ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-84/74

S.R.Amendolia et al.:
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Estratto da:
Phys. Letters 146B, 116 (1984)

Servizio Documentazione
dei Laboratori Nazionali di Frascati
Cas. Postale 13 - Frascati (Roma)

A MEASUREMENT OF THE PION CHARGE RADIUS

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Received 15 May 1984

We report a measurement of the negative pion electromagnetic form factor in the range of space-like four-momentum transfer $0.014 < q^2 < 0.122\,(\mathrm{GeV}/c)^2$. The measurement was made by the NA7 collaboration at the CERN SPS, by observing the interaction of 300 GeV pions with the electrons of a liquid hydrogen target. The form factor is fitted by a pole form with a pion radius of $\langle r^2 \rangle^{1/2} = 0.657 \pm 0.012$ fm.

The interaction of a charged pion with a photon of four-momentum q is modified from a point interaction by the form factor $F(q^2)$. At $q^2 = 0$ the slope $\mathrm{d}F/\mathrm{d}q^2$ is simply related to the mean square charge radius. Measurements of the form factor for space-like q^2 are restricted to pion-electroproduction and direct pion-electron scattering. There is evidence [1] that recent electroproduction results are incompatible with a smooth extrapolation from time-like data, while a series of three measurements of the pion radius by direct scattering [2–4] produced inconsistent results. We have made an improved measurement of direct scattering, using a beam of 300 GeV π^- at the CERN SPS and collecting data up to $q^2 = 0.28\,(\mathrm{GeV}/c)^2$. Here we report our data in the range $0.014 < q^2 < 0.122\,(\mathrm{GeV}/c)^2$.

The experimental apparatus (fig. 1) was based on the FRAMM forward spectrometer, with a vertex detector optimised for the detection of elastic π–e scattering. The event trigger was a coincidence of signals from counters in the regions BEAM, VERTEX and SPECTROMETER. A clean incident beam signal was defined by the logical combination:

$$\mathrm{BEAM} = \mathrm{S1} \cdot \mathrm{S_h} \cdot \mathrm{S_v} \cdot \overline{\mathrm{S2}} \cdot \overline{\mathrm{V1}}\,.$$

S1 was vetoed if an additional particle was detected within ±50 ns. $\mathrm{S_h}$, $\mathrm{S_v}$ required one counter in each hodoscope. S2 signalled two or more simultaneous particles.

VERTEX was defined by

$$\mathrm{VERTEX} = \mathrm{S3} \cdot \mathrm{MULT2} \cdot \overline{(\mathrm{TV} + \mathrm{V2} - \mathrm{V5} + \mathrm{BSTOP})}\,.$$

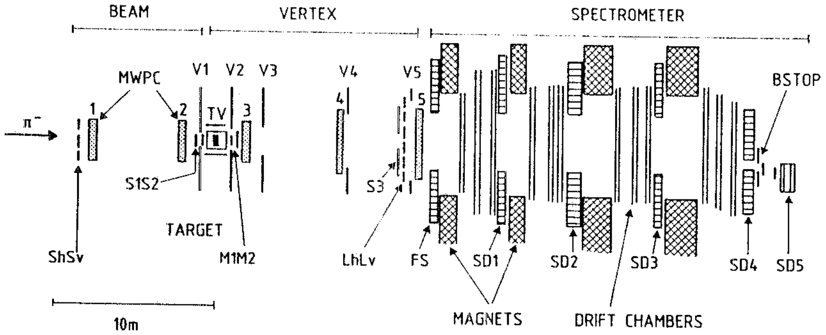

Fig. 1. Schematic diagram of the apparatus. The target was a 28 cm long vessel of liquid hydrogen with 50 cm vacuum pipes at each end. The detectors were, in the BEAM region: Hodoscope (S_h, S_v); scintillators S1, S2 and V1 (veto); MWPC stacks 1, 2. In the VERTEX region: multiplicity counters M1, M2 and hodoscopes L_h, L_v. S3 had a circular hole slightly larger than the beam dimensions. TV, V2–V5 were veto counters, faced with lead and aluminiu. MWPC stacks: 3–5. SPECTROMETER: 4 magnets and drift chamber stacks [5]. FS, SD1, SD5 were lead scintillator detectors. SD2, SD3, SD4 were lead-glass arrays. Front SD sections were 4 radiation lengths, rear section 20 radiation lengths with 3.5 cm lateral granularity. BSTOP was a beam veto telescope of 3 counters.

