PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 45, NUMBER 11 1 JUNE 1992

RAPID COMMUNICATIONS

Rapid Communications are intended for important new results which deserve accelerated publication, and are therefore given priority in editorial processing and production. A Rapid Communication in **Physical Review D** *should be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but because of the accelerated schedule, publication is generally not delayed for receipt of corrections unless requested by the author.*

Production of π^0 mesons at high p_T in π^-Be and pBe collisions at 500 GeV/c

G. Alverson,[f] W. F. Baker,[c] G. Ballocchi,[j] R. Benson,[e] D. Berg,[c] S. Blusk,[i] C. Bromberg,[d] D. Brown,[d] D. Carey,[c] T. Chand,[b] C. Chandlee,[j] B. C. Choudhary,[b] W. H. Chung,[i] L. de Barbaro,[j] W. DeSoi,[j] W. Długosz,[f] J. Dunlea,[j] S. Easo,[h] E. Engels, Jr.,[i] W. Faissler,[f] G. Fanourakis,[j] T. Ferbel,[j] D. Garelick,[f] G. Ginther,[j] G. Glass,[f] M. Glaubman,[f] P. Gutierrez,[g] K. Hartman,[h] J. Huston,[d] C. Johnstone,[c] V. Kapoor,[b] I. Kourbanis,[f] A. Lanaro,[j] C. Lirakis,[f] F. Lobkowicz,[j] P. Lukens,[e] S. Mani,[a] A. Maul,[d] J. Mansour,[j] R. Miller,[d] C. A. Nelson, Jr.,[c] B. Oh,[h] D. Orris,[i] E. Pothier,[f] E. Prebys,[j] B. M. Rajaram,[b] R. Roser,[j] K. Ruddick,[e] P. Shepard,[i] R. K. Shivpuri,[b] A. Sinanidis,[f] D. Skow,[j] P. Slattery,[j] L. Sorrell,[d] W. Toothacker,[h] N. Varelas,[j] D. Weerasundara,[i] J. Whitmore,[h] G. Wu,[f] T. Yasuda,[f] C. Yosef,[f] and M. Zieliński[j]

[a]*University of California-Davis, Davis, California 95616*
[b]*University of Delhi, Delhi 11 00 07, India*
[c]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[d]*Michigan State University, East Lansing, Michigan 48824*
[e]*University of Minnesota, Minneapolis, Minnesota 55455*
[f]*Northeastern University, Boston, Massachusetts 02115*
[g]*University of Oklahoma, Norman, Oklahoma 73019*
[h]*Pennsylvania State University, University Park, Pennsylvania 16802*
[i]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[j]*University of Rochester, Rochester, New York 14627*

(Fermilab E706 Collaboration)

(Received 16 August 1991)

We present new measurements of π^0 production at high transverse momenta (p_T) for π^- and p interactions on Be and Cu targets at 500 GeV/c. The observed dependence of the yields as a function of p_T and rapidity (y) is compared with expectations from leading-log QCD over a kinematic range in which the inclusive cross sections fall by more than 4 order of magnitude.

PACS number(s): 13.85.Ni, 12.38.Qk, 25.40.Ve, 25.80.Ls

The measurement of inclusive single-particle production at high transverse momenta in hadron-induced collisions can be viewed as a high-energy analogue of the Rutherford scattering experiment. Within the framework of quantum chromodynamics (QCD), high-p_T processes are understood to proceed through the pointlike scattering of quarks and gluons, which subsequently fragment into jets of hadrons. Although the presence of hadronization complicates the detailed analysis, the study of secondary particle production at high transverse momenta has nevertheless proved to be a most valuable probe of hadronic matter at the constituent level [1].

In this paper, we present new measurements of π^0 production for π^- and p interactions on Be and Cu targets at 500 GeV/c, and compare these results to leading-log (LL) QCD calculations. The data were collected using the E706 spectrometer at Fermilab, which features a 3-m diam electromagnetic liquid-argon calorimeter (EM-

LAC) with r-ϕ readout, plus a sophisticated charged-particle tracking system employing silicon microstrip detectors in the vertex region and multiwire proportional chambers for tracking downstream of the analysis magnet [2]. We report here results obtained from an analysis of $\sim$0.5 pb^{-1} of π^- Be and $\sim$0.8 pb^{-1} of pBe data acquired during the 1987–1988 Fermilab fixed-target run. The average beam momentum was 500 GeV/c, with an uncertainty of $\pm 2\%$; the momentum band was $\pm 4\%$.

