Study of Inclusive γ and π^0 Production in 12.4-GeV/c pp Interactions

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From an exposure of the Argonne National Laboratory 12-foot bubble chamber to a beam of 12.4-GeV/c protons we have obtained a 3649-event sample of the reaction $pp \to \gamma +$ anything, where we observe photon conversions into e^+e^- pairs in the liquid hydrogen. We find that the invariant cross section for this reaction does not separate in its x and $P_\perp$ dependence at our energy. By setting upper bounds on the cross sections for inclusive η and Σ^0 production, we show that π^0 decay is the dominant source of photons and therefore measure the cross section for inclusive π^0 production to be $\sigma(\pi^0) = (31.5 \pm 2.6)$ mb. Comparison with the inclusive π^+ and π^- cross sections at 12.0 GeV/c shows that the relation $2\sigma(\pi^0) = \sigma(\pi^+) + \sigma(\pi^-)$ is well satisfied. We confirm earlier indications that the average number of π^0's per inelastic pp interaction is approximately independent of the number of associated charged particles produced.

The description of pion production in pp interactions requires, in general, three independent isotopic spin amplitudes. Thus π^0 production cannot be derived from π^+ and π^- data in a model-independent way. We report here an experiment which measures π^0 production by means of the inclusive photon reaction, where the dominant source of photons is from the decay of π^0's. These results were obtained from the first exposure of the Argonne National Laboratory 12-foot bubble chamber,[1] to a 12.4-GeV/c proton beam extracted from the Zero-Gradient Synchrotron (ZGS).

We have analyzed the V^0 topology events in which a neutral particle converts or decays into two charged particles in the liquid hydrogen. The film was double-scanned for all V^0 events which might be associated with a beam proton interaction. The two charged tracks from the V^0's, and the vertices of all beam interactions to which they might point, were then measured on the Argonne POLLY III CRT measuring machine.[2] The primary interaction tracks were not measured. After remeasurements were completed, all events reconstructed by the geometry program TVGP were processed through the kinematics routine SQUAW, in which three-constraint pointing tests were made. After applying appropriate selections,[3] we find 3649 three-constraint e^+e^- pairs. The small number (5% of all γ's) of ambiguities between pair production and strange-particle decays were resolved on a statistical basis.[4]

The initial weight for each γ event was the inverse of the probability that it converts within the chosen fiducial volume, using the momentum-dependent pair-production cross section as given by quantum electrodynamics[5] and requiring a minimum photon length of 12 cm. The average weight so obtained is 11.3 and the average photon detection efficiency calculated from this weight only is 10.5%.

The double scan efficiency for finding and correctly associating the γ events was ~96%, but is somewhat lower (~92%) for large ($\gtrsim 45°$) laboratory angles. Since the laboratory and center-of-mass production angles are one-to-one related, independent of the photon momentum, we have corrected the data for scan efficiency in six equal bins of $\cos\theta^*_\gamma$.

Due to the falloff of the pair-production cross section at small γ momentum,[5] special attention has to be given to low-energy γ's. The correction due to this effect is based on the forward-backward symmetry in the pp center of mass. We vary the lab momentum $P_\gamma^{\rm lab}$ and compare the weighted numbers of events in the forward and backward center-of-mass hemispheres, after eliminating those which fall under the $P_\gamma^{\rm lab}$ curve (region A of Fig. 1) as well as those which fall under its reflection into the forward hemisphere (region B of Fig. 1). For $P_\gamma^{\rm lab} \geq 90$ MeV/c, we find the two hemispheres to be equally populated with weighted events. We therefore eliminate all events with $P_\gamma^{\rm lab} \leq 90$ MeV/c

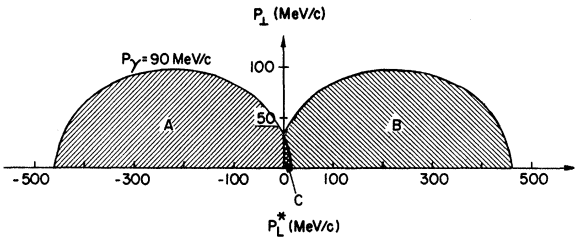

FIG. 1. $P_\gamma^{\rm lab} \leq 90$ MeV/c region and its reflection in the Peyrou plot.

