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

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Abstract

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.

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 $qg \to q\gamma$ is expected to dominate, while in π^--nucleon collisions, even at moderate values of p_T, the annihilation reaction $\overline{q}q \to g\gamma$ 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 is described in the accompanying paper on high-p_T inclusive π^0 production.[1]

The primary sources of background in a fixed target direct photon experiment arise from two sources: muons in the beam halo and two-photon decays of π^0 and η mesons. Muons can occasionally shower in the EMLAC, and, particularly when this process occurs at large distances relative to the beam axis, generate high-p_T electromagnetic triggers. Most of these events are rejected at the trigger stage using two walls of veto counters located upstream of the target. In addition, timing and entrance angle information on EMLAC showers is used off-line to eliminate any residual muon-induced background. Interactions in which π^o 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 was illustrated in the accompanying paper for the case of $\gamma\gamma$ energy asymmetries in the π^0 mass region. This is a particularly important 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.

A second major consideration in an experiment of this type is the need to establish accurately an absolute energy scale. By virtue of the very rapid falloff with p_T of the relevant single-particle inclusive cross sections (γ, π^0, η), even a small ($\sim 1\%$) uncertainty in the energy scale can translate into a very substantial ($> 10\%$) systematic uncertainty in the extracted direct photon inclusive cross section at any specific value of p_T (particularly if the γ and $\gamma\gamma$ energy scales are inconsistent). One technique for setting the energy scale is to rescale the measured data to yield standard mass values for π^o mesons. This can, however, be unreliable since relatively small changes in the algorithms used to split the energies of overlapping showers can significantly alter the reconstructed mass of a $\gamma\gamma$ pair, while leaving its overall energy essentially unchanged. We therefore established the experiment's energy scale using those events in which one or more photons converted into e^+e^- pairs in material downstream of the primary interaction, but upstream of the analysis magnet. Such conversion electrons are characterized by an oppositely charged pair of tracks with zero opening angle, and can therefore be readily identified. The momenta and energies of the constituents of such e^+e^- pairs can be measured independently using the charged particle tracking system and the EMLAC, respectively, and used to study a variety of systematic effects.

The charged particle tracking system was calibrated using the decays $K^o_S \rightarrow \pi^+\pi^-$, $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$ (using muon pairs identified by Fermilab experiment E672, which is positioned downstream of our apparatus and takes data simultaneously with E706). The electron energies measured in the EMLAC were first corrected for energy loss due to showering in the cryostat walls and in other known material in front of the EMLAC. They were then corrected empirically to match the corresponding momentum measurements to account for other effects (such as possible argon leakage into low density excluder material located within the cryostat upstream of the active region of the EMLAC). Subsequently, Monte Carlo showers were used to convert our empirical electron correction to one that was applicable to photons.

Figure 1 displays the variation with photon energy of fitted means of $e^+e^-\gamma$ mass combinations in the π^0 region, using electron momenta measured in the charged particle tracking system, and photon energies measured in the EMLAC (after applying the aforementioned corrections). Because $e^+e^-\gamma$ events are in general characterized by single isolated photon showers in the LAC (the analysis magnet deflects conversion electrons away from the unconverted photon), there is no need in such events to disentangle overlapping showers. The absence of residual energy dependence in Fig. 1 provides strong confirmation that we have correctly established the energy scale of the EMLAC. Using the energy scale determined from $e^+e^-\gamma$ events, we obtain π^o and η peaks in their $\gamma\gamma$ decay modes within 1% of the accepted mass values (both the means and widths of these mass peaks are accurately reproduced by our Monte Carlo simulation). We estimate that our absolute energy scale is known to $\pm 0.9\%$.

Figures 2(a) and 2(b) display the observed γ/π^0 production ratios for π^-Be and pBe interactions, respectively. The lower curves are Monte Carlo estimates of the contributions to these ratios from photons originating from meson decays; about 80% of this background is due to π^o decays and the rest is dominantly due to η mesons.[2] The upper curves correspond to the sums of the indicated background estimates (lower curves) and the expected true γ/π^0 ratios calculated from leading-log QCD. The calculations are by Owens, using $Q^2 = p_T{}^2/4$ and a recently extracted set of nucleon structure functions.[3] A statistically significant direct photon signal is evident above the estimated background (lower curves) 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 $-0.7 \leq y \leq 0.7$, and have been corrected for acceptance and trigger effects. 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 ISR experiments.