Figure 1(a) displays the reconstructed mass spectrum of photon pairs having $p_T \geq 3.5$ GeV/c and $|y| \leq 0.7$. The standard deviations of the π^0 and η mass peaks are 8 and 24 MeV/c^2, respectively, in agreement with expectations from our Monte Carlo simulation. Figure 1(b) depicts the energy asymmetry distribution (defined as $|E_{\gamma 1} - E_{\gamma 2}|/[E_{\gamma_1} + E_{\gamma 2}]$) for $\gamma\gamma$ pairs falling within the π^0 mass region (defined as 110–160 MeV/c^2). The data in Fig. 1(b) have been corrected for the background under the π^0 peak by subtracting the corresponding energy asymmetry distributions for mass pairs falling into either of two sideband regions: 75–100 MeV/c^2 and 170–195 MeV/c^2. Also shown in Fig. 1(b) is a Monte Carlo simulation, which agrees very well with the subtraction-corrected data. The shaded histogram in Fig. 1(a) is the mass spectrum of photon pairs with an energy asymmetry less than 0.75; this restriction is employed to select an especially clean sample of events for studying inclusive π^0 production.

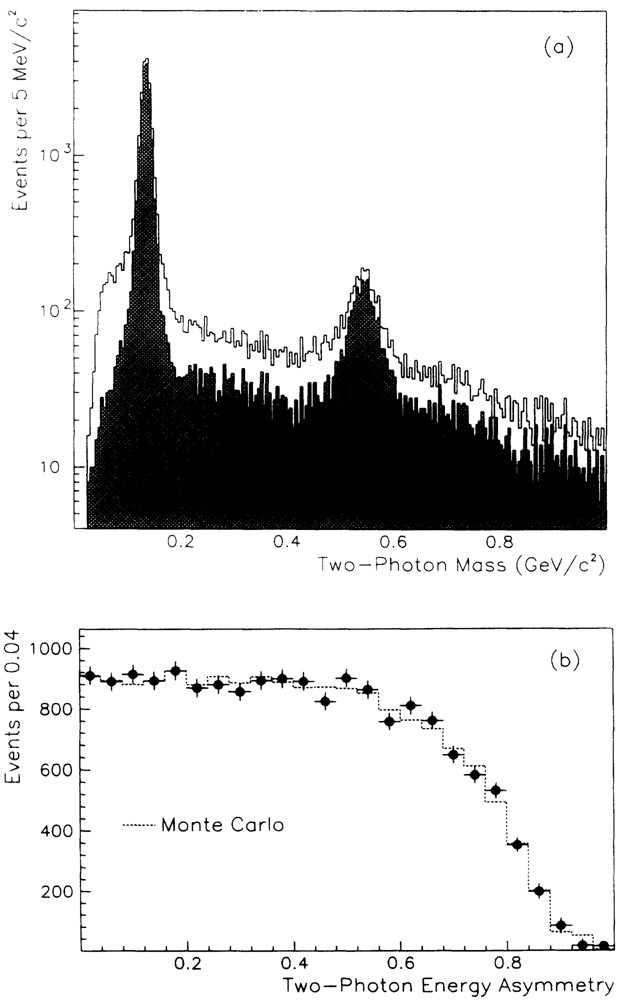

FIG. 1. (a) The inclusive two-photon mass distribution for 500 GeV/c positive and negative data combined for $p_T^{\gamma\gamma} \geq 3.5$ GeV/c and $|y^{\gamma\gamma}| \leq 0.7$. The shaded histogram displays the mass of photon pairs with energy asymmetries ≤ 0.75. (b) The background-subtracted energy asymmetry distribution for photon pairs having an invariant mass between 110 and 160 MeV/c^2. The histogram represents a Monte Carlo simulation of this distribution.

