Inclusive π^0 and η Photoproduction at High Transverse Momenta*

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We report measurements of inclusive π^0 and η production from 21-GeV bremsstrahlung on protons, at p_T between 1 and 2 GeV/c. The π^0 cross section is reasonably well described by a single term of the constituent-interchange model, involving the irreducible subprocess $\bar{q}p \to qq\pi$. The π^0/π^+ ratio is approximately 0.8 throughout our kinematic region. The η/π^0 ratio averages 0.53 ± 0.17.

In an experiment at the Stanford Linear Accelerator Center, we have measured the yields of photons[1] and photon pairs produced by a 21-GeV bremsstrahlung beam striking a proton target. In this Letter we describe the photon-pair results and present cross sections for the inclusive photoproduction of π^0 and η mesons at transverse momenta (p_T) between 1 and 2 GeV/c and energies (E) between 8 and 14 GeV. We provide the first information on π^0/π^+ comparisons for this large a p_T, the first data on inclusive η photoproduction in any region, and the first photoproduction tests of the constituent-interchange model.[2]

The beam [3 to 5×10^6 equivalent quanta (Q) per 1.6-μsec beam pulse] was incident upon a 26.2-cm liquid-hydrogen target and was monitored by a gas quantameter. Our detector consisted of 88 lead-glass Cherenkov shower counters located 762 cm from the target and arranged in two stacks. The upper stack consisted of forty 6.35 ×6.35×34.3-cm³ blocks of SF2 glass,[3] while the lower consisted of 48 7.9×7.9×71.1-cm³ blocks of F2 glass.[4] Each stack could be remotely moved vertically and tilted so as to point toward the target. The entire array was mounted in a shielded carriage which could be remotely moved in angle. We collected data at two angular settings, corresponding to average angles of 7.3° and 8.25° for the upper stack.

Summed phototube dynode signals for each stack generated a trigger for total energy $\gtrsim 6$ GeV. We also triggered on two-stack coincidences with $\gtrsim 4.5$ GeV in each stack. For each event the anode pulse areas from all 88 counters and timing information by four-counter groups were digitized and recorded on magnetic tape by our on-line computer.

Energy calibrations were done at 2, 7, and 12 GeV by moving each counter (properly oriented) into a very low-intensity positron beam, defined by an $\frac{1}{8}$-in.-square scintillation-counter tele-scope. The measured energy resolutions were ≈0.30–0.35 GeV (rms) at 12 GeV. Photon-initiated showers start later in a counter than positron-initiated showers, so that light attenuation in the lead glass and (partly compensating for this in the shorter counters) shower leakage out the rear[5] result in a photon-positron pulse height difference of up to 3 or 4%. Calculations of this effect agreed reasonably well with calibrations using bremsstrahlung photons.

In order to keep track of counter calibration during data taking, we fed light from a TRW thyratron-driven nitrogen lamp to all 88 counters via fiber-optics light guides. The lamp was monitored by a vacuum photodiode. Pulser events were collected (between beam pulses) at a rate of about one per second; in our data analysis, counter gains were updated after every 25 pulser events. To monitor the deviation from linearity of our entire system, we periodically did runs in which pulser events were recorded for eight neutral density filters remotely interposed just before the fiber optics. This also extended our energy scale.

Our overall energy uncertainties from 0.2 to 14 GeV are ± 0.5% in scale and ≲ 60 MeV locally for most counters in the upper stack, and correspondingly ± 0.8% and ≲ 100 MeV for the lower stack (which had inferior phototubes). Because yields vary quite rapidly with energy, a 100-MeV error would lead to about a 12% error in the cross section.

When a particle enters near the edge of a counter, a significant portion of the shower leaks out of that counter. We assigned the "apparent photon energy" as the energy in the highest energy counter of each group of counters identified as a photon pattern. Apparent energies averaged about 0.5 GeV lower than real ones. (The alternative of adding neighboring counter energies was not used, because of high background rates

and the large fraction of counters lying on stack edges.) For π^0 events we required two photons in a single stack with apparent energies ≥ 2.25 GeV (upper stack) or 1.75 GeV (lower stack) and a two-photon apparent energy ≥ 7 GeV. A Monte Carlo program generated π^0, η, and single-photon spectra in apparent variables from spectra in real variables (with a trial production cross section, adjusted for agreement with the data). Our acceptance for $\pi^0 \rightarrow 2\gamma$ decays was ≈ 15–30% (a function of energy and stack). No significant uncertainties arose from Monte Carlo statistics or acceptance calculations. The program included parametrizations of the counters' response as a function of the entering particle's position, obtained by using the positron calibration beam to do detailed mapping of several counters in each stack at several energies. (For the upper stack, a small measured correction was applied to allow for photon-positron differences.)