S3 required at least one particle outside the beam profile 10 m downstream of the target. MULT2 required a combination of signals from the pulse height counters M1 and M2 and the hodoscopes L_h, L_v consistent with two charged particles. The counters TV, V2–V5 vetoed events at angles of more than 10 mr, discriminating against hadronic events in the target and downstream material. Unscattered beam was vetoed by the telescope BSTOP.

SPECTROMETER was defined by:

$$\mathrm{SPECTROMETER} = \mathrm{SD}n \cdot \overline{\mathrm{FS}} ,$$

where SDn was a signal from any of the front sections of SD1–SD4 consistent with an electron shower. The Front Shower detector (FS) was operated at a threshold of 1 GeV and defined the spectrometer acceptance.

Approximately 2.5 million event triggers were collected. This sample contained 15% π^-e events generated in the target, the remainder being dominated by hadronic events with two or three observed forward tracks. The vertex MWPC were used to search for a coplanar two-track vertex, with a measured coordinate along the beam direction within 50 cm of the target centre. Events with three separated tracks having a clean vertex in the target were rejected. For all events satisfying the vertex conditions, tracks were reconstructed in the spectrometer and events with a positive track from the vertex were rejected. A momentum cut rejected events with a track of less than 1 GeV/c, where the momentum acceptance of the spectrometer fell below 100%.

In the scatter plot of the two angles (fig. 2a) most events lie along the curves expected from elastic kinematics. The majority of events below the kinematic line are due to the radiative process $\pi e \to \pi e \gamma$ which results in a concentration of events near the axes. Each event was assigned a value of q^2 corresponding to the minimum distance D_θ to the elastic kinematic line below $q^2 = 0.15$ (GeV/c)^2. A histogram of D_θ is shown in fig. 2b, after subtraction of estimated contaminations from K–e (0.9%) and μ–e (1.3%) events. The shape of this distribution is explained by elastic and radiative πe events, with a small component of hadronic background. The shape of the radiative component, which populates the region of negative D_θ, agrees well with a Monte-Carlo simulation of this effect. A final cut was made at $D_\theta = \pm 0.22$ mr, and the residual background, varying from 0.4% at $q^2 = 0.014$ to 1.2% at 0.12 GeV/c^2, estimated from the level of events at positive D_θ.

Corrections to the data which have negligible q^2 dependence are listed in table 1. They contribute an uncertainty of 0.006 to the overall normalisation.

The following corrections were q^2 dependent:

(a) The geometric acceptance of the spectrometer was determined from the measured beam distribution and the aperture of the front shower detector. It was 100% above $q^2 = 0.023$ and fell smoothly to 20% at 0.014 (GeV/c)^2.