A major consideration in an experiment of this type is the need to establish accurately an absolute energy scale. We established our 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 a zero opening angle, and can 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 systematic effects. The tracking system was calibrated using charged two-body decays of K_S^0 and J/ψ mesons. 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 2 displays the fitted mean values of γe^+e^- mass combinations in the π^0 region as a function of photon energy, using electron momenta measured in the charged-particle tracking system and photon energies measured in the EMLAC (after applying the aforementioned corrections). Because γe^+e^- events are in general characterized by single isolated photon showers in the EMLAC, there is no need in such events to disentangle overlapping showers. The absence of residual

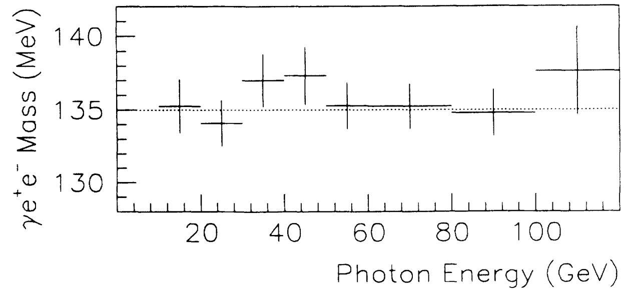

FIG. 2. The variation with photon energy (as measured in the EMLAC) of fitted means of γe^+e^- mass combinations in the π^0 region.

TABLE I. Invariant cross sections per nucleon for inclusive π^0 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.

p_T (GeV/c)	$\pi^- + \text{Be} \to \pi^0 + X$ (pb/GeV^2)	$p + \text{Be} \to \pi^0 + X$ (pb/GeV^2)
3.5–3.75	$18400 \pm 400 \pm 2200$	...
3.75–4.0	$8900 \pm 200 \pm 1000$	...
4.0–4.25	$4370 \pm 110 \pm 500$	$3540 \pm 90 \pm 420$
4.25–4.5	$2330 \pm 70 \pm 270$	$1890 \pm 60 \pm 220$
4.5–4.75	$1080 \pm 40 \pm 130$	$920 \pm 30 \pm 110$
4.75–5.0	$665 \pm 28 \pm 76$	$437 \pm 19 \pm 50$
5.0–5.5	$284 \pm 12 \pm 33$	$195 \pm 8 \pm 22$
5.5–6.0	$86.6 \pm 6.1 \pm 9.9$	$50 \pm 4 \pm 6$
6.0–7.0	$13.0 \pm 1.6 \pm 1.5$	$8.8 \pm 1.1 \pm 1.0$
7.0–8.0	$1.8 \pm 0.6 \pm 0.2$	$0.35 \pm 0.18 \pm 0.04$
8.0–10.0	$0.20 \pm 0.14 \pm 0.02$	$0.11 \pm 0.08 \pm 0.01$

energy dependence in Fig. 2 provides confirmation that we have correctly established the energy scale of the EMLAC. Using the energy scale determined from γe^+e^- events, we obtain π^0 and η peaks in their $\gamma\gamma$ decay modes, and an ω peak in its $\pi^0\gamma$ decay mode, within 1% of the accepted mass values. We estimate that the uncertainty in our corrected energy scale is $\pm 0.9\%$.

Table I presents the invariant cross sections per nucleon for inclusive π^0 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 (including reconstruction losses) and trigger effects, and for background via sideband subtraction. The dominant contribution to the systematic errors presented in Table I is the uncertainty in the absolute normalization ($\pm 10\%$). Other effects (such as uncertainties in the trigger corrections, in the procedures used to linearize the energy scale, and in correcting for reconstruction losses) are typically 2–3% each. The results in Table I are in general agreement with trends displayed by earlier experiments, which in the case of π^--induced collisions [3] are all at lower energy, whereas for p-induced collisions [4] the energy of this experiment