Test Monte Carlo runs using intentionally incorrect mapping and resolution functions showed that our results are sensitive mainly to the *average* relationship between real and apparent energies, and not to the details of this relationship. The ultimate test of the average relationship is
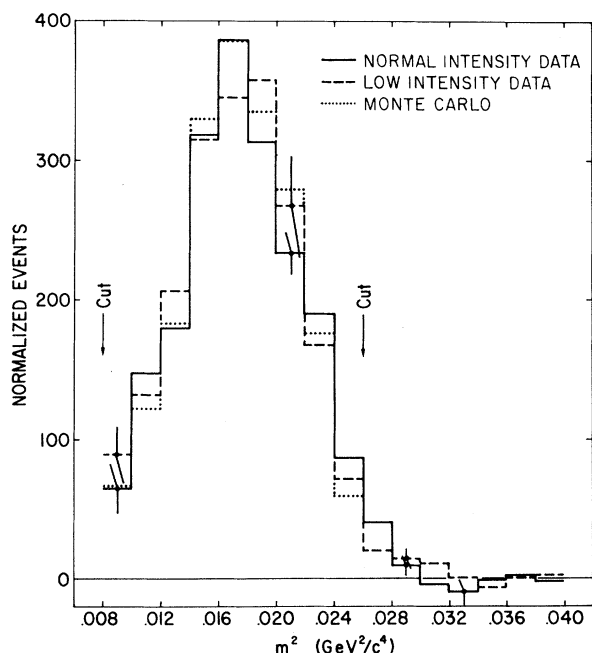
the comparison of predicted and observed π^0 (apparent) mass peaks, as illustrated in Fig. 1. An energy-scale adjustment of only 0.5% was needed in order to obtain this excellent agreement.

For this plot, and for all of our data reduction, out-of-time events were used to measure photon-photon accidental coincidence rates, which were then subtracted in apparent E versus p_T bins. This correction averaged $\approx -10\%$ and -22% for the two stacks at the 7.3° setting, and $\approx -16\%$ and -28% at $8\frac{1}{4}°$. Corrections were also applied for empty-target rates (-6%); beam attenuation in the target ($+1\%$); events lost due to timing cuts ($+2$ to 5%); and pileup—the simulation of one photon in a single counter by two or more (-5 to -11% for the upper stack, -10 to -23% for the lower stack). The dominant systematic uncertainties were due to the pileup correction and to the energy-scale uncertainties. The four data points (two stacks, two angular settings) were analyzed separately; their cross sections were found to be in good overall agreement. The final results (based upon a total of approximately 189 000 detected π^0 events after corrections) were obtained by averaging these cross sections as well as their systematic uncertainties, and are shown in Fig. 2 versus the real kinematic variables. (Points at additional values of p_T have

FIG. 1. Apparent mass-squared spectra for the upper stack at 8.25°. The normal-intensity plot represents about $\frac{1}{3}$ of those data normalized to the same number of equivalent quanta as in the low-intensity data. The latter are from a special run at $\approx 30\%$ of the normal beam intensity.
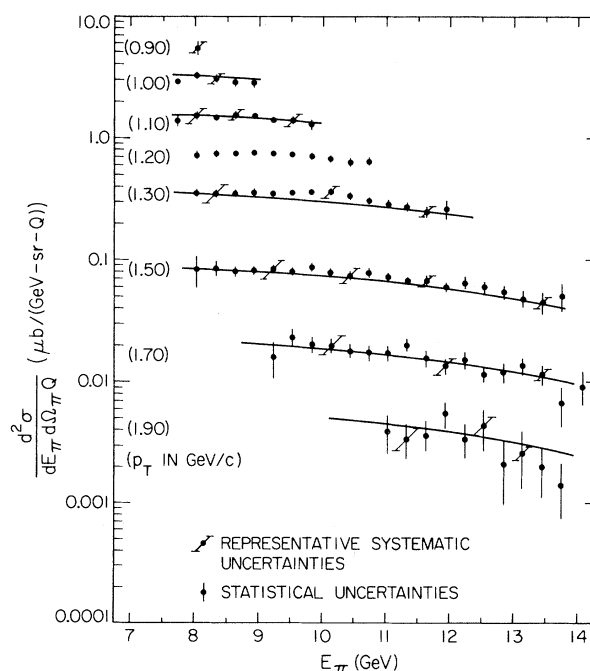