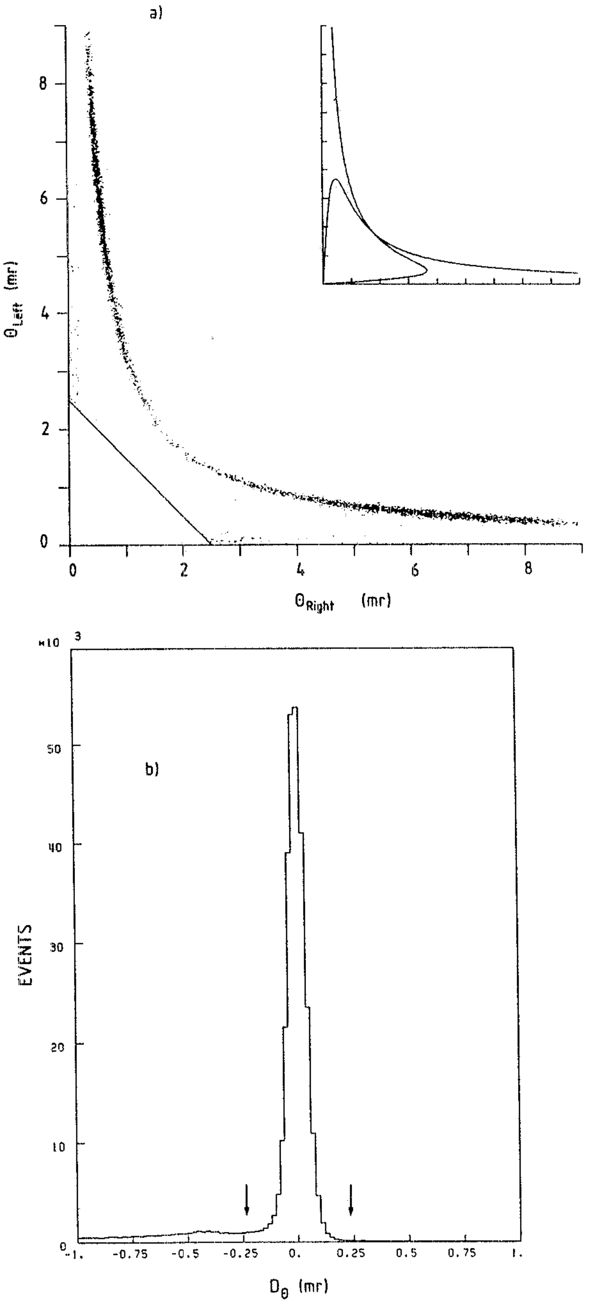

Fig. 2. (a) The angle of the left-going particle versus angle of the right-going particle for a fraction of the event sample. (Events with opening angle less than 2.5 mr were discarded.) Inset, the two curves predicted for elastic π–e kinematics. q^2 increases from 0.014 (GeV/c)^2 at 9 mr electron angle to 0.15 (GeV/c)^2 at the cross-over point. (b) The distribution of D_θ for the whole sample, and (arrows) the final cuts applied.

Table 1
q^2 independent corrections to the data (%)

beam kaon contamination	0.85 ± 0.03
beam muon contamination	1.20 ± 0.10
incident pion absorption	1.85 ± 0.20
target electron density	0 ± 0.25
downstream pion absorption	3.4 ± 0.20
vetoing by δ-rays	2.5 ± 0.3
spectrometer trigger loss	1.0 ± 0.2
downstream MWPC inefficiency	0.7 ± 0.2

(b) The trigger multiplicity (MULT2) efficiency varied linearly from 94% to 92% with increasing q^2. For multiplicity less than four this was calibrated by studying the redundant response of individual trigger components. The contribution to high multiplicity from secondary interactions of the electron or an associated photon was estimated from a Monte Carlo simulation to be 0.7%.

(c) The radiative correction was determined from a Monte Carlo generation of πe events to order α^3 [6], and varied from 1.3% to 3.7%. Since our analysis used only angle measurement to determine πe kinematics, no correction was required for kinematic bias due to external bremsstrahlung of the electron.

(d) Above $q^2 = 0.07$ (GeV/c)2 the ambiguity in pion–electron assignment is not resolved by the angle measurement, and the sample is contaminated by a fraction of events with $q^2 > 0.15$. The correction for this effect, which rises to 18% at $q^2 = 0.12$, was computed from the high q^2 cross section and the measured angular precision. It is insensitive to the values of these parameters, and is confirmed by the information from the shower detectors.

The square of the form factor was computed by dividing the corrected, measured cross section by the theoretical lowest order point cross section. The result is given in table 2 and plotted in fig. 3.

We have fitted the data with the normalisation, n, as a free parameter. A pole form, $F^2 = n/(1 + \langle r^2\rangle q^2/6)^2$ gives values of $n = 0.990 \pm 0.004$ and $\langle r^2\rangle = 0.431 \pm 0.013$ fm^2, with a χ^2 probability of 37%. We have estimated the error due to uncertainties in the q^2 dependent corrections to be 0.006 in n and 0.010 in $\langle r^2\rangle$. Combining all sources of error gives: $n = 0.990 \pm 0.010$, $\langle r^2\rangle = 0.431 \pm 0.016$ fm^2, or $\langle r^2\rangle^{1/2} = 0.657 \pm 0.012$ fm. A dipole fit, $F^2 = n/(1 + \langle r^2\rangle q^2/12)^4$, gives $\langle r^2\rangle^{1/2} = 0.641 \pm 0.012$ fm, with a similar nor-

