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HIGH ENERGY MUON INELASTIC SCATTERING*

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ABSTRACT

Muon inelastic scattering has been measured using muons with momenta between 8.6 and 12.9 GeV/c on a carbon target. The virtual photoproduction cross section is presented as a function of the four momentum transfer from the muon.

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An experiment to measure muon inelastic scattering and muon bremsstrahlung has recently been completed at the Brookhaven Alternating Gradient Synchrotron. The data for both processes were taken simultaneously with the same beam and apparatus because both occur with roughly equal rates when a muon scatters in carbon with appreciable energy loss. The inelastic scattering is described here and the bremsstrahlung is discussed in the following Letter.[1] Inelastic muon scattering is also being measured at SLAC and preliminary results have been reported.[2]

A plan view of the experimental apparatus is shown in Fig. 1. The muon beam was produced by the decay of a high intensity pion beam.[3] The muons entered the experimental area through a 24 ft. long carbon filled collimator which served to attenuate the remaining pions. There were 2 x 10^4 μ^+ per pulse or 10^4 μ^- per pulse with momenta between 8.6 and 12.9 GeV/c and 10^{-4} pions per muon. The beam was defined by the beam counters S1, S2 and S3 in anticoincidence with counter AS, which had a round hole. The angular divergence of the beam was $\pm$ 20 mr. Muons with momenta below 8.6 GeV/c were supressed by requiring a sufficiently high pulse from a momentum measuring hodoscope system[4], HA, HB, and HC. The momentum of the triggering muon was ultimately measured to $\pm$2% using four aluminum plate spark chambers which flanked magnet D6. The carbon target consisted of the first 21 plates of a spark chamber, each 1/2" thick; the second half of this chamber had aluminum foil plates. The muons then passed through a large aperture magnet and five spark chambers. The first two of these chambers each had five aluminum plates. This arrangement permitted detection and momentum analysis of recoil muons produced at angles up to 12° with final momenta in the region 1.5 to 6.0 GeV/c. The final three chambers each had eight plates of lead and a ninth plate of aluminum. The scattered muon was detected in the F bank which had six scintillation counters. After it passed through a 40" iron pion filter, the muon was detected by a crossed array of counter banks, A, B, C, and D. A trigger required at least one count in F in coincidence with at least one count from A or B and at least one count in C or D. Three counters centered on the unscattered beam line served to veto unscattered muons. The 54 rear counters were connected to gate circuits which flashed lights that were photographed by one of the cameras, thus recording which of the rear counters actually participated in the coincidence. Each event consisted of four photographs; one of the beam momentum chambers, one of the target chamber, and two of the rear chambers. The experimental detection efficiency for various final energies and physical scattering angles was calculated by a Monte Carlo program in which trajectories were traced through the apparatus.

We report here on the data from two μ^+ runs; one with the beam as described and one with 101.2 g/cm^2 (2 feet) of the carbon in the collimator removed. The pion contamination in the beam was much greater than we had anticipated. Even though the iron pion filter rejected pions with an efficiency of ∿95%, about 10% of the events with the full collimator were pion induced. Since the pion attenuation length in carbon is 95.1 ± 5.8 g/cm^2,[5] the pion flux in the beam with the filter partially removed was increased by a factor of 2.9 ± 0.2. By comparing the two sets of data we are able to deduce the cross section due to muon induced events alone.

The pictures of the beam momentum chambers were measured by the SPASM[6] automatic scanning system. Only events which were successfully reconstructed using the SPASM measurements and which had incident momenta between 8.6 and 12.9 GeV/c were measured in the other chambers. An event is defined as an interaction in the carbon target which produced two or more prongs; obvious knock-ons, in which the muon was undeflected and the second prong had very low energy, were not included. The incident track and the interaction vertex in the target chamber, and the triggering particle in the rear chambers were measured on image plane digitizer measuring machines. We made no attempt to determine from the target chamber pictures which of the particles emerging from the vertex was the muon. The direction of the scattered muon was reconstructed using the vertex position and the measurement in the rear chambers.