FIG. 2. Inclusive π^0 photoproduction cross section per equivalent quantum from 21-GeV bremsstrahlung. The solid curves are the predictions of the CIM (see text) with $b = 0.6$, $a = 6.5$, and $\mu^2 = 0.80$ $(\text{GeV}/c^2)^2$.
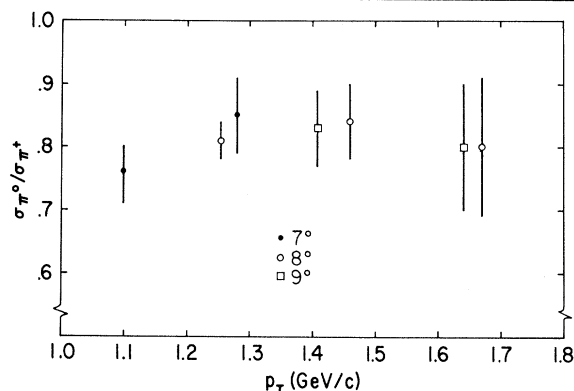
FIG. 3. Ratio of π^0 to π^+ differential photoproduction cross sections per equivalent quantum, for 21-GeV bremsstrahlung. Error bars are systematic only.

FIG. 4. Mass-squared spectra for two-stack coincidences. (a) In-time and out-of-time data; (b) a subtracted spectrum.

been omitted for clarity.)

Because we utilized a bremsstrahlung beam, we cannot display our data in terms of c.m. "scaling" variables. However, we can still make comparisons with the predictions of specific models. One of the most successful descriptions of high-p_T phenomena has been the constituent-interchange model (CIM) of Blankenbecler, Brodsky, and Gunion.[2] They represent inclusive cross sections as a sum of terms involving irreducible subprocesses (essentially, high-p_T exclusive processes without hadronic bremsstrahlung). Each such term contributes a cross section of the form

$$E\frac{d\sigma^3}{dp^3} \propto \frac{\epsilon^b}{(p_T^2 + \mu^2)^a}, \qquad (1)$$

where $\epsilon \approx 1 - (p/p_{max})_{c.m.}$ measures how far a kinematic point is from the circumference of the Peyrou plot. Our data cover a region of Feynman x from 0.3 to 0.8 and $0 \le \epsilon \le 0.4$. Although there are corrections to the formula for the larger ϵ, we have compared our results to a single term of this kind integrated over a bremsstrahlung spectrum.[6] Reasonably good agreement is obtained for $b \approx 0.6 \pm 0.3$, $a \approx 5.8$ to 7.6, and $\mu^2 \approx 0.5$ to 1.2 $(\text{GeV}/c^2)^2$. (The values of a and μ^2 are correlated and increase together.) The curves in Fig. 2 represent the predictions for $b = 0.6$, $a = 6.5$, and $\mu^2 = 0.80$. The results are consistent with the subprocess being of the type $\bar{q}p \rightarrow qq\pi$ ($a = 6$ and $b = 0$ to 1, depending upon the extent to which the photon behaves as a vector meson), and are inconsistent with a CIM process of the type $\gamma q \rightarrow \pi q$ ($a = 3$ to 4 and $b = 3$). Blankenbecler and Brodsky[2] point out that pp inclusive pro-
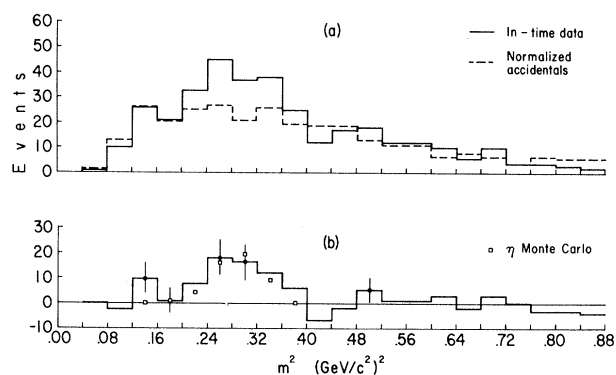
cesses at small ϵ show a similar effect.

The data may be compared with spectrometer measurements of inclusive π^+ and π^- production from 20.5-GeV bremsstrahlung.[7] The π^0-to-π^+ ratios, corrected to 21 GeV, are shown in Fig. 3. Several π^- data points (at 8°) lie slightly lower than the π^0 results. The π^0/π^+ ratio is consistent with 0.8 over our entire range. It may be increasing slightly with p_T, but shows nothing like the dramatic increase with increasing p_T observed at DESY for $p_T < 1$ GeV/c.[8]

Figure 4 shows a mass-squared plot for two-stack coincidences. With accidentals subtracted, the resulting peak agrees in shape and position with Monte Carlo calculations for η detection. The full m^2 spectrum was fitted by a sum of accidentals plus η, resulting in 51 ± 13 η events. After applying corrections we obtain an overall $\eta \rightarrow 2\gamma$ yield of 0.20 ± 0.065 times the π^0 yield in the same kinematic region ($1.1 \lesssim p_T \lesssim 1.7$ GeV/c, $E \gtrsim 10$ GeV). Within our limited statistics, this ratio is probably constant or slightly decreasing with p_T. Allowing for the branching ratio, it implies an η cross section averaging 0.53 ± 0.17 of the π^0 cross section.