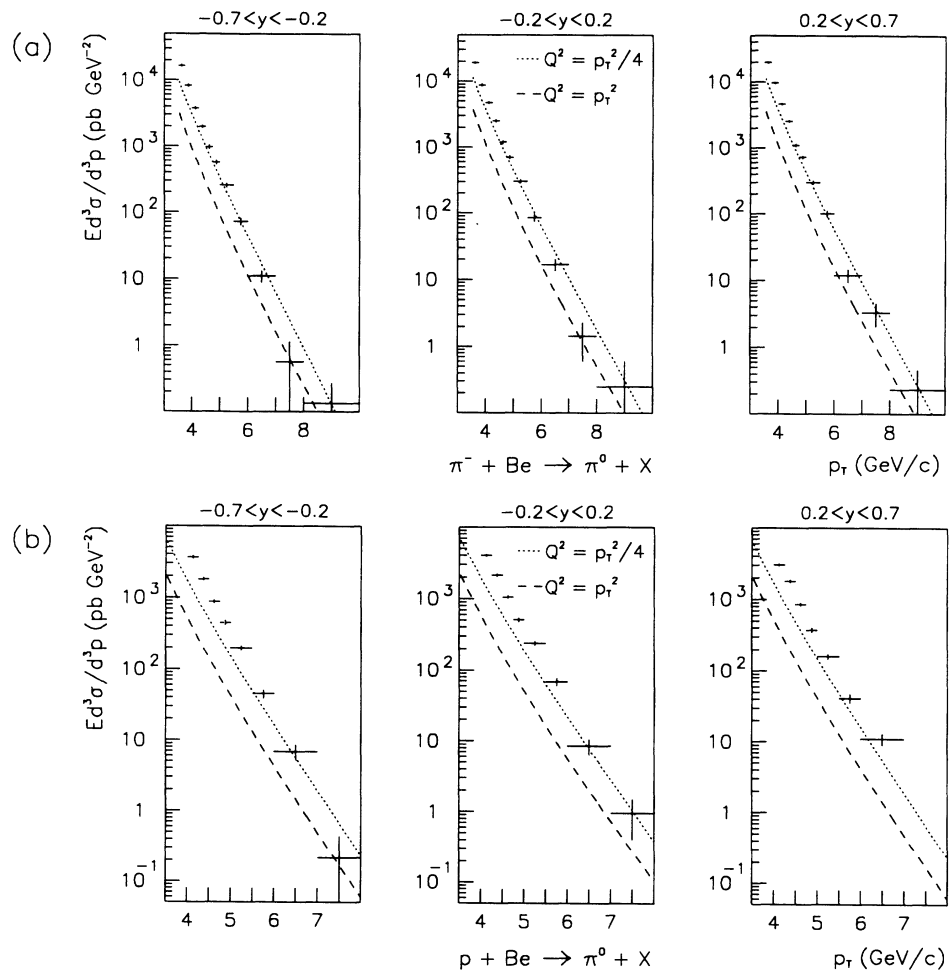

FIG. 3. Comparison with LL QCD (Owens, Refs. [6,7]) of the inclusive cross sections per nucleon versus p_T for π^0 production at 500 GeV/c for the indicated rapidity intervals: (a) for π^-Be collisions and (b) for pBe collisions. The error bars represent only statistical uncertainties.

falls between those of previous fixed-target and CERN ISR experiments. We have also measured the inclusive production of π^0's from Cu. When the Cu and Be cross sections are parametrized in the form A^α, the best-fit value for α is 1.07 ± 0.02, in both π^-- and p-induced collisions. This result is similar to previous observations at high p_T [5].

Figures 3(a) and 3(b) display our results for three rapidity intervals. Shown for comparison purposes are the results of LL QCD calculations by Owens [6] for two representative values of the scale parameter Q^2 (p_T^2 and $p_T^2/4$), using his parton fragmentation functions, and a recently extracted set of nucleon structure functions [7] that update the earlier Duke-Owens parametrizations [8]. Comparison of the measured data and the QCD predictions reveals approximate agreement over a p_T range in which the inclusive cross sections decrease by more than 4 orders of magnitude, although the data fall more rapidly with p_T than predicted by the QCD calculations. (Other LL QCD formulations exhibit similar behavior [9].) When the discrepancies between the measured cross sections and the LL QCD predictions are parametrized as intrinsic transverse-momentum (k_T) smearing, we require an effective $\langle k_T \rangle$ of approximately 1.25 GeV/c (and $Q^2 \sim p_T^2/2$); this is consistent with what is expected from extrapolation of lower-energy results on Drell-Yan and diphoton production to our energy [10].

We wish to thank the U.S. Department of Energy, the National Science Foundation, including its Office of International Programs, and the Universities Grants Commission of India for their support of this research. We are also pleased to acknowledge the many contributions of the Fermilab management and technical staff to the success of the experiment. Finally, we thank our colleagues on Fermilab experiment E672 for their contributions to these results.

[1] For a comprehensive recent review of this subject, see W. M. Geist *et al.*, Phys. Rep. **197**, 263 (1990).

[2] Further details concerning the E706 spectrometer can be found in F. Lobkowicz *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. A **235**, 332 (1985); E. Engels, Jr. *et al.*, *ibid.* **253**, 523 (1987); **279**, 272 (1989); and in a forthcoming full length article.

