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ELASTIC SCATTERING DETERMINATION OF THE NEGATIVE PION FORM FACTOR

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ABSTRACT

A new measurement of the elastic scattering of 250 GeV/c negative pions by electrons provides form factor results from $0.0368 < q^2 < 0.0940$ $(GeV/c)^2$. The resulting value of $\langle r_\pi^2 \rangle = 0.439 \pm 0.030 F^2$ is significantly higher than that obtained in an earlier 100 GeV/c scattering experiment. An evaluation of all elastic scattering results suggests a best value of

$$\langle r_\pi^2 \rangle = 0.405 \pm 0.047$$

In a previous letter[1] we have reported the electromagnetic form factor of the negative kaon. During the same experiment we also measured the electromagnetic form factor of the pion in the q^2 range from 0.0368 to 0.0940 $(GeV/c)^2$. This experiment is the third in a series of direct measurements of the negative pion form factor by elastic scattering of electrons (stationary electrons from a liquid hydrogen target).

This experiment was done in the M_1 beam line at Fermilab. The beam energy was 250 GeV/c; the flux was typically 2.6×10^5 usable beam particles per spill, with 98% of the beam being pions and 2% being kaons. The pions and kaons were distinguished by a differential Cerenkov counter. The details of the event trigger are given in our previous letter.

The apparatus consisted of a magnetic spectrometer employing the high resolution and high redundancy of 32 proportional wire chamber planes and 32 drift chamber planes together with lead-glass shower counters for electron identification. A complete description of the experimental details is in preparation. The experiment differed from the kaon measurement[1] in only two regards. The pion trigger was prescaled down by a factor of 4, and there was a two-particle requirement in a scintillation counter hodoscope. Subsequently the prescaler has been tested under a variety of conditions and found to perform satisfactorily. The trigger efficiency (.999 ± .001) of the hodoscope has been determined from the kaon data in which it was latched. Its geometric efficiency was typically 100%, but dropped as low as 73% near the high end of the q^2 range.

After finding and fitting the beam tracks entering the electron target and the secondary tracks leaving the target, both before and after traversing the magnet, each event was tested against the hypothesis of elastic scattering with an unseen photon radiated in the electron's direction. In this fit it was assumed that an undetected photon was produced in the electron's direction either by radiation accompanying the elastic scattering or by electron bremsstrahlung in the target or spectrometer material. Elastic scatters were identified by requiring (1) a chi square less than 30 for the 3C fit, (2) a radiated photon determined in the fit to have less than 12 GeV energy, (3) a shower counter pulse height consistent with the electron energy, and (4) a scattering vertex in the target; 13945 events survived the cuts which are shown in Fig. 1. In order to obtain the differential pion-electron elastic scattering cross section, a series of corrections were applied, the major ones being (1) primary pion attentuation (3.3 ± 0.1%), (2) secondary pion attenuation (4.8 ± 0.1%), (3) geometric inefficiency (0.0 to 27.0 ± 2.3%), (4) radiative corrections (4.1 ± 0.5 to 8.0 ± 0.7%), (5) track finding inefficiency (2.7 ± 0.5 to 3.3 ± 0.8%), and (6) external bremsstrahlung photons with energy greater than 12 GeV (12.8 ± 0.3 to 18.4 ± 0.4%). The correction for hadronic interaction background was reduced to less than 1% after the shower counter requirement. The chi-square cut was varied from 10 to 80 and the bremsstrahlung energy cut was varied from 8 to 36 GeV to test their correction: no significant effect on the result was found.

The numbers of events which survive the cuts are listed in Table I as a function of q^2. Also given are the corrected numbers of events and the resulting cross sections and form factor squared. The square of the form factor is plotted in Figure 2(a). The solid curve is a fit to a pole form $|F_\pi|^2 = (1-(\langle r_\pi^2\rangle/6)q^2)^{-2}$ constrained to be unity at $q^2 = 0$. The error matrix is well represented by the statistical error and an overall normalization error of 1.0%. The chi-square probability of the fit is 71.3% (14 data points with 13 degrees of freedom). The fitted pion radius is $\langle r_\pi^2\rangle = .439 \pm .030F^2$. A loose measure of internal consistency is provided by an unnormalized fit shown as the dashed line with $\langle r_\pi^2\rangle = .384 \pm .088F^2$ and fitted value of $.974 \pm .039F$ for $|F_\pi|^2 = 1$ at $q^2 = 0$. The chi-squared probability of the fits is 67.5%. If the dipole is used instead of the pole form for $|F_\pi|^2$, the fitted radius squared becomes $0.426 \pm 0.028\ F^2$ and has a chi-square probability of 70%.