and $P_L^* \leq 0.0$ (region A). To correct for these events, we double the weights for all events which lie in the reflection of A, namely region B. We then have a fully corrected sample of events in the folded distributions $|P_L^*|$, $|x|$, etc., except for the small region (C in Fig. 1) bounded by $P_\perp \leq 35$ MeV/c and $0 \leq P_L^* \leq 17$ MeV/c. Those events found in region C have been included in the distributions, with doubled weights. Since region C is a small fraction of the populated phase space (35 events), we have not attempted to make any further corrections for the loss of very-low-momentum photons. After folding in corrections due to scanning efficiency, unbiased reconstruction failures, the cut on probability of χ^2, and the requirement that $P_\gamma^{\rm lab} \geq 90$ MeV/c, the over-all average weight factor is 18.7, and the corresponding average total detection efficiency is 6.9%.

The cross-section normalization was obtained from a count of the beam tracks entering the fiducial volume and corresponds to 1.05 events/μb. All cross sections in this paper include an 8% systematic error due to cross section normalization (~ 5%), the redistribution of track reconstruction failures (~ 4%), and scanning efficiency (~5%). These errors have been quadratically added to the statistical errors.

We discuss our results first in terms of the invariant cross section

$$F(x, P_\perp^2, s) = \frac{E^*}{\pi P_{\rm max}^*} \frac{d^2\sigma}{dx\, dP_\perp^2} .$$

We denote by $F_1(x)$ and $F_2(P_\perp^2)$ the integrals of $F(x, P_\perp^2)$ over $P_\perp^2$ and x, respectively.[6] In Fig. 2 we show $F_1(x)$ and $F_2(P_\perp^2)$. Our results on $F_1(x)$ and $2P_\perp F_2(P_\perp^2)$ (not shown) may be compared with those of Neuhofer *et al.*,[7] who have studied the reaction $pp \to \gamma$ + anything at the CERN Intersecting Storage Rings (ISR) at stationary-target-equivalent momenta of 500, 1100, and 1500 GeV/c. They found that the invariant cross section could be represented by the formula $F(x, P_\perp^2) \propto F_1(x) F_2(P_\perp^2)$, with the x and $P_\perp$ dependences $F_1(x) \sim e^{-x/0.083}$ and $P_\perp F_2(P_\perp^2) \sim \exp(-P_\perp/0.162\ {\rm GeV}/c)$ over the ranges $0 \leq x \leq 0.15$ and $0.1 \leq P_\perp \leq 0.6$ GeV/c, respectively. In our experiment, we obtain $F_1(x) \sim \exp[-|x|/(0.126 \pm 0.013)]$ for $0 \leq |x| \leq 0.6$ as shown in Fig. 2, and $P_\perp F_2(P_\perp^2) \sim \exp[-P_\perp/(0.196 \pm 0.020)\ {\rm GeV}/c]$ for $0.15 \leq P_\perp \leq 1.15$ GeV/c. These slopes are similar to those from the ISR, even though the incident beam momenta differ by two orders of magnitude and the latter data are restricted to small x and $P_\perp$ ranges. That the similarities are illusory is illustrated in Fig. 3, where we test separation

