	< 0.02

background estimates were obtained from the previously mentioned Monte Carlo simulation, which was tuned to reproduce the observed characteristics of our reconstructed π^0 and η events. A statistically significant direct photon signal is evident above the estimated background at all values of p_T for both π^- and proton data.

Table I presents the invariant cross sections per nucleon for inclusive direct photon production in π^-Be and pBe collisions at 500 GeV/c. The data are for $|y| \le 0.7$, and have been corrected for acceptance and trigger effects. The dominant contributions to the systematic errors presented in Table I are the uncertainty in the absolute normalization ($\pm 10\%$), and in the π^0 and η background subtraction ($\pm 21\%$ at $p_T = 4$ GeV/c, falling to 3% at 8 GeV/c for π^-Be and $\pm 24\%$ at $p_T = 4$ GeV/c, falling to 5% at 8 GeV/c for pBe). The results in Table I are in general agreement with trends displayed by earlier experiments, which in the case of π^--induced collisions [4] are all at lower energy, whereas for p-induced collisions [5] the energy of this experiment falls between those of previous fixed-target and CERN ISR experiments.

Figures 2(a) and 2(b) display our results for three rapidity intervals. Shown for comparison are representative NLL QCD calculations by Aurenche and co-workers [6], using the nucleon structure function sets of Aurenche-Baier-Fontannez-Owens-Werlen [7] and the pion structure functions of Aurenche, Baier, Fontannez, Kienzle, Focacci, and Werlen [8]. The dashed curves employ the principle of minimum sensitivity (PMS) [9], and the dotted curves are calculated using a fixed Q^2 scale of $p_T^2/4$. The curves in Fig. 2 are absolute QCD predictions that do not use our data as input. Our data are in general agreement with these predictions, especially those carried