Radiative corrections were calculated using the elastic cross section, inelastic scattering with the production of the first, second and third nucleon resonances in the zero width approximation, and an approximate fit to the inelastic continuum beyond the resonances.[7] The correction was 2% to 8% depending on q^2, the square of the four momentum transfer from the muon, and was assumed to be accurate to within a factor of two. Corrections were also made for scanning and measuring efficiencies.

The cross section for inelastic muon scattering assuming one photon exchange and detection of only the scattered muon is[8]

$$\frac{d^2\sigma}{d\Omega\, dE'} = \Gamma_T(q^2,k) \quad \sigma_T(q^2,k) + \Gamma_o(q^2,k) \quad \sigma_o(q^2,k)$$

where E and E' are the initial and final laboratory lepton energies,

M is the mass of the proton, and

$k = E - E' - |q^2|/2M$. is the effective virtual photon energy.

The first term is the contribution of transversely polarized virtual photons and the second term is that of scalar photons. The Γ factors may be interpreted as the number of virtual photons per MeV per steradian (of the scattered muon). In the limit $q^2 \to 0$, σ_o vanishes while σ_T becomes equal to the total cross section for real photons of energy k. The Γ factors may be expressed as

$$\Gamma_T(q^2,k) = \frac{\alpha}{4\pi^2} \frac{k}{q^2} \frac{E'}{E} \left[2 + \frac{4 E^2 E'^2 \sin^2\theta}{q^2 (\vec{p} - \vec{p}')^2}\right]$$

$$\Gamma_o(q^2,k) = \frac{\alpha}{4\pi^2} \frac{k}{q^2} \frac{E'}{E} \left[\frac{4 E^2 E'^2 \sin^2\theta}{q^2 (\vec{p} - \vec{p}')^2} + \frac{4m^2}{q^2}\right]$$

where θ is the muon scattering angle and m is the muon mass. We present our data as

$$\sigma_T(q^2,k) + \sigma_o(q^2,k) = \frac{d^2\sigma}{d\Omega\, dE'} \;/\; \Gamma_T(q^2,k) \;.$$

Figure 2 shows $(\sigma_T + \sigma_o)$ as a function of q^2 with the pion contamination removed as described above; the inset shows the distribution of events plotted as a function of the virtual photon energy, k. The errors shown are due to statistics and to uncertainties in the radiative corrections, the pion attenuation length in carbon, and in the scanning and measuring efficiencies. Also shown are two preliminary points from inelastic electron scattering from hydrogen[9] multiplied by 12 (the number of nucleons in carbon). The electron data indicate that in the deep inelastic region, $W_2(q^2,k)$ is independent of q^2 for $q^2 > 0.8\,(\mathrm{GeV/c})^2$ where

$$W_2(q^2,k) = \frac{k(\sigma_T + \sigma_o)}{4\alpha\pi^2(0.04 \times 10^{-26})} \quad \frac{q^2}{(q^2 + q_o^2)} \;.$$

The solid line in figure 2 shows the fit

$$(\sigma_T + \sigma_o)\ (\mathrm{mb.}) = (1.62 \pm .19) \times \frac{1}{(1 + q^2(2.5 \pm 0.3))}$$

where q^2 is expressed in $(\text{GeV/c})^2$. This fit has a χ^2 of 2.9 for 5 degrees of freedom or a 70% confidence level. Its form was chosen to express the constancy of W_2 at high q^2 when $q_o^2 > q^2$, and to give a simple form at $q^2=0$. Another fit of the form

$$(\sigma_T + \sigma_o)\ (\text{mb.}) = \frac{A}{(1 + q^2/m_\rho^{\,2})^2} + \frac{B\,q^2}{(1 + q^2/m_\rho^{\,2})^2}$$

where m_ρ is the rho meson mass, gave a similar χ^2 with $A = (1.60 \pm .33)$.