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Commission.

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[1]Single-photon results are discussed by D. O. Caldwell et al., following Letter [Phys. Rev. Lett. 33, 868 (1974)].

[2]The most comprehensive reference on the CIM is R. Blankenbecler and S. J. Brodsky, SLAC Report No. SLAC-PUB-1430, 1974 (to be published). See also references referred to therein.

[3]Manufactured by Ohara Optical Glass Mfg. Co., Ltd.

[4]Manufactured by Schott Optical Glass, Inc.

[5]For shower properties, see two unpublished DESY reports by U. Völkel (1965).

[6]H. Davies, H. A. Bethe, and L. C. Maximon, Phys. Rev. 93, 788 (1954).

[7]These data were collected by our group with the aid of the physicists of Stanford Linear Accelerator Center experiment 66, and reduced with the help of D. Sherden.

[8]H. Burfeindt et al., DESY Report No. 73/61, 1973 (unpublished); C. Berger et al., Phys. Lett. 47B, 377 (1973).

Measurements of Inelastic Compton Scattering*

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We have measured inelastic Compton scattering of 21-GeV bremsstrahlung photons on protons, for p_T above 1 GeV/c. The yield of photons after subtracting π^0 and η decay contributions appears to be nonhadronic and is greater than parton-model predictions for integer-charged partons. The constituent-interchange model provides a possible explanation.

Shortly after the first deep inelast   electron-proton scattering experiments, Bjo   en and Paschos[1] suggested that inelastic Compton scattering might also probe the proton's structure. In their simple parton model, inelastic Compton scattering at sufficiently large four-momentum transfer (t) is the incoherent sum of processes in which the photon is elastically scattered by a pointlike parton of charge Q_i. The inelastic Compton cross section thus measures $\langle \sum_i Q_i^4 \rangle$, where the sum is over all partons in a configuration, and the average is over all contributing configurations.

Inelastic electron scattering in such a model measures $\langle \sum_i Q_i^2 \rangle$. Bjorken and Paschos predicted that (for spin-0 or spin-$\frac{1}{2}$ partons)

$$\left(\frac{d^2\sigma}{dE\,d\Omega}\right)_{\gamma p} = \frac{(k-E)^2}{kE}\left(\frac{d^2\sigma}{dE\,d\Omega}\right)_{ep}\frac{\langle \sum_i Q_i^4 \rangle}{\langle \sum_i Q_i^2 \rangle}, \qquad (1)$$

where k and E are the incident and scattered energies and the electron scattering cross section is evaluated for $q^2 = t$.[1] The charge-ratio factor should depend only upon $\omega = 2M(k-E)/(-t)$. If the partons are of charges 1 and 0, the factor is just unity (constant). For any quark-parton model in which the nucleon consists of three quarks and a $q\bar{q}$ sea, the ratio must lie[2] between $\frac{1}{9}$ and $\frac{4}{9}$ for all ω; the upper limit of $\frac{4}{9}$ is attained for p-quark dominance. Hence, it was suggested,

inelastic Compton scattering measurements can distinguish between integrally charged and fractionally charged partons.

In an experiment at the Stanford Linear Accelerator Center, we have measured the yields of single photons produced from a 21-GeV bremsstrahlung beam striking a proton target. We simultaneously measured the yields of π^0 mesons and (with limited statistics) η mesons, by detecting two-photon coincidences.[3] Their contributions to the photon yields can therefore be subtracted, leaving an inelastic Compton scattering cross section.

Two related experiments have been reported. One was our preliminary look at inelastic Compton scattering in which only single photons were detected.[4] After the π^0 contribution was subtracted under the assumption that π^0's and π^+'s were produced equally, the remaining photon yield was too large for even charge-1 partons. The second experiment measured the deep inelastic photoproduction of low-mass muon pairs from a Be target.[5] The yield (integrated over a large kinematic region) was about ten times that expected from Bethe-Heitler and inelastic Compton processes in the simple parton model.

Our apparatus, experimental procedure, and data reduction scheme have been described previously.[3] The single-photon yields were correct-