[3] See, for example, M. Bonesini *et al.*, Z. Phys. C **37**, 39 (1987); J. Badier *et al.*, *ibid.* **30**, 45 (1986); C. De Marzo *et al.*, Phys. Rev. D **36**, 16 (1987); G. Donaldson *et al.*, Phys. Rev. Lett. **36**, 1110 (1976).

[4] See, for example, M. Bonesini *et al.*, Z. Phys. C **38**, 371 (1988); De Marzo *et al.* [3]; Badier *et al.* [3]; Donaldson *et al.* [3]; J. Povlis *et al.*, Phys. Rev. Lett. **51**, 967 (1983); T. Åkesson *et al.*, Phys. Lett. **158B**, 282 (1985); A. Angelis *et al.*, *ibid.* **79B**, 505 (1978).

[5] D. Antreasyan *et al.*, Phys. Rev. D **19**, 764 (1979); H. Frisch *et al.*, *ibid.* **27**, 1001 (1983).

[6] J. F. Owens, Rev. Mod. Phys. **59**, 465 (1987); Phys. Rev. D **19**, 3279 (1979).

[7] J. F. Owens, Phys. Lett. **B266**, 126 (1991).

[8] D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984); J. F. Owens, *ibid.* **30**, 943 (1984).

[9] H. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. **46**, 43 (1987).

[10] E. Bonvin *et al.*, Phys. Lett. B **236**, 523 (1990), and references therein. Effective $\langle k_T \rangle$ values are strongly model dependent, since they depend not only upon the specific parton structure functions used and the level of QCD dynamics (e.g., LL or NLL) included in the calculations, but also on the definition of Q^2, and the manner in which k_T effects are incorporated into the quark and gluon structure and fragmentation functions employed.

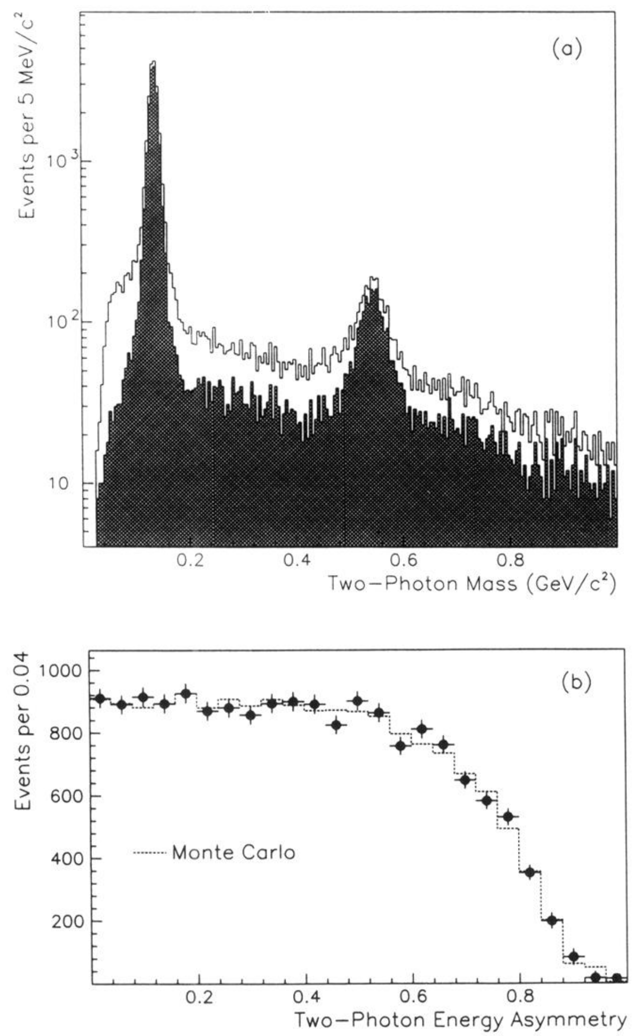

FIG. 1. (a) The inclusive two-photon mass distribution for 500 GeV/c positive and negative data combined for $p_T^{\gamma\gamma} \geq 3.5$ GeV/c and $|y^{\gamma\gamma}| \leq 0.7$. The shaded histogram displays the mass of photon pairs with energy asymmetries ≤ 0.75. (b) The background-subtracted energy asymmetry distribution for photon pairs having an invariant mass between 110 and 160 MeV/c^2. The histogram represents a Monte Carlo simulation of this distribution.