To the extent that the extrapolation to $q^2=0$ is correct, we obtain for the total photoproduction cross section

$$\sigma_{\gamma C} = 1.62 \pm .19 \text{ mb. for } 5.5 < k \le 9.5 \text{ GeV.}$$

The vector dominance model and the optical theorem may be used to obtain[10]

$$\sigma_{tot}(\gamma A) = \frac{\sqrt{16\pi}}{\sqrt{1+\beta^2}} \sum_{V=\rho,\omega,\phi} \frac{e}{f_V} \sqrt{\frac{d\sigma}{dt}(\gamma A \to VA)}\Big|_{t=0}$$

where β is the ratio of the real part of the forward Compton scattering amplitude to the imaginary part. An integration of the dispersion relation for the real part[11] yields $\beta \simeq 0.12$ at 7.5 GeV,[12] which is negligible. Using the measured cross sections for forward photoproduction of ρ[13] and ϕ[14] mesons from carbon, and an estimate of the contribution of ω mesons, we find that vector dominance predicts 1.0 ± 0.2 mb. for the total photoproduction cross section from carbon.

One would expect the photoproduction cross section to scale as A because the gamma ray does not get absorbed strongly in a nucleus. However a vector dominance model calculation indicates that the photoproduction cross section from carbon is about a factor of 10 times the hydrogen cross section[15,16], not a factor of 12, at 7.5 GeV. We compare our results with these two different scalings with other experimental[17,18] and theoretical[19,20,21] results for the total photoproduction cross section from hydrogen, in Table 1. Our data are consistent with all previous determinations of the hydrogen cross section if we scale as A while we do not agree well if we scale with a factor of 10.

We also verify the lack of a strong q^2 dependence of the cross section at large k observed in inelastic electron scattering.[9] Because even vector dominance predicts an ~A behavior at medium and large q^2,[15] we see no difference between muon and electron inelastic scattering. However electron data at lower momentum transfers and more accurate muon data are needed before any definite conclusions can be drawn.

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Figure Captions

Figure 1 - Experimental arrangement.

Figure 2 - The total virtual photon cross section on carbon as a function of the square of the four momentum transfer from the muon. The inset shows the distribution of the virtual photon energies.

Table Caption

Table 1 - Results from other sources compared with those from the present work.

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TABLE 1

Reference	Technique Used	Photon Energy (GeV)	$\sigma_{\gamma p}$ Obtained (μb)
This work	Inelastic μ scattering. Scale from carbon ∿ A.	$5.5 < k < 9.5$	135 ± 16
This work	Inelastic μ scattering. Scale from carbon, factor of 10.	$5.5 < k < 9.5$	162 ± 19
ABBHHM Collaboration	Bubble Chamber - photoproduction	$3.5 < k < 5.4$	116 ± 17
J. Ballam et. al.	Bubble Chamber - photoproduction	$7 < k < 8$	126 ± 17
M. Davier et. al.	Vector Dominance Model	$k = 9$	130 ± 30
G. Knies	Quasielastic Optical Theorem	$3 < k < 5$	99 ± 12
Buccella and Colocci	Regge Pole Theory	$k > 5$	130

Results from other sources compared with those from the present work.

