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Direct Measurement of the π^- Form Factor

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We have measured the electromagnetic form factor of the charged pion by direct scattering of 100-GeV/c π^- from stationary electrons in a liquid-hydrogen target at Fermilab. The deviations from the pointlike pion-scattering cross section may be characterized by a root-mean-square charge radius for the pion of $\langle r_\pi^2\rangle^{1/2} = 0.56\pm 0.04$ F.

We have performed an experiment in a 100-GeV/c negatively charged-pion beam at the Fermi National Accelerator Laboratory to measure the form factor of the pion by elastically scattering pions from the atomic electrons in a liquid-hydrogen target. The square of the pion form factor as a function of the square of the four-momentum transfer, q^2, is defined to be the π-e elastic (el) differential scattering cross section after radiation correction, divided by that predicted for a point (pt) pion;

$$(d\sigma/dq^2)_{\rm el} = (d\sigma/dq^2)_{\rm pt} |F_\pi(q^2)|^2 = \frac{4\pi\alpha^2}{q^4}\left(1-\frac{q^2}{q_{\rm max}{}^2}\right)\left|1-\frac{\langle r_\pi{}^2\rangle}{6}q^2+\cdots\right|^2.$$

In the second line the point-pion cross section is written in terms of the fine-structure constant α and $F_\pi(q^2)$ has been expanded in powers of q^2. In our experiment the maximum recoil energy of the electron was 84 GeV corresponding to $q_{\rm max}{}^2 = 0.086$ (GeV/c)^2. In this Letter we present data on the pion form factor in the range $0.03 \leq q^2 \leq 0.07$ (GeV/c)^2.

The charged pion is a particularly simple system compared to the proton. Its isovector character implies that it couples almost exclusively to the ρ meson. In the timelike domain the pion form factor has been well measured experimentally.[1] Measurements of the pion form factor at spacelike momentum transfers, coupled with analyticity, provide a useful test of the vector-dominance model. Furthermore, the size of the pion can be extracted directly from these spacelike measurements.

The first direct measurement[2] of the pion form factor by π-e elastic scattering obtained $\langle r_\pi{}^2\rangle = 0.61\pm0.15$ F^2. Our experiment provides an improved measurement through refinement of the techniques employed in the earlier experiment and by exploiting the higher-momentum-transfer values available at Fermilab.

The apparatus is shown in Fig. 1. The principal features of the experiment are as follows:

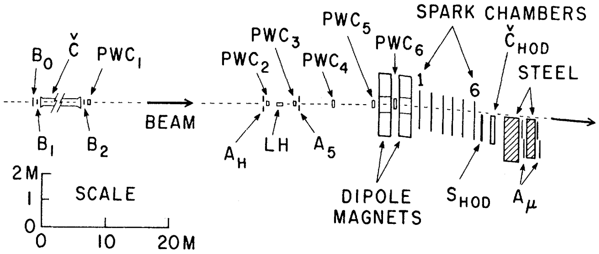

FIG. 1. Spectrometer layout. Trajectories of particles entering and leaving the 50-cm-long liquid hydrogen target (LH) were determined by six proportional wire chamber (PWC) stations of four chambers each. Trajectories after deflection by the two dipole magnets (21 mrad for 100 GeV/c) were measured by six magnetostrictive wire spark chambers of two planes each. Scintillation counters B_0, B_1, and B_2, a threshold Čerenkov counter, $\check{C}$, and beam halo anticounter A_H identify incident beam pions. A trigger on possible π-e scattering events included an anticoincidence counter, A_5, a scintillation counter hodoscope, S_{HOD}, and an array of ten lead-glass shower counters, $\check{C}_{HOD}$. Muons transversing the steel filter were tagged by counters A_μ.

(1) measurement of the trajectories and momenta of the recoiling π-e pair and the incident pion trajectory to an angular precision of 0.05 mrad; (2) direct identification of the electron by lead-glass shower counters; (3) a "zero beam intensity" requirement in the trigger to insure unambiguous event reconstruction with high efficiency; (4) minimal spectrometer mass to reduce bremsstrahlung corrections and multiple scattering; and (5) a geometrical acceptance close to 100%.