Figures 3(a) and 3(b) display our results for three rapidity intervals. Shown for comparison are representative NLL QCD calculations by Aurenche and collaborators,[6] using the nucleon structure function sets of ABFOW[7] and the pion structure functions of ABFKW.[8] The dashed curves employ the principle of minimum sensitivity (PMS),[9] while the dotted curves are calculated using a fixed Q^2 scale of $p_T^2/4$. (Fixed Q^2 NLL QCD calculations by Owens, using his previously referenced sets of nucleon and pion structure functions,[3] lie ~5% and ~25% below the corresponding curves in Figs. 3(a) and 3(b) for π^-Be and pBe collisions, respectively.) The data are in general agreement with the QCD predictions, especially those carried out according to the PMS procedure, over a kinematic range in which the inclusive cross sections fall by more than three orders of magnitude. This provides strong support for the overall reliability of NLL QCD calculations, when used in conjunction with these specific sets of quark and gluon structure functions.

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Table I. Invariant cross sections per nucleon for inclusive direct photon production in π^-Be and pBe collisions at 500 GeV/c, averaged over $-0.7 \leq y \leq 0.7$ and the indicated p_T bands. In addition to the indicated statistical uncertainties, there is also a p_T-dependent systematic uncertainty that varies from 25% at low-p_T to 15% at high-p_T.

p_T	$\pi^- + Be \rightarrow \gamma + X$	$p + Be \rightarrow \gamma + X$
(GeV/c)	(pb/GeV^2)	
$3.5 - 3.75$	540 ± 140	–
$3.75 - 4.0$	299 ± 89	–
$4.0 - 4.25$	252 ± 40	168 ± 30
$4.25 - 4.5$	86 ± 26	91 ± 20
$4.5 - 4.75$	124 ± 16	60 ± 11
$4.75 - 5.0$	53 ± 10	33.4 ± 7.2
$5.0 - 5.5$	32.4 ± 4.8	5.6 ± 2.8
$5.5 - 6.0$	14.7 ± 2.7	6.2 ± 1.6
$6.0 - 7.0$	5.39 ± 0.87	1.28 ± 0.43
$7.0 - 8.0$	0.45 ± 0.24	
$8.0 - 10.0$	0.157 ± 0.084	0.021 ± 0.030

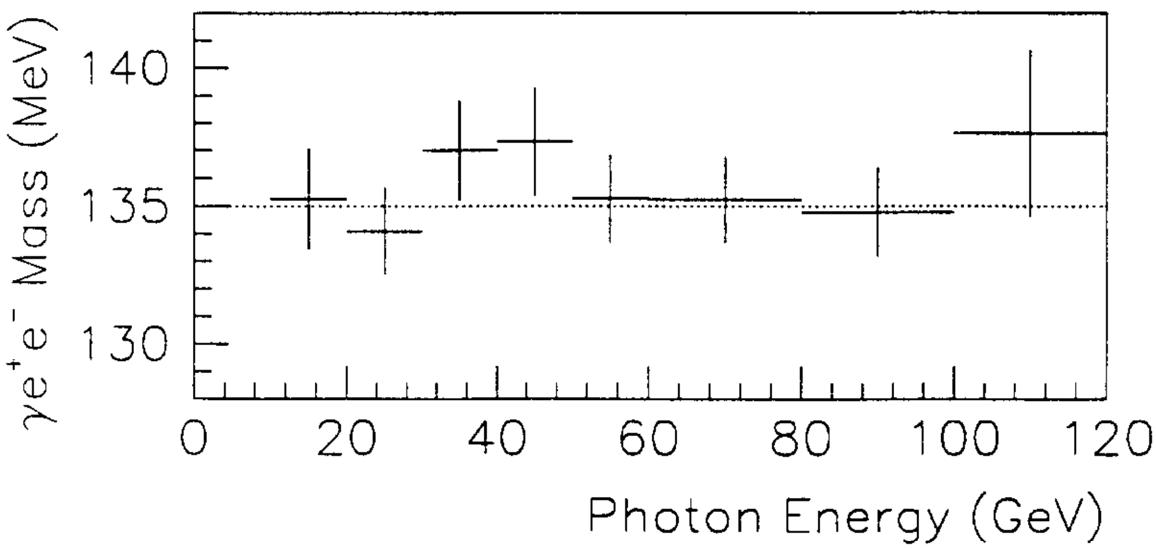

Figure 1. The variation with photon energy (as measured in the EMLAC) of fitted means of $\gamma e^+ e^-$ mass combinations in the π^o region.