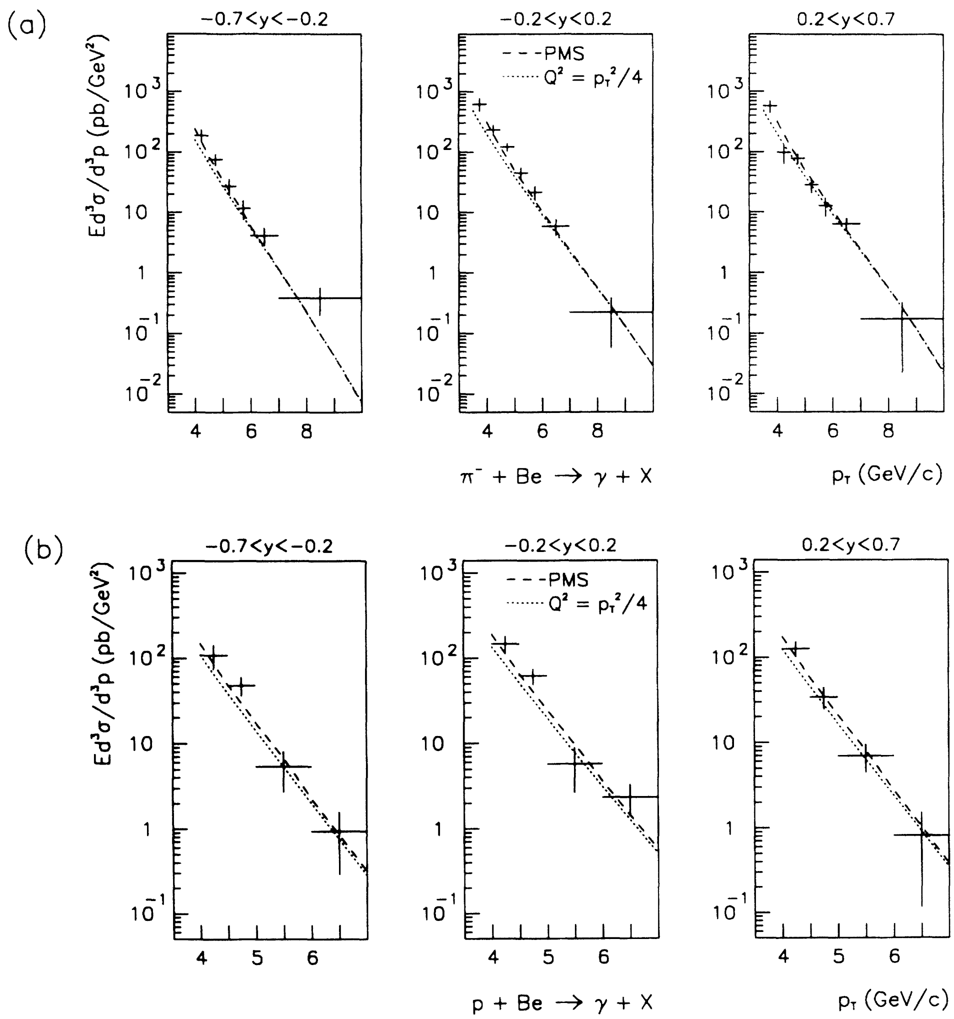

FIG. 2. Comparison with NLL QCD (Aurenche and co-workers, Refs. [6–8]) of the inclusive cross sections per nucleon vs p_T for direct photon production at 500 GeV/c for the indicated rapidity intervals (a) for π^-Be collisions and (b) for pBe collisions. The error bars represent only statistical uncertainties.

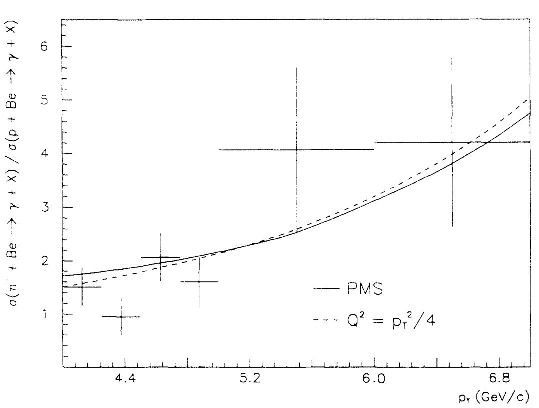

FIG. 3. Comparison with NLL QCD (Aurenche and co-workers, Refs. [6–8]) of the ratio of the inclusive cross section per nucleon for direct photon production, averaged over $|y| \leq 0.7$, in π^-Be and pBe collisions at 500 GeV/c. The error bars represent only statistical uncertainties.

out according to the PMS procedure, over a kinematic range in which the inclusive cross sections fall by more than 3 orders of magnitude [10].

It is also of interest to compare directly our π^-- and p-induced results, since such a comparison is less model specific than are fits to absolute cross sections. Figure 3 displays the ratio of the direct photon cross sections in π^-Be and pBe collisions at 500 GeV/c. The curves are ratios of the predictions of Aurenche and co-workers [6–8], averaged over rapidity. The data and the predictions are in good agreement, and reveal a significant increase in this ratio with p_T. This is consistent with the underlying QCD phenomenology, which has valence quarks in the pion carrying higher momentum fractions than quarks in the proton, and predicts a larger contribution from the annihilation diagram in the case of π^- interactions at large p_T.

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[1] G. Alverson *et al.*, Phys. Rev. D (to be published).

[2] We employed η/π^0 ratios calculated using the results of M. Bonesini *et al.*, Z. Phys. C **42**, 527 (1989); G. Donaldson *et al.*, Phys. Rev. Lett. **40**, 684 (1978), which are consistent with but more precise than our own current measurements.

[3] J. F. Owens, Phys. Lett. B **266**, 126 (1991); Phys. Rev. D **30**, 943 (1984); **19**, 3279 (1979). We employed $\langle k_T \rangle = 1.25$ GeV/c and $Q^2 = p_T^2/2$ in calculating the π^0 and γ cross sections in Fig. 1 (see Ref. [1]). Because k_T smearing enters in both the scattering and fragmentation processes, π^0 cross sections are more sensitive than γ cross sections to such effects.

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[5] See, for example, M. Bonesini *et al.*, Z. Phys. C **38**, 371 (1988); De Marzo *et al.* (Ref. [4]); Badier *et al.* (Ref. [4]); M. McLaughlin *et al.*, Phys. Rev. Lett. **51**, 971 (1983); T. Åkesson *et al.*, Phys. Lett. **158B**, 282 (1985); A. Angelis *et al.*, *ibid.* **94B**, 106 (1980).

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[10] We have investigated other structure function choices and, as might be anticipated, have observed some differences. For example, when the Owens structure function sets of Ref. [3] are substituted for those of Refs. [7] and [8], the QCD predictions of Fig. 2 fall by 5% (13%) at $p_T = 4$ GeV/c and by 17% (30%) at $p_T = 7$ GeV/c for π^-Be (pBe) collisions. This comparison assumes fixed $Q^2 = p_T^2/4$; we cannot validly compare the corresponding PMS predictions since this procedure forces the Owens structure functions below their Q^2 range of validity.