The present results (F2) can be combined with two earlier direct form factor measurements. The first was done at Serpukhov[2] (S) at a beam energy of 50 GeV for a q^2 range of 0.0135 to 0.0358 $(GeV/c)^2$. The second was done at Fermilab[3] (F1) at 100 GeV for a q^2 range of 0.0307 to 0.0715 $(GeV/c)^2$. Figure 2(b) shows the form factor squared obtained in these three experiments. A fit to the pole form was made to the 56 data points utilizing the full error matrix from each experiment. The result is shown as the solid curve in Figure 2(b) and corresponds to $\langle r_\pi^2\rangle = 0.405 \pm 0.024F^2$ with a chi-square of 51.0 for 55 degrees of freedom. Detailed results are given in Table II for each individual experiment and for all combinations. If the constraint of $|F_\pi|^2 = 1$ at $q^2 = 0$ is removed, the overall fit to the three experiments yields $\langle r_\pi^2\rangle = 0.454 \pm 0.067F^2$ with fitted value $|F_\pi|^2 = 1.021 \pm 0.027$ at $q^2 = 0$ and chi-square probability 62%.

The chi-square value is indicative of a very good overall fit to the three experiments as is evident in Figure 2(b). However, the statistical fluctuations mask systematic differences which are seen in the separate results for the pion radius squared; the F1 result of $0.315 \pm 0.041F^2$ is 2.1 standard deviations below the joint fit whereas the Serpukhov and F2 results of 0.610 ± 0.150 and $0.439 \pm 0.030F^2$ are 1.4 and 1.2 standard deviations above. This suggests that the experiments be combined with an error scale[4] of 2.0 and that the overall result with scaled error be taken as

$$\langle r_\pi^2\rangle = 0.405 \pm 0.047F^2$$

The form factor of the pion has been measured in both the space-like and time-like regions in a large number of experiments. At the present time only 2 experiments in addition to ours have measured the pion radius to a high accuracy. One is the electroproduction experiment of Bebek et al.[5] giving $<r_{\pi}^2> = 0.506 \pm 0.026F^2$. It should be pointed out that extraction of the form factor from electroproduction is inherently model dependent. The other is the annihilation experiment of Quenzer, et al.[6] Their result of $<r_{\pi}^2> = 0.460 \pm 0.011F^2$ depends on a correct parameterization of the multipion inelastic channel. Heyn and Lang[7] have done an analysis of all pion form factor data in the q^2 region -9.61 to +9.77 $(GeV/c)^2$ in a way which is largely model independent. They find $<r_{\pi}^2> = 0.47 \pm 0.02F^2$. If the electroproduction data of Bebek is excluded they obtain $<r_{\pi}^2> = 0.43F^2$, in good agreement with our present measurement and in fair agreement with the best fit to all three direct-measurement experiments.

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FOOTNOTES

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TABLE I. Events (corrected in parenthesis) measured cross section and form factor *versus* q^2.

q^2 $[(GeV/c)^2]$	Number of events	$d\sigma/dq^2$ $[\mu b(GeV/c)^{-2}]$	$\lvert F_\pi \rvert^2$
0.039	2583(3895)	123.9 ± 2.7	0.857 ± 0.019
0.043	2184(3150)	100.3 ± 2.4	0.865 ± 0.021
0.047	1738(2440)	77.6 ± 2.0	0.821 ± 0.022
0.051	1496(2069)	65.8 ± 1.8	0.840 ± 0.024
0.055	1238(1716)	54.6 ± 1.6	0.831 ± 0.025
0.059	953(1342)	42.7 ± 1.4	0.767 ± 0.027
0.063	873(1255)	39.9 ± 1.4	0.838 ± 0.029
0.067	658(978)	31.0 ± 1.2	0.757 ± 0.032
0.072	569(886)	28.1 ± 1.2	0.791 ± 0.035
0.076	454(747)	23.7 ± 1.1	0.762 ± 0.038
0.080	383(662)	20.9 ± 1.1	0.765 ± 0.041
0.084	328(607)	19.3 ± 1.1	0.802 ± 0.045
0.088	256(483)	15.3 ± 1.0	0.720 ± 0.047
0.092	232(432)	13.7 ± 0.9	0.728 ± 0.050

TABLE II. Results of fits of the pion form factor to the dipole form.