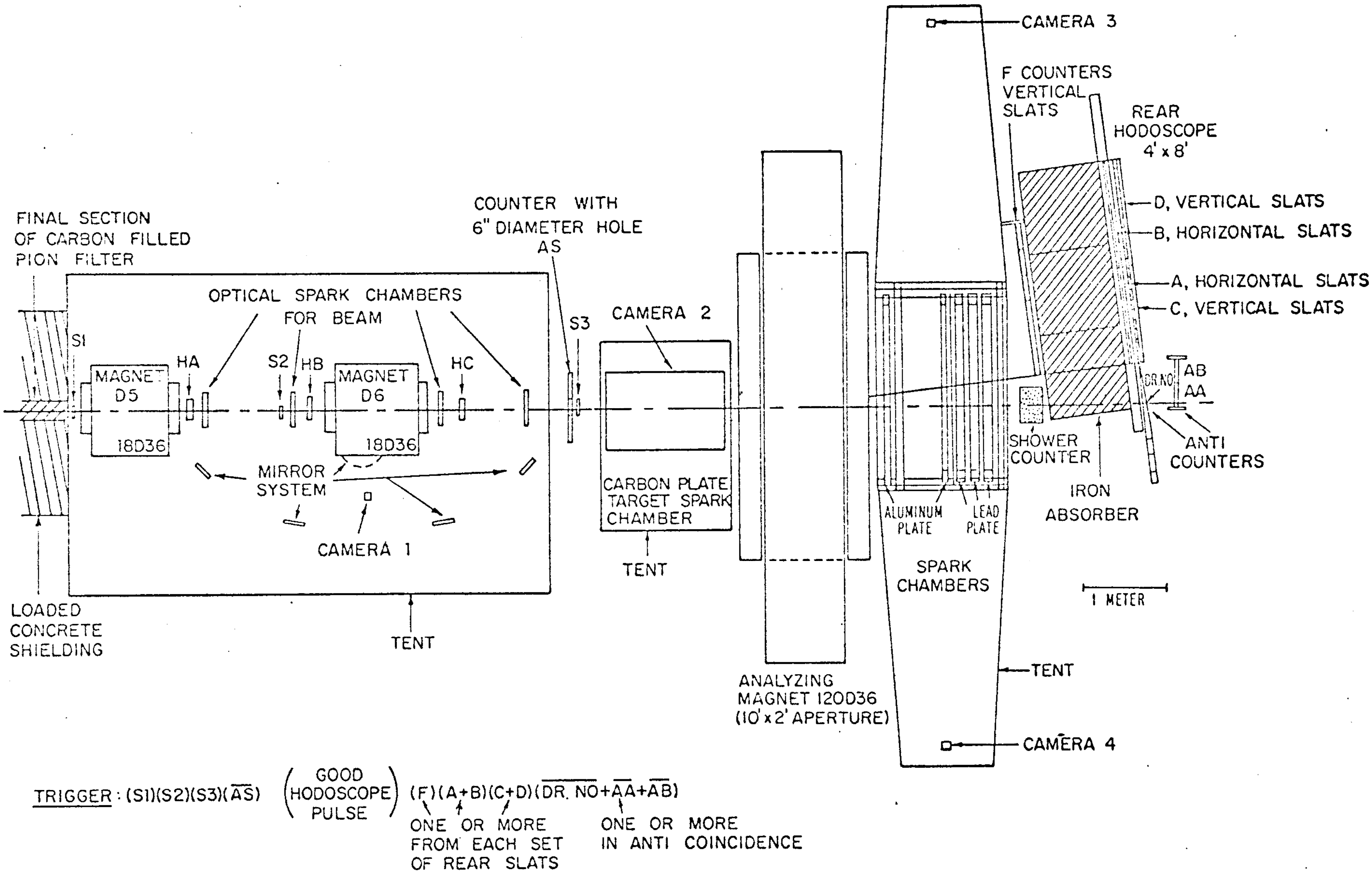
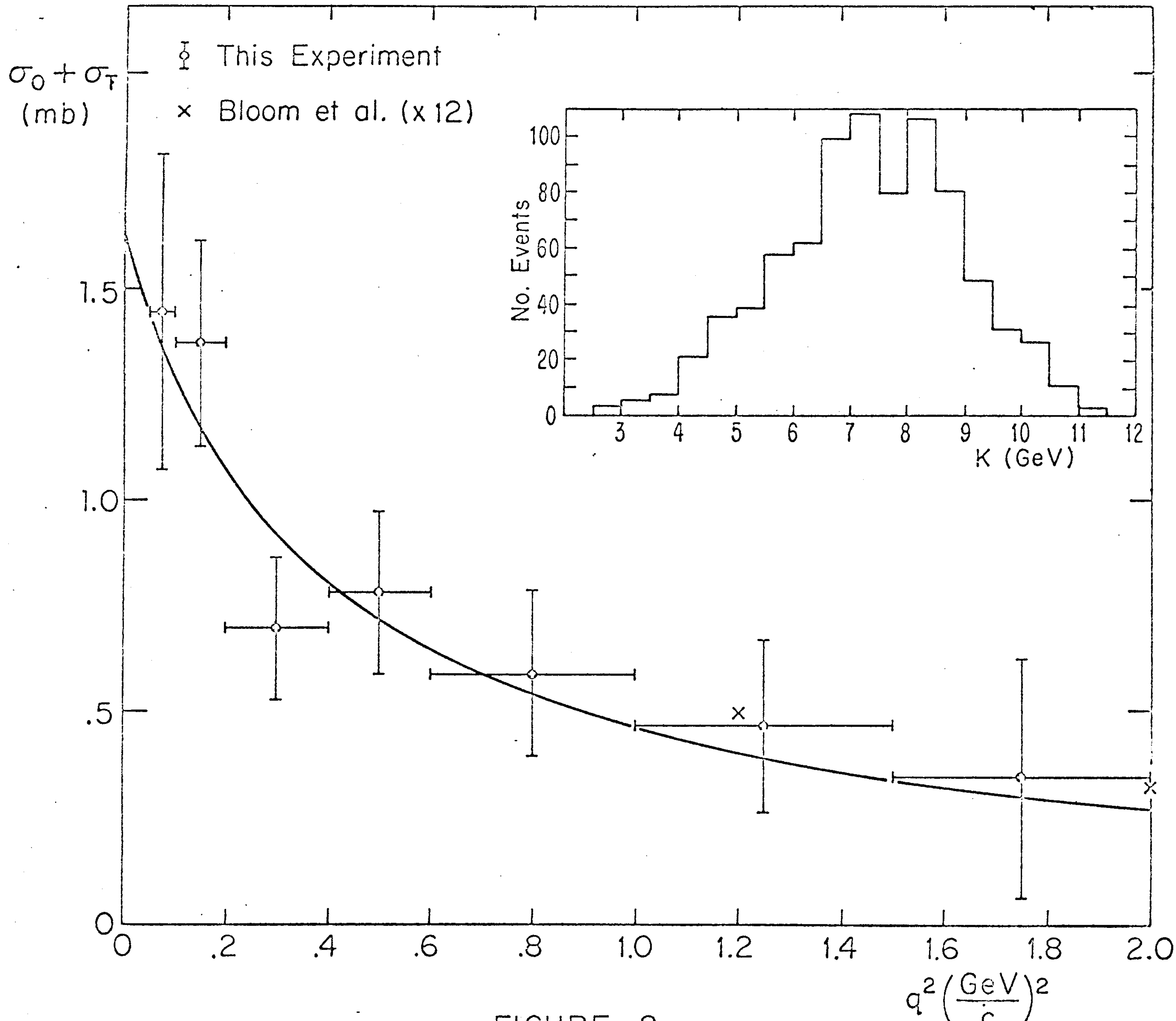