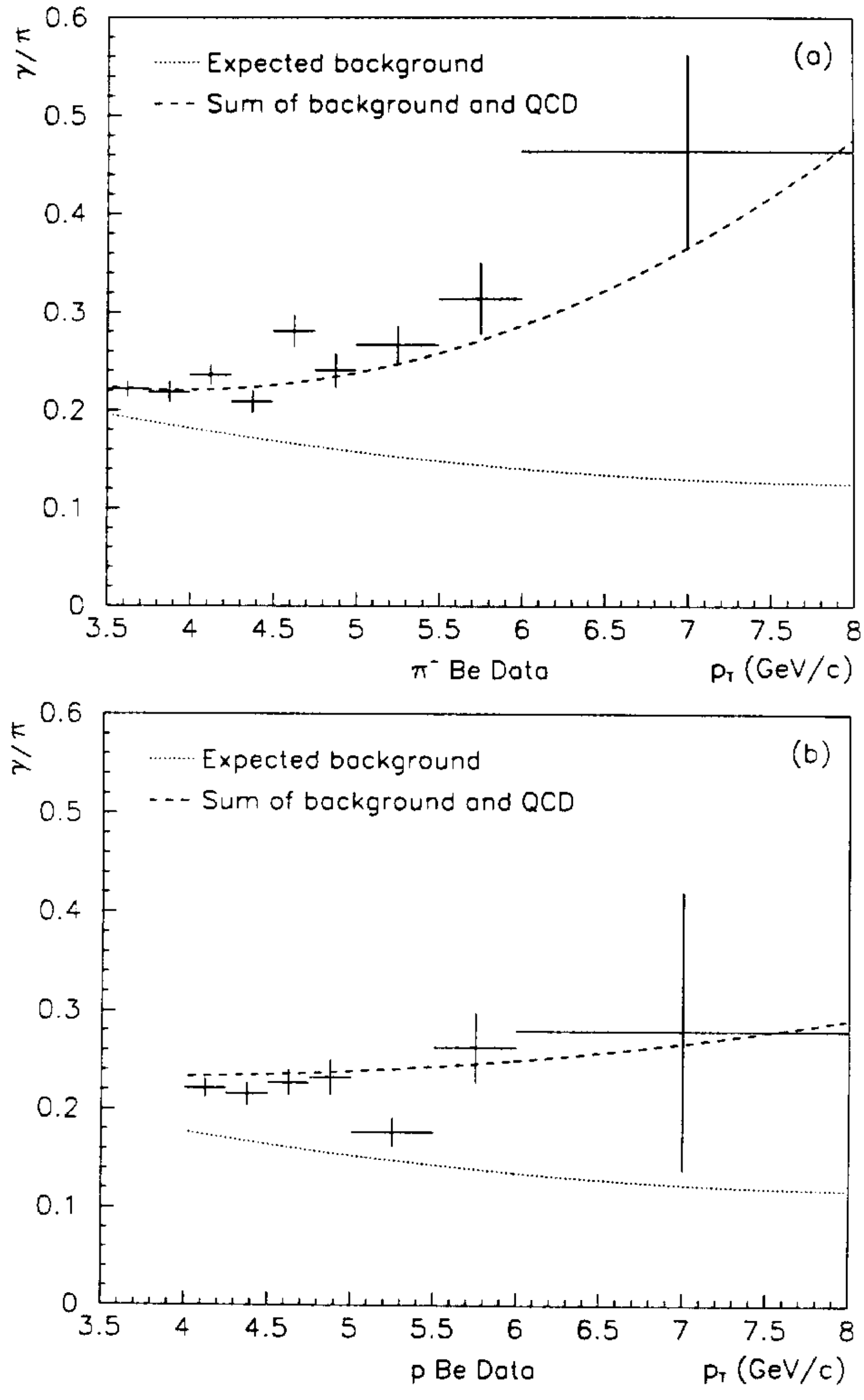

Figure 2. The observed γ/π^o ratios at 500 GeV/c. The lower (dotted) curves are Monte Carlo estimates of contributions from meson decays. The upper (dashed) curves are sums of contributions from meson decays and leading-log calculations of the true γ/π^0 ratios (see text); (a) for π^-Be collisions and (b) for pBe collisions.