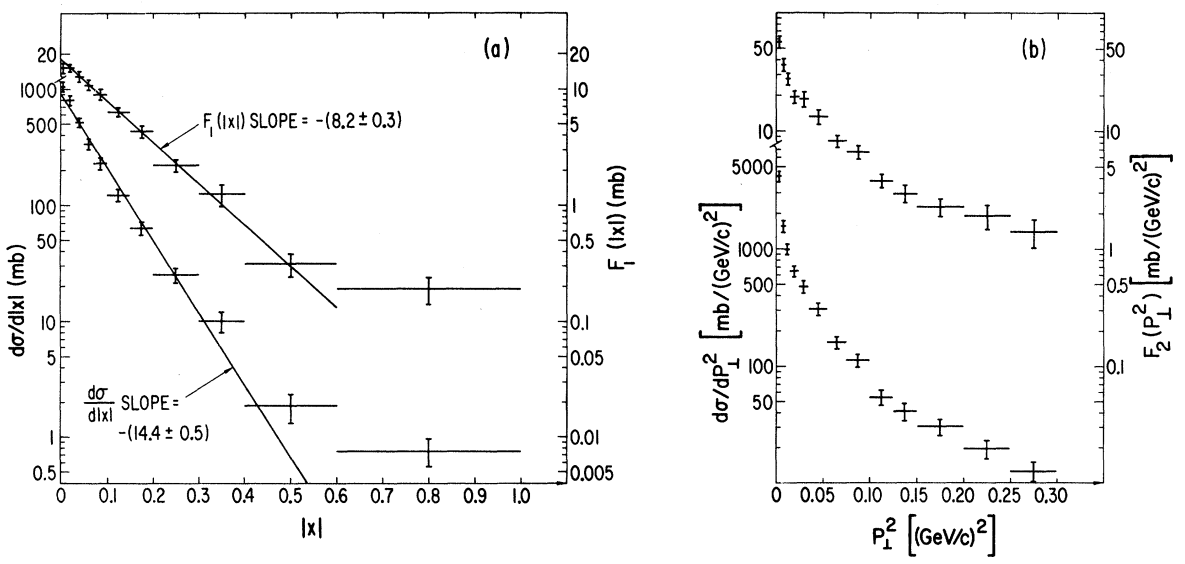

FIG. 2. (a) $d\sigma/d|x|$ below, and its invariant counterpart $F_1(|x|)$ above (see text). (b) $d\sigma/dP_\perp^2$ and $F_2(P_\perp^2)$.

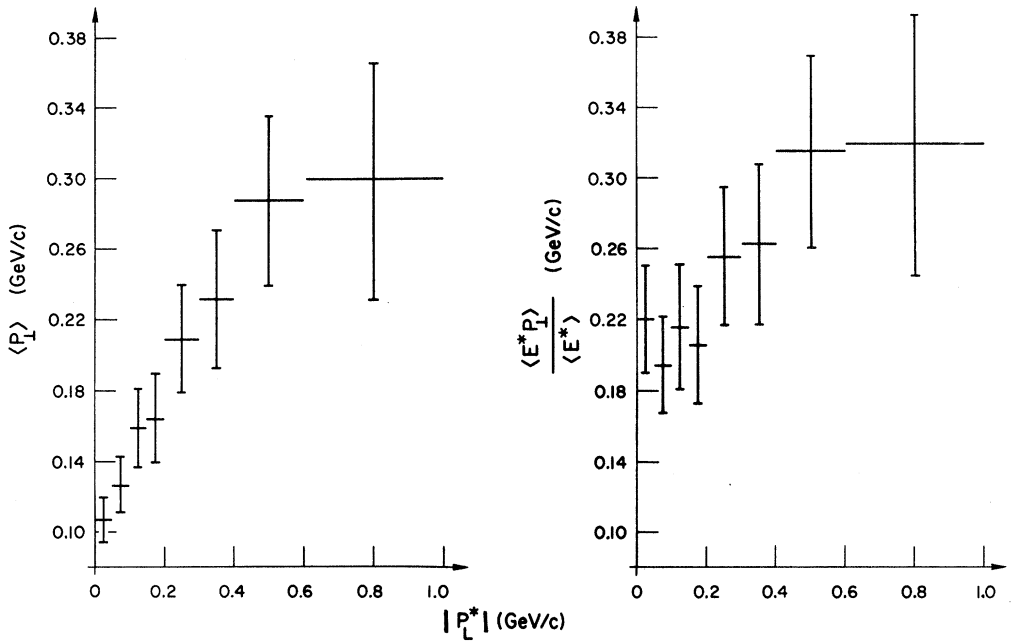

FIG. 3. (a) $\langle P_\perp \rangle$ and $\langle E^* P_\perp \rangle / \langle E^* \rangle$ as a function of $|P_L^*|$ (see text).