FINAL SECTION
OF CARBON FILLED
PION FILTER
LOADED
CONCRETE
SHIELDING
S1
MAGNET
D5
18D36
HA
OPTICAL SPARK CHAMBERS
FOR BEAM
S2
HB
MAGNET
D6
18D36
HC
MIRROR
SYSTEM
CAMERA 1
TENT
COUNTER WITH
6" DIAMETER HOLE
AS
S3
CAMERA 2
CARBON PLATE
TARGET SPARK
CHAMBER
TENT
ANALYZING
MAGNET 120D36
(10'x2' APERTURE)
CAMERA 3
CAMERA 4
F COUNTERS
VERTICAL
SLATS
REAR
HODOSCOPE
4'x8'
D, VERTICAL SLATS
B, HORIZONTAL SLATS
A, HORIZONTAL SLATS
C, VERTICAL SLATS
DR.NO
AB
AA
ANTI
COUNTERS
SHOWER
COUNTER
IRON
ABSORBER
ALUMINUM
PLATE
LEAD
PLATE
SPARK
CHAMBERS
TENT
1 METER
TRIGGER: (S1)(S2)(S3)($\overline{AS}$) (GOOD HODOSCOPE PULSE) (F)(A+B)(C+D)($\overline{DR. NO}$+$\overline{AA}$+$\overline{AB}$)
ONE OR MORE
FROM EACH SET
OF REAR SLATS
ONE OR MORE
IN ANTI COINCIDENCE

FIGURE 1



This Experiment
Bloom et al. (x 12)
$\sigma_0 + \sigma_T$ (mb)
1.5
1.0
.5
0
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
$q^2 \left(\frac{GeV}{c}\right)^2$
No. Events
100 80 60 40 20 0
3 4 5 6 7 8 9 10 11 12
K (GeV)

FIGURE 2