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Production of Large-Transverse-Momentum Gamma Rays in pp Collisions from 50 to 400 GeV

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We have measured $d^2\sigma_\gamma/dk\,d\Omega$ for the reaction $p+p\to\gamma+$anything at incident proton energies from 50 to 400 GeV. The experiment was performed in the National Accelerator Laboratory internal target area, using a lead-glass total-absorption counter. The cross sections show a deviation from simple exponential behavior in p_t for incident proton energies above 50 GeV and p_t greater than about 1 GeV/c. We present preliminary results on the energy dependence of this effect.

The behavior of cross sections for processes occurring with large transverse momentum is currently of considerable interest. In particular, measurements of inclusive pion production at the CERN intersecting storage rings (ISR)[1-3] have exhibited at large p_t a strong enhancement over the simple exponential falloff found at small p_t (<1 GeV/c). We have studied the process $p+p\to\gamma+$anything in the range of p_t from about 0.2 to 3 GeV/c for incident proton energies from 50 to 400 GeV. Using the method of Sternheimer[4] and assuming all the observed photons come from π^0 decay, the invariant π^0 cross sections can be derived from these measurements.

The experiment was carried out in the C_0 straight section of the National Accelerator Laboratory (NAL) main ring, using the circulating proton beam incident on a thin internal target. Thus, data could be taken over the range of proton energies available during the accelerator cycle. Figure 1 shows the layout of the apparatus in the internal target area and a schematic of the detection system. The target was either a hydrogen gas jet[5,6] or 7-μm carbon fibers on a rotating wheel. For the data presented here, the apparatus was set at a lab angle of 100 mrad with respect to the beam direction. Permanent magnets were used to sweep away low-momentum charged particles. A lead collimator prevented the apparatus from detecting both photons from the decay of π^0's with transverse momenta in the range studied.

The detection system consisted of a veto counter (No. 1), a removable lead converter (1.1 radi-

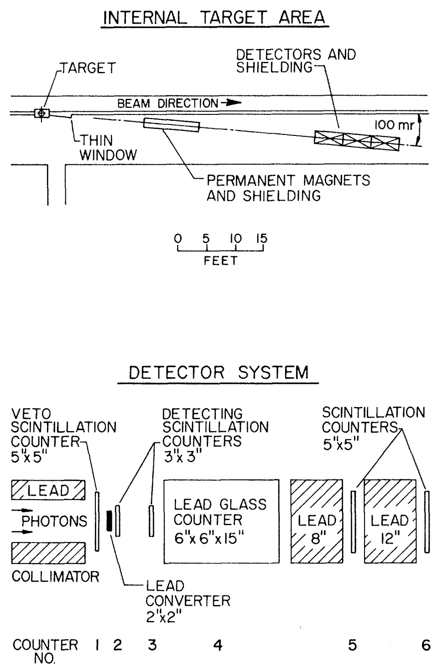

FIG. 1. Layout of the experiment in the internal target area, and schematic of the detection apparatus.

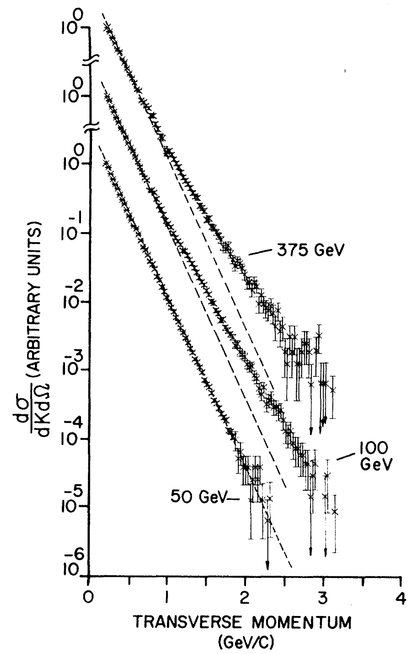

FIG. 2. Single-photon inclusive cross sections as a function of transverse momentum for protons incident on hydrogen at 50, 100, and 375 GeV. The straight lines are exponential fits to the data at low transverse momentum.

ation lengths), two coincidence counters (Nos. 2 and 3), a lead-glass shower counter (No. 4, 14.1 radiation lengths), and two more scintillation counters (Nos. 5 and 6) plus lead absorber for identifying energetic muons and charged hadrons. Photons were selected by a $\overline{C}_1C_2C_3C_4$ trigger, and "muons" by a $C_1C_2C_3C_5C_6$ trigger. The solid angle for photons accepted by the system was 9.5 μsr, defined by the converter which was 54 ft from the target.