of variables at our energy by plotting

$$\langle P_\perp \rangle = \int \frac{P_\perp d^2\sigma}{d|x|dP_\perp^2}\, dP_\perp^2 \Big/ \int \frac{d^2\sigma}{d|x|dP_\perp^2}\, dP_\perp^2$$

and

$$\frac{\langle E^* P_\perp \rangle}{\langle E^* \rangle} = \frac{\int E^* P_\perp \frac{d^2\sigma}{d|x|dP_\perp^2}\, dP_\perp^2}{\int E^* \frac{d^2\sigma}{d|x|dP_\perp^2}\, dP_\perp^2}$$

as a function of $|P_L^*|$. It is clear that there are correlations between $|P_L^*|$ and $\langle P_\perp \rangle$ in both distributions. This indicates that $F(x, P_\perp{}^2)$ for γ production at 12.4 GeV/c does not separate in its x and $P_\perp$ dependences.

The observed 3649 events of the reaction $pp \to \gamma$ + anything correspond to an inclusive γ cross section of (63.0 ± 5.1) mb. The most plausible sources of photons other than from π^0's are η and Σ^0 decays. For the events in which we observe two or more γ's, or a Λ and a γ associated with the same pp interaction, we form the $\gamma\gamma$ or $\Lambda\gamma$ invariant mass distribution. The π^0 signal in the $\gamma\gamma$ mass distribution yields a total inclusive π^0 cross section which is consistent with the one quoted below. No η signal is observed in this distribution. A weak Σ^0 enhancement is noted above a small background in the $\Lambda\gamma$ mass distributions. We find the following upper limits for the inclusive η and Σ^0 cross sections at 12.4 GeV/c:

$$pp \to \eta + \text{anything}\ ,\quad \eta \to 2\gamma$$

$\sigma \leq 0.5$ mb (95% confidence level)

and

$$pp \to \Sigma^0 + \text{anything}\ ,\quad \Sigma^0 \to \Lambda\gamma$$

$\sigma \leq 1.3$ mb (95% confidence level).

The cross section for non-$\pi^0\gamma$ production is then less than 2.3 mb and has been neglected in obtaining the cross section for inclusive π^0 production:

$pp \to \pi^0 + \text{anything}\ ,\quad \sigma(\pi^0) = (31.5 \pm 2.6)$ mb.

This cross section may be compared with the inclusive π^+ and π^- cross sections[8] at 12.0 GeV/c: $\sigma(\pi^+) = (42.7 \pm 0.7)$ and $\sigma(\pi^-) = (21.1 \pm 0.4)$ mb. We observe that these cross sections are consistent with the relation

$$\sigma(\pi^0) = \tfrac{1}{2}[\sigma(\pi^-) + \sigma(\pi^+)]\ .$$

Although this equality does not follow from general symmetry arguments alone,[9] it has been suggested by several authors[9,10] as a consequence of $I = 0$ t-channel exchange dominance in pp interactions,[11] and has also been derived[12] from a Mueller-Regge point of view by assuming isosinglet, $C = +1$ dominance in the appropriate Regge exchanges.

From the inclusive π^0 cross section given above, which is, of course, equal to $\langle n_{\pi^0} \rangle \sigma_{\text{in}}$, and the total inelastic pp cross section of 29.1,[13] we find

TABLE I. Topological γ and π^0 production cross sections and π^0 multiplicities.