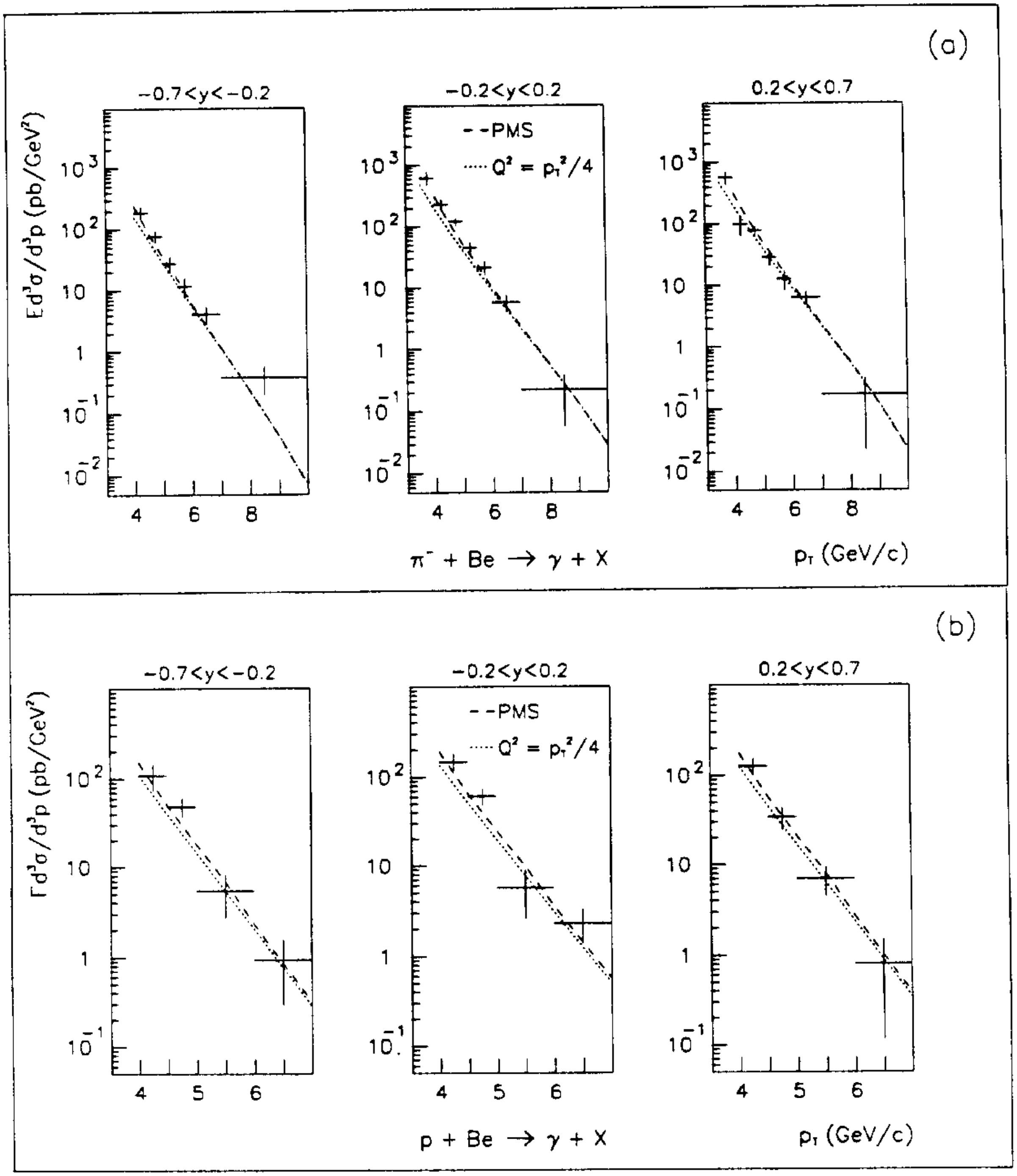

Figure 3. Comparison with NLL QCD (Aurenche *et al.*, Refs. 6, 7 and 8) of the inclusive cross sections per nucleon versus p_T for direct photon production at 500 GeV/c for the indicated rapidity intervals; (a) for π^-Be collisions and (b) for pBe collisions.