Data were collected using a CAMAC system of scalers, analog-digital converters, and latches linked to a PDP-11 computer. When a trigger occurred, the computer recorded on magnetic tape the pulse heights in all counters, the main-ring magnetic field (giving the incident proton momentum for the event), plus certain scaler information. In addition to normal photon runs, data were taken with the Pb converter removed and also with the "muon" trigger. The converter-out data rate was found to be about 1.5% of the converter-in rate at all transverse momenta measured, consistent with photon conversion in the counters and wrappings. For runs with the "muon" trigger, the pulse-height distribution in lead-glass counter No. 4 showed a clean peak, the position of which could be determined to better than ± 2%. These runs then served to monitor the lead-glass-counter energy calibration,[7] which had been derived from measurements using electrons of 1.8 to 5 GeV/c in a momentum-analyzed charged beam at the Argonne zero-gradient synchrotron.

For the preliminary analysis presented here, the photon events were binned in 25-GeV intervals of incident proton energy. A cut was made on the pulse height in counter No. 2 to select events with greater than minimum-ionizing pulse height, corresponding to pair production in the lead converter. Fewer than 2% of the events failed this cut. The events were then histogrammed as a function of pulse height in the lead-glass counter, expressed as photon energy or transverse momentum using the calibration described above. Checks for possible backgrounds showed them to be negligible, so no subtraction was necessary. A single calibration constant was used, as the photomultiplier tube and base for the lead-glass counter had been tested with a light pulser and found to be linear up to a response equivalent to 280 GeV photon energy.

Examples of these photon energy spectra from the hydrogen jet are shown in Fig. 2 for 50, 100, and 375 GeV incident proton energy. On this semilogarithmic scale, the 50-GeV spectrum appears as a straight line, while the higher energies show significant curvature. The deviation

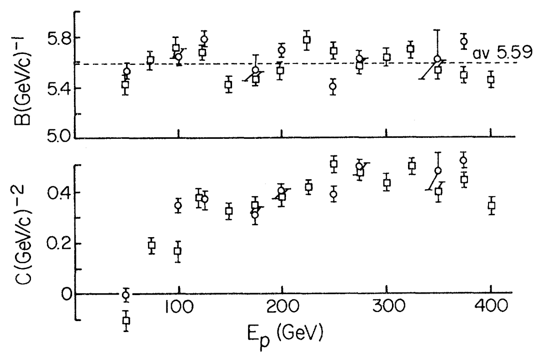

FIG. 3. Fit parameters B and C as a function of incident proton energy for photon distributions from hydrogen and carbon. Hydrogen points are identified by circles and carbon points by squares. The error bars shown do not include systematic effects.

becomes significant above about $p_t = 1$ GeV/c. A least-squares fit with a function of the form[2,3,8]

$$d^2\sigma_\gamma/dk\,d\Omega = A\exp(-Bp_t + Cp_t^2) \tag{1}$$

was made for all energies, from both hydrogen and carbon targets, with A, B, and C being free parameters. Good fits were obtained in all cases, and the results for the shape parameters B and C are plotted in Fig. 3. The error bars are only statistical and do not include overall systematic errors, such as in the calibration of the lead-glass counter. The dashed line is included only to guide the eye. It can be seen that there is good agreement between hydrogen and carbon measurements. The B (slope) values appear essentially constant with energy, while C is approximately zero at 50 GeV, increases sharply between 50 and 100 GeV, then increases relatively slowly with energy at higher energies.