Topology	σ_{inel} (mb)	$\sigma_n(\gamma)$ (mb)	$\sigma_n(\pi^0)$ (mb)	$\langle n_{\pi^0}\rangle$
2-prong	10.4 ±0.6	25.5 ±2.2	12.8 ±1.1	1.23±0.13
4-prong	14.1 ±0.6	28.8 ±2.4	14.4 ±1.2	1.02±0.10
6-prong	4.1 ±0.3	8.6 ±0.8	4.3 ±0.4	1.05±0.13
8-prong	0.52 ±0.10	0.94±0.16	0.47 ±0.08	0.91±0.23
10-prong	0.014±0.010	0.01±0.01	0.005±0.005	0.36±0.36
Total	29.1 ±2.3	63.9 ±5.1	32.0 ±2.6	1.10±0.13

that the average number of π^0's produced per inelastic collision is $\langle n_{\pi^0}\rangle = 1.08 \pm 0.13$. By examining the dependence of $\langle n_{\pi^0}\rangle$ on the number of associated charged particles, n, we may study the correlation between neutral and charged pion production.[14] The topological γ and π^0 production cross sections as well as π^0 multiplicities for this experiment are given in Table I.[15]

In Fig. 4 we present $\langle n_{\pi^0}\rangle$ as a function of n for this experiment and for experiments at 19 GeV/c,[16] 205 GeV/c,[17] and 303 GeV/c.[18] At low energies, the number of charged particles produced in the final state has little influence on $\langle n_{\pi^0}\rangle$. This is in contrast to high-energy data,[19] which indicate a definite correlation between charged and neutral pion production.

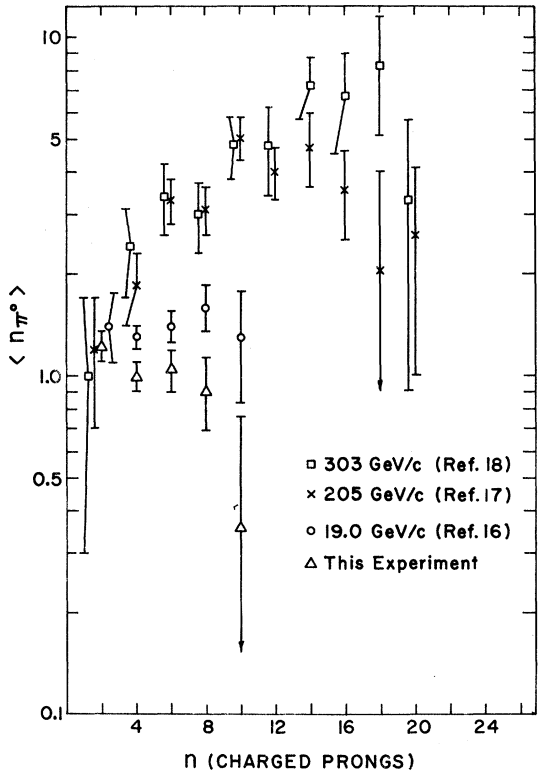

FIG. 4. The average number of π^0's per inelastic pp collision as a function of the number of charged particles produced.

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[1]See the presentations by H. Yuta, J. Campbell, and E. G. Pewitt, in proceedings of the International Conference on Bubble-Chamber Technology, ANL, 1970 (unpublished), and K. Jaeger, ANL Report No. ANL/HEP 7210, 1972 (unpublished).

[2]F. Beck, ANL Report No. ANL/HEP 7128, 1971 (unpublished); F. Beck *et al.*, in proceedings of the Informal Colloquium on POLLY and POLLY-Like Devices, ANL Report No. ANL-7934, 1972 (unpublished).

[3]The beam proton interaction was restricted to a 226-cm-long region in the center of the chamber. This was enclosed by a cylindrical fiducial volume for the e^+e^- pair conversion which was 135 cm in radius, 110 cm deep, and located at the center of the chamber. The photon length before conversion was required to be greater than 12 cm. The probability of χ^2 obtained from the three-constraint fit was required to be greater than 1%.

[4]With respect to the line of flight of the V^0, the transverse-momentum distribution of the negative particles from the V^0 peaks at 0.0, 0.1, and 0.2 GeV/c for γ, Λ, and K^0, respectively.

[5]T. M. Knasel, DESY Report Nos. 70/2 and 70/3, 1970 (unpublished). With limited statistics and after making appropriate cuts on the data, the γ-length distribution for this experiment has been found to be consistent with the above cross-section determination.