An event trigger required two conditions. The first logic requirement is for incident beams pions: $B_\pi = C\cdot B_0\cdot B_1$(single particle)$\cdot B_2\cdot \mathrm{PWC}_{1-2}$ (single particle)$\cdot A_H$. This logic also demanded that a usable beam particle was neither preceded within 1 μsec nor followed within 40 nsec by another incident particle. This "zero beam intensity" requirement created a clean environment for the operation of the spectrometer which removed ambiguities from the track-finding procedure and inefficiencies from the hardware. In a pulse of 3×10^5 particles about 1×10^5 satisfied the above restrictions.

The second trigger logic condition, together with B_π, defined the π-e scattering candidates: $B_\pi\circ T_P\cdot S_{\mathrm{HOD}}\cdot \check{C}_{\mathrm{HOD}}\cdot \bar{A}_5$ where T_P is a fast analog signal formed by requiring two simultaneous "hits" in PWC_5 and in PWC_6; S_{HOD} is a two-particle requirement; $\check{C}_{\mathrm{HOD}}$ is derived by requiring a shower-counter pulse height corresponding to an electron shower; and A_5 is an anticoincidence counter with a 10-cm-diam hole. The trigger event rate was 1.5×10^{-4} usable pion.

Events were reconstructed by first finding those track projections from the proportional-wire-chamber and spark-chamber data which were matched by means of rotated-chamber information. Events with one track upstream and two tracks downstream of the target were selected if consistent with a common vertex in the target re-

TABLE I. Corrections to the data.

Effect	% correction ± error
q^2-independent corrections	
Beam cut	2.70 ± 0.12
Primary π decay, attentuation	3.06 ± 0.07
μ, e, K contaminations	0.40 ± 0.20
Target electron density	0.00 ± 0.27
Secondary attenuation	4.71 ± 0.10
δ rays in A_5	0.39 ± 0.04
Track-finding inefficiencies	0.91 ± 0.54
Trigger inefficiencies	0.12 ± 0.45
The range of the q^2-dependent corrections and their average errors	
Geometric inefficiency	$(0.56-4.69)\pm0.1$
Radiative corrections (Ref. 3)	$(7.50-8.84)\pm0.4$
Secondary pion decay	$(0.43-1.09)\pm0.1$
μ-e background	$(0.00-0.47)\pm0.2$
Hadronic background	$(0.10-0.90)\pm0.4$
External bremsstrahlung	$(17.6-26.8)\pm0.5$

TABLE II. Events, measured cross section, and form factor versus q^2.

q^2 $\frac{\text{GeV}}{c}$	No. of Evts.	Evts. after Corr.	$d\sigma/dq^2$ $\frac{\mu b}{(\text{GeV}/c)^2}$	$\lvert F_\pi\rvert^2$ ± total error
.0317	1420	2016	148.3	.903 ± .026
.0337	1247	1726	126.9	.910 ± .027
.0358	1083	1503	110.5	.927 ± .030
.0378	992	1374	101.0	.988 ± .033
.0399	782	1093	80.3	.911 ± .034
.0419	683	964	70.9	.930 ± .038
.0439	550	790	58.1	.879 ± .039
.0460	483	688	50.6	.881 ± .040
.0480	420	598	43.9	.880 ± .043
.0501	383	547	40.3	.927 ± .047
.0521	348	501	36.8	.971 ± .052
.0542	284	410	30.1	.915 ± .054
.0562	196	287	21.1	.735 ± .053
.0583	176	263	19.4	.779 ± .059
.0603	172	250	18.4	.853 ± .065
.0623	150	219	16.1	.870 ± .071
.0644	120	177	13.0	.818 ± .075
.0664	101	150	10.9	.813 ± .081
.0685	83	122	9.0	.790 ± .087
.0705	66	100	7.3	.768 ± .095