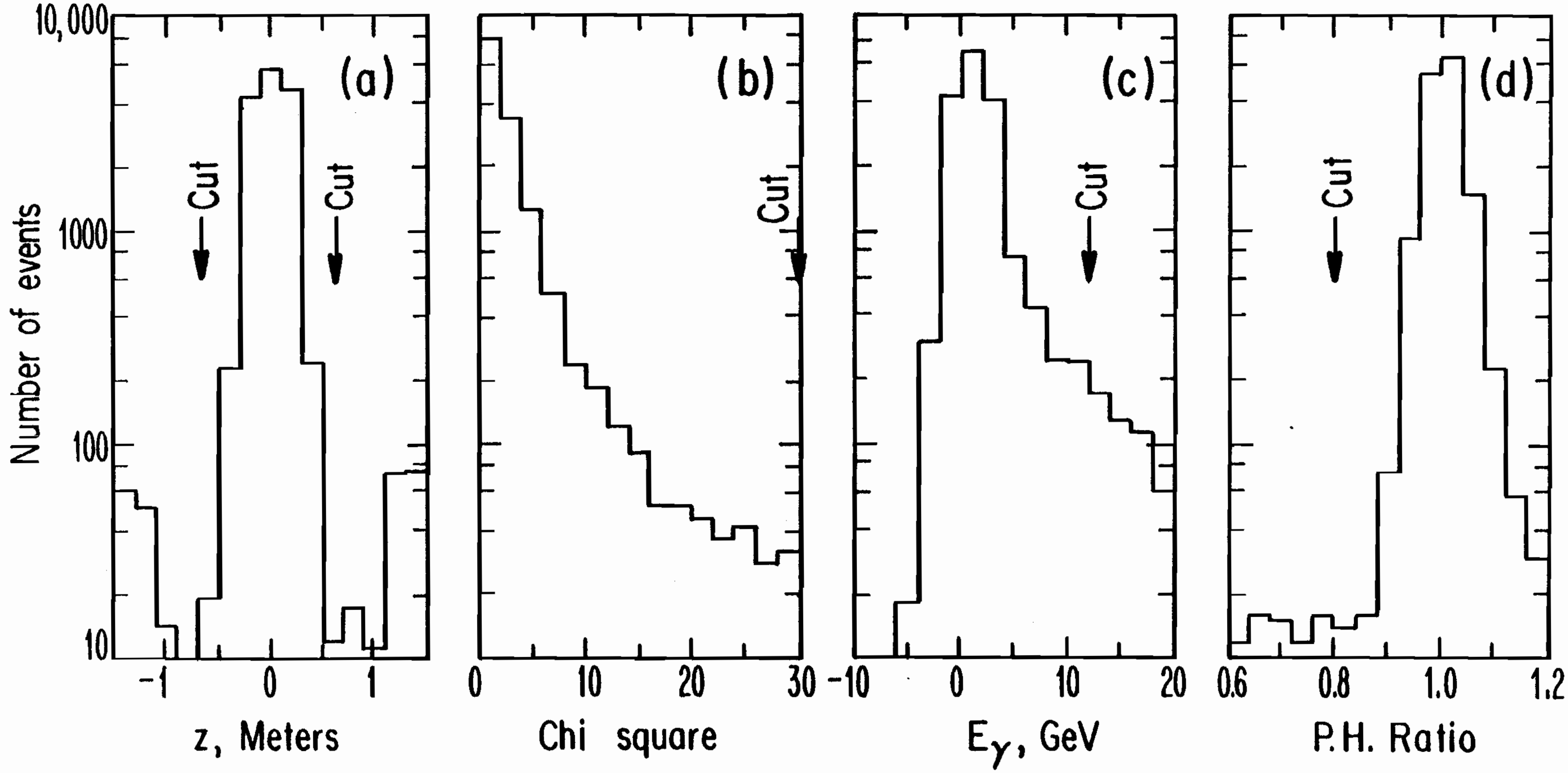
Experiments S, F1, and F2 refer to references 2, 3, and this experiment.

Experiment	Number of Data Points	$F_\pi(0) \equiv 1$				
		$\langle r^2 \rangle$	Chi-Square (& Probability)	$\langle r^2 \rangle$	$F_\pi(0)$ Fitted Normalization	Chi-Square (& Probability)
S+F1+F2	56	0.405 ± 0.024	51.0(62.9%)	0.454 ± 0.067	1.021 ± 0.027	50.3(61.6%)
S+F1	42	0.339 ± 0.040	37.2(64.1%)	0.420 ± 0.118	1.029 ± 0.040	36.6(62.3%)
S+F2	36	0.447 ± 0.029	20.8(97.3%)	0.421 ± 0.076	0.988 ± 0.032	20.6(96.5%)
F1+F2	34	0.399 ± 0.024	39.2(21.1%)	0.453 ± 0.073	1.024 ± 0.030	38.5(19.7%)
S	22	0.610 ± 0.150	9.6(98.3%)	1.024 ± 0.348	1.106 ± 0.080	7.7(99.4%)
F1	20	0.315 ± 0.041	23.5(19.5%)	0.418 ± 0.145	1.039 ± 0.052	22.9(21.7%)
F2	14	0.439 ± 0.030	9.8(71.4%)	0.384 ± 0.088	0.974 ± 0.039	9.3(67.5%)

FIGURES

Figure 1: Distributions of (a) reconstructed vertex position Z, (b) chi-square for 3C fit, (c) fitted energy of radiated or bremsstrahlung photon, and (d) ratio of pulse height from the lead glass shower counter to that expected, showing the cuts used in selecting elastic events.