[6]In the pp center-of-mass frame, s = (total energy)^2, E^* is the photon energy, and P_L^* and $P_\perp$ its longitudinal and transverse momenta. We compute Feynman's x variable from $x = P_L^*/P_{\max}^*$, with $P_{\max}^* = 2.16$ GeV/c.

[7]G. Neuhofer *et al.*, Phys. Lett. 37B, 438 (1971); 38B, 51 (1972).

[8]V. Blobel *et al.*, DESY Report No. 73/36, 1973 (unpublished).

[9]H. J. Lipkin and M. Peshkin, Phys. Rev. Lett. 28, 862 (1972).

[10]J. Hohnerkamp and K. M. Mütter, Nucl. Phys. B38, 565 (1972).

[11]See, for example, V. D. Barger and D. B. Cline, *Phenomenological Theories of High Energy Scattering* (Benjamin, New York, 1969), Chap. 5.

[12]R. N. Cahn and M. B. Einhorn, Phys. Rev. D 4, 3337 (1971).

[13]Particle Data Group, LBL Report No. UCRL-20000 *NN*, 1970 (unpublished). From the published values, the weighted average is estimated as σ_T(inelastic) = (29.1 ± 2.3) mb.

[14]The implications of such correlations have been discussed by E. L. Berger, D. Horn, and G. H. Thomas [Phys. Rev. D 7, 1412 (1973)].

[15]Inelastic topological cross sections were extrapolated from the 12.88-GeV/c data of B. Y. Oh and G. Smith (private communication).

[16]H. Bøggild *et al.*, Nucl. Phys. B27, 285 (1971). The γ conversions in this experiment were counted but not measured. We have computed the values of $\langle n_{\pi^0} \rangle$ shown in Fig. 4 from the raw data in this publication. The errors are statistical only.

[17]G. Charlton *et al.*, Phys. Rev. Lett. 29, 1759 (1972). The data shown are the most recent results. See K. Jaeger *et al.*, paper submitted to Berkeley Conference, August, 1973 (unpublished).

[18]F. T. Dao *et al.*, Phys. Rev. Lett. 30, 1151 (1973).

[19]G. Flügge *et al.*, in *Proceedings of the XVI International Conference on High Energy Physics, Chicago-Batavia, Ill., 1972,* edited by J. D. Jackson and A. Roberts (NAL, Batavia, Ill., 1973), Vol. 1, p. 561.

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Proton Compton Scattering at 0.55-to-4.5-GeV Energy and 0.12-to-1.0-(GeV/c)^2 Momentum Transfer*

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Results are presented on the elastic scattering of photons by protons. The incident photon energy ranged from 0.55 GeV to 4.5 GeV, and the four-momentum transfer t ranged from 0.12 to 1.0 (GeV/c)^2. The data at large angles, $60° < \theta^* < 115°$, are characterized by a pronounced excitation of the $D_{13}(1518)$ resonance, a shoulder in the 1688-MeV mass region, and a precipitous drop thereafter in the cross section as a function of incident energy. The low-t data are characterized by a diffraction slope of 5 (GeV/c)$^{-2}$. The data are inconsistent with the predictions of the vector-dominance model if the latter is restricted to ρ^0, ω, and ϕ vector mesons.

I. INTRODUCTION

We report a series of experiments on the elastic scattering of photons by protons conducted at the Cornell and Cambridge Electron Accelerators. The incident photon energy ranged from 0.55 to 4.5 GeV and the four-momentum transfer from 0.12 to 1.0 (GeV/c)^2. The experiments fall into two groups:

(i) "Large-angle" experiments with incident photon energy < 2.5 GeV and the center-of-mass angles in the range $60° < \theta^* < 115°$. The main motivation here was to search for resonance structure in the differential cross section.

The data exhibit a decrease of two orders of magnitude in the cross section in going from 0.5 to 2.5 GeV in the incident momentum. We were therefore limited by counting rate in extending these large-angle experiments to higher energies. A similar precipitous drop in cross section is