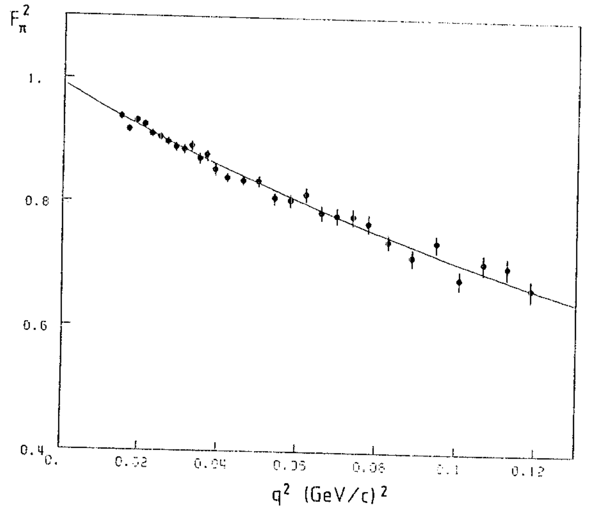

Fig. 3. F^2_π for $0.014 < q^2 < 0.122$. The line shows the pole fit described in the text.

malisation and χ^2. Since the results are slightly sensitive to the form assumed for $F(\pi)$, we have made a form independent fit, to the sum of orthogonal polynomials up to the term in $(q^2)^2$, over the range of the data. This gives the form independent result $\langle r^2\rangle^{1/2} = 0.660 \pm 0.024$ fm.

Previous results from direct πe scattering are confined to the series of measurements by the Soviet–American collaboration [2–4]. In table 3 we have quoted their results from a pole fit, but without the constraint $F^2(0) = 1$ which resulted in discrepancy between the three measurements. Other determinations of the pion radius from individual experiments are less direct, involving extrapolation of the form factor from higher $|q^2|$. Heyn and Lang [1] have reported a model-independent fit to both space- and time-like data, finding values for $\langle r^2\rangle^{1/2}$ between 0.65 and 0.70 fm. In a similar analysis, Dubnicka et al. [7] found for their

Table 2

q^2 ((GeV/c)²)	F^2	Error (statistical)
0.015	0.939	0.006
0.017	0.918	0.006
0.019	0.933	0.006
0.021	0.927	0.006
0.023	0.911	0.006
0.025	0.906	0.007
0.027	0.899	0.007
0.029	0.889	0.008
0.031	0.886	0.008
0.033	0.891	0.009
0.035	0.872	0.009
0.037	0.876	0.010
0.039	0.853	0.010
0.042	0.840	0.008
0.046	0.836	0.009
0.050	0.834	0.009
0.054	0.806	0.010
0.058	0.803	0.011
0.062	0.814	0.012
0.066	0.784	0.013
0.070	0.780	0.013
0.074	0.778	0.014
0.078	0.768	0.015
0.083	0.739	0.013
0.089	0.714	0.014
0.095	0.737	0.015
0.101	0.680	0.016
0.107	0.705	0.017
0.113	0.700	0.018
0.119	0.665	0.018

best fit $\langle r^2\rangle^{1/2} = 0.663 \pm 0.037$ fm. Recent time-like data reported by us and by the Novosibirsk groups [8–10] should improve the determination of the radius from this type of analysis. We conclude that our result is consistent with the most reliable determinations of $\langle r^2\rangle^{1/2}$ reported to date, and represents the most precise direct measurement.

Table 3
Results of a pole fit to direct πe scattering data taken from ref. [4] and this experiment

Source	q^2	$\langle r^2\rangle^{1/2}$	$F^2(0)$ (fitted)
Adylov (50 GeV) [2]	0.013–0.036	1.01 ± 0.17	1.11 ± 0.08
Dally (100 GeV) [3]	0.031–0.071	0.65 ± 0.11	1.039 ± 0.052
Dally (250 GeV) [4]	0.037–0.094	0.620 ± 0.071	0.974 ± 0.039
Data of refs. [2–4] combined	0.013–0.094	0.674 ± 0.050	1.021 ± 0.027
this experiment	0.014–0.122	0.657 ± 0.012	0.990 ± 0.010

We thank D. Bardin for many useful discussions about the radiative correction, in particular the Dubna Monte Carlo program which we have freely adapted to suit our particular experimental conditions. We thank the CERN SPS operations group, and the North Experimental Area group who provided us with a very stable, well-tuned pion beam. We are grateful for financial assistance and facilities provided by CERN, SERC (UK) and INFN (Italy).

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