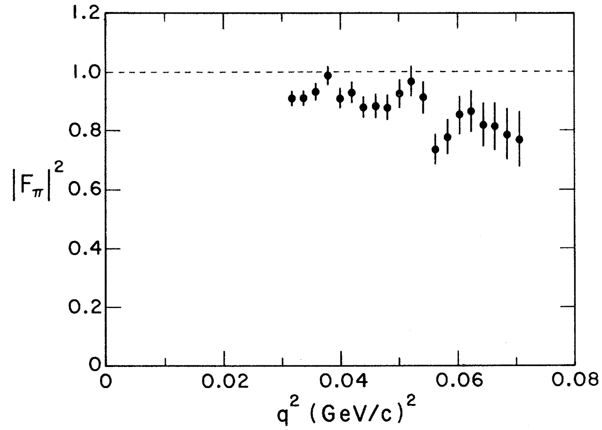

FIG. 2. The square of the pion form factor vs q^2.

TABLE III. M_{ij} correlation coefficients times 1000. The matrix is symmetric with $M_{ii} = 1$. Examples: $M_{18} = 0.079$; by interpolation $M_{28} = 0.075$.

j \ i	1	3	5	7	9	11	13	15	17	19
2	126	111	94	79	69	62	47	43	36	30
4	112	99	85	71	62	56	42	39	33	27
6	94	83	71	60	52	48	36	33	28	23
8	79	70	60	51	44	40	31	29	24	20
10	70	62	53	45	40	36	27	26	22	18
12	59	53	46	39	34	31	24	22	19	16
14	46	41	36	31	27	25	19	18	15	13
16	42	38	33	28	25	23	18	17	14	12
18	34	31	27	23	21	19	14	14	12	10
20	28	25	22	19	17	15	12	11	9	8

gion. The efficiency with which π-e elastic scattering events were correctly reconstructed was calculated by a Monte Carlo method based upon measured chamber inefficiencies and background distributions superimposed on measured π-e elastic events. The overall event-finding efficiency was $(99.1 \pm 0.5)\%$.

The π-e elastic scatters are separated from the large hadronic background by employing the constraints of energy and momentum conservation. For each event a χ^2 fit was made to the kinematic hypothesis of an elastic π-e reaction modified by an additional photon emitted along the electron direction. Events were selected with confidence levels greater than 10^{-6}. Events were rejected if the fitted photon energy exceeded 4.0 GeV. The target vacuum windows were 1 m from either end of the hydrogen flask enabling clear identification of events originating in the target flask. The electron energies measured in the lead-glass shower counter had a full width at half-maximum of 12%. A cut was made requiring the pulse height to be greater than 50% of that expected from the momentum measurement of the electron. The background which survived these cuts was less than 1%.

Table I lists the corrections applied to the data. The resulting form factor is shown as a function of q^2 in Table II and in Fig. 2. The errors shown are the combined statistical and systematic errors. The systematic errors result in error correlations between the individual data points. The correlation coefficient M_{ij} between the ith and the jth data points is defined to be $M_{ij} = \langle \epsilon_i \epsilon_j \rangle (\langle \epsilon_i^2 \rangle \times \langle \epsilon_j^2 \rangle)^{-1/2}$ and is given in Table III; the $\langle \epsilon_i^2 \rangle^{1/2}$ values are the errors listed in Table II.

A fit to the data in Table II with the pole form $|F_\pi(q^2)|^2 = (1 + q^2 \langle r_\pi^2 \rangle / 6)^{-2}$ using the full error matrix $\langle \epsilon_i \epsilon_j \rangle$ gives the value $\langle r_\pi^2 \rangle = 0.31 \pm 0.04$ F^2; or $\langle r_\pi^2 \rangle^{1/2} = 0.56 \pm 0.04$ F. A fit using a dipole form $|F(q^2)|^2 = (1 + q^2 \langle r_\pi^2 \rangle / 12)^{-4}$ gives the same result. The result was also found to be insensitive to changes in the cuts on the photon energy, the geometry, and on the χ^2 confidence level. For comparison, the size of the proton is $\langle r_p^2 \rangle^{1/2} = 0.81$ F. The vector-dominance model predicts[4] $0.58 \leq \langle r_\pi^2 \rangle^{1/2} \leq 0.69$ F, and the Chou-Yang model[5] predicts $\langle r_\pi^2 \rangle^{1/2} = 0.62 \pm 0.02$ F.

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