Figure 2: Pion form factor squared versus q^2 for (a) the present experiment (F2) and for (b) the experiments of References 2 and 3 (S and F1) as well, The solid curves are fits with the constraint $|F_\pi|^2 = 1$ at $q^2 = 0$. The dashed curves are unconstrained fits with fitted value at $q^2 = 0$ indicated by the open-square points.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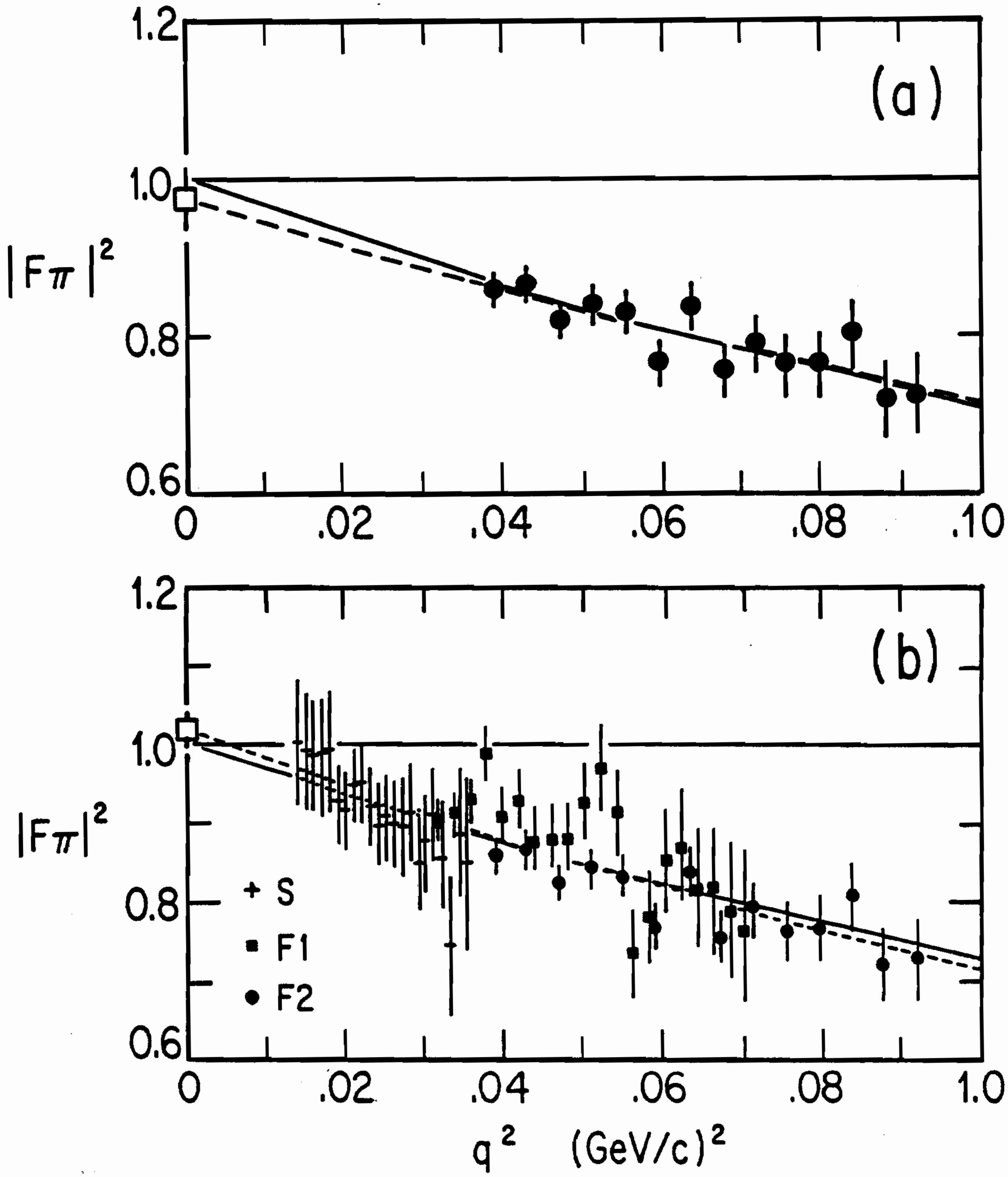
1000
100
10
Number of events
(a)
(b)
(c)
(d)
Cut
Cut
Cut
Cut
Cut
-1
0
1
z, Meters
0
10
20
30
Chi square
-10
0
10
20
E_γ, GeV
0.6
0.8
1.0
1.2
P.H. Ratio

FIGURE 1


1.2
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(a)
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(b)
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+ S
▪ F1
● F2
0
.02
.04
.06
.08
1.0
q² (GeV/c)²

FIGURE 2