The invariant π^0 cross sections can be derived from the inclusive photon spectra if one assumes all the γ rays came from π^0 decay. In that case, as shown by Sternheimer,[4]

$$E\frac{d^3\sigma_\pi}{dp^3} \propto \frac{\partial}{\partial k}\left(\frac{d^2\sigma_\gamma}{dk\,d\Omega}\right). \tag{2}$$

Since the fits described above are a good representation of the data, it is convenient to substitute Eq. (1) in Eq. (2), yielding

$$E\frac{d^3\sigma_\pi}{dp^3} \propto (B - 2Cp_t)\frac{d^2\sigma_\gamma}{dk\,d\Omega}. \tag{3}$$

A measured photon spectrum and corresponding fit parameters can then be substituted in Eq. (3) to yield the invariant π^0 spectrum. The distributions so derived were fitted with Eq. (1), yielding a new set of B's and C's. Within errors, these parameters for π^0 spectra were the same as for the original photon spectra.

The fact that the parameter B is approximately constant with energy is a well-known feature of particle production and is true up to the highest cosmic-ray energies. The new result reported here is the very strong energy dependence of the parameter C in the region of 100 GeV incident proton energy. This result could be due to (a) dynamic or kinematic effects or (b) the onset of new inelastic channels. It should be emphasized that at a fixed lab angle, the c.m. angle at which photons are detected increases as the incident proton energy increases. For c.m. angles other than 90°, the Feynman variable x varies with p_t at a given incident proton energy, and measurements at the ISR[9] show significant dependence of the cross section on x. Indeed, it is in the energy region where we observe rapid variation of the parameter C that there is appreciable x variation. At this time we are making measurements at different laboratory angles to study this further. In addition, it must be noted that at lower energies our spectra reach a larger fraction of the kinematic limit on p_t and at some point this edge of phase space must cause the spectra to cut off.

In conclusion, we confirm the result from the ISR on inclusive single-pion production, that the distributions at high incident proton energy and large p_t deviate markedly from a simple exponential in p_t. Our values of the parameter C (which is a measure of this deviation) for π^0 spectra at 300 to 400 GeV are in reasonable agreement with those found at the ISR[2] for charged pions at similar c.m. energy. In addition, we present preliminary results on the energy dependence of this effect showing rapid change of C between 50 and 100 GeV. This energy dependence is being studied further.

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Electroproduction of Protons in the Forward Direction*

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We present data on electroproduction off protons in which a proton moving in approximately the same direction as the virtual photon is detected. Measurements were made at data points with (Q^2, W) values of (0.6, 2.67), (1.2, 2.67), (2.0, 2.67), and (1.2, 2.15) in (GeV^2, GeV). The virtual photoproduction cross section for p +MM is studied as a function of scaling variables x' and $P_\perp^2$, azimuthal angle φ, Q^2, and W.

The large cross section for deep inelastic electron-nucleon scattering, which is a function of a single variable $\omega = 2M\nu/Q^2$, has aroused considerable theoretical and experimental interest in the details of the processes which are responsible for it. This paper reports an experiment at center-of-mass energies just above the resonance region (the range 2–3 GeV) in which a proton moving in approximately the same direction as the virtual photon is detected.

In what is now standard notation,[1] electroproduction can be treated as photoproduction by a virtual photon, where the square of the photon's mass $-Q^2$, energy ν, direction, and polarization parameter ϵ are tagged by the scattered electron. We present the virtual-photon–target-proton cross sections in terms of the same kinematic variables which were defined and used in Bebek *et al.*[2] Instead of differential cross sections, we show the invariant structure function,

$$F = \frac{E}{\sigma_{\rm tot}}\frac{d^3\sigma}{dp^3} = \frac{1}{\sigma_{\rm tot}}\frac{1}{\pi}\frac{E^*}{[P_{\rm max}^{*2} - P_\perp^{\;2}]^{1/2}}\frac{d\sigma}{dx'dP_\perp^{\;2}},$$

where $\sigma_{\rm tot}$ is the total virtual photoproduction cross section for the W and Q^2 of the reaction. The value of $\sigma_{\rm tot}$ was taken from a fit to the Stanford Linear Accelerator Center–Massachusetts Institute of Technology measurements of νW_2 with the assumption that $\sigma_S/\sigma_T = 0.18$.[3]

Two magnetic spectrometers were used to detect the scattered electron and the electroproduced hadron. A combination of a Cherenkov counter and a lead-acetate shower counter identified the electrons. Pions were identified by a threshold gas Cherenkov counter when their momentum was greater than 1.8 GeV/c and by their time of flight when their momentum was less than that. Neither protons nor kaons gave a sig-