$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

$\pi^{\pm}$ MASS

The most accurate charged pion mass measurements are based upon x-ray wavelength measurements for transitions in π^--mesonic atoms. The observed line is the blend of three components, corresponding to different K-shell occupancies. JECKELMANN 94 revisits the occupancy question, with the conclusion that two sets of occupancy ratios, resulting in two different pion masses (Solutions A and B), are equally probable. We choose the higher Solution B since only this solution is consistent with a positive mass-squared for the muon neutrino, given the precise muon momentum measurements now available (DAUM 91, ASSAMAGAN 94, and ASSAMAGAN 96) for the decay of pions at rest. Earlier mass determinations with pi-mesonic atoms may have used incorrect K-shell screening corrections.

Measurements with an error of > 0.005 MeV have been omitted from this Listing.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
139.57018±0.00035 OUR FIT	Error includes scale factor of 1.2.				
139.57018±0.00035 OUR AVERAGE	Error includes scale factor of 1.2.				
139.57071±0.00053	[1] LENZ	98	CNTR	−	pionic N2-atoms gas target
139.56995±0.00035	[2] JECKELMANN	94	CNTR	−	π^- atom, Soln. B
• • • We do not use the following data for averages, fits, limits, etc. • • •					
139.57022±0.00014	[3] ASSAMAGAN	96	SPEC	+	$\pi^+ \to \mu^+ \nu_\mu$
139.56782±0.00037	[4] JECKELMANN	94	CNTR	−	π^- atom, Soln. A
139.56996±0.00067	[5] DAUM	91	SPEC	+	$\pi^+ \to \mu^+ \nu$
139.56752±0.00037	[6] JECKELMANN	86B	CNTR	−	Mesonic atoms
139.5704 ±0.0011	[5] ABELA	84	SPEC	+	See DAUM 91
139.5664 ±0.0009	[7] LU	80	CNTR	−	Mesonic atoms
139.5686 ±0.0020	CARTER	76	CNTR	−	Mesonic atoms
139.5660 ±0.0024	[7,8] MARUSHEN...	76	CNTR	−	Mesonic atoms

[1] LENZ 98 result does not suffer K-electron configuration uncertainties as does JECKELMANN 94.

[2] JECKELMANN 94 Solution B (dominant 2-electron K-shell occupancy), chosen for consistency with positive $m^2_{\nu_\mu}$.

[3] ASSAMAGAN 96 measures the μ^+ momentum p_μ in $\pi^+ \to \mu^+ \nu_\mu$ decay at rest to be 29.79200 ± 0.00011 MeV/c. Combined with the μ^+ mass and the assumption $m_{\nu_\mu} = 0$, this gives the π^+ mass above; if $m_{\nu_\mu} > 0$, m_{π^+} given above is a lower limit. Combined instead with m_μ and (assuming *CPT*) the π^- mass of JECKELMANN 94, p_μ gives an upper limit on m_{ν_μ} (see the ν_μ).

[4] JECKELMANN 94 Solution A (small 2-electron K-shell occupancy) in combination with either the DAUM 91 or ASSAMAGAN 94 pion decay muon momentum measurement yields a significantly negative $m^2_{\nu_\mu}$. It is accordingly not used in our fits.

[5] The DAUM 91 value includes the ABELA 84 result. The value is based on a measurement of the μ^+ momentum for π^+ decay at rest, $p_\mu = 29.79179 \pm 0.00053$ MeV, uses $m_\mu = 105.658389 \pm 0.000034$ MeV, and assumes that $m_{\nu_\mu} = 0$. The last assumption means that in fact the value is a lower limit.

[6] JECKELMANN 86B gives $m_\pi/m_e = 273.12677(71)$. We use $m_e = 0.51099906(15)$ MeV from COHEN 87. The authors note that two solutions for the probability distribution of K-shell occupancy fit equally well, and use other data to choose the lower of the two possible $\pi^\pm$ masses.

[7] These values are scaled with a new wavelength-energy conversion factor $V\lambda = 1.23984244(37) \times 10^{-6}$ eV m from COHEN 87. The LU 80 screening correction relies upon a theoretical calculation of inner-shell refilling rates.

[8] This MARUSHENKO 76 value used at the authors' request to use the accepted set of calibration γ energies. Error increased from 0.0017 MeV to include QED calculation error of 0.0017 MeV (12 ppm).

$m_{\pi^+} - m_{\mu^+}$

Measurements with an error > 0.05 MeV have been omitted from this Listing.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
33.91157±0.00067		[9] DAUM	91	SPEC	+	$\pi^+ \to \mu^+\nu$
33.9111 ±0.0011		ABELA	84	SPEC		See DAUM 91
33.925 ±0.025		BOOTH	70	CNTR	+	Magnetic spect.
33.881 ±0.035	145	HYMAN	67	HEBC	+	K^- He

[9] The DAUM 91 value assumes that $m_{\nu_\mu} = 0$ and uses our $m_\mu = 105.658389 \pm 0.000034$ MeV.

$(m_{\pi^+} - m_{\pi^-})$ / $m_{\rm average}$

A test of *CPT* invariance.

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*
2±5	AYRES	71	CNTR

$\pi^\pm$ MEAN LIFE

Measurements with an error > 0.02×10^{-8} s have been omitted.

VALUE (10^{-8} s)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2.6033 ±0.0005 OUR AVERAGE	Error includes scale factor of 1.2.				
2.60361±0.00052	[10] KOPTEV	95	SPEC	+	Surface μ^+'s
2.60231±0.00050±0.00084	NUMAO	95	SPEC	+	Surface μ^+'s
2.609 ±0.008	DUNAITSEV	73	CNTR	+	

2.602	±0.004		AYRES	71	CNTR ±
2.604	±0.005		NORDBERG	67	CNTR +
2.602	±0.004		ECKHAUSE	65	CNTR +

• • • We do not use the following data for averages, fits, limits, etc. • • •

2.640	±0.008	[11]	KINSEY	66	CNTR +

[10] KOPTEV 95 combines the statistical and systematic errors; the statistical error dominates.
[11] Systematic errors in the calibration of this experiment are discussed by NORDBERG 67.

$(\tau_{\pi^+} - \tau_{\pi^-}) / \tau_{\rm average}$

A test of *CPT* invariance.

VALUE (units 10^{-4})		*DOCUMENT ID*		*TECN*
5.5± 7.1		AYRES	71	CNTR

• • • We do not use the following data for averages, fits, limits, etc. • • •

−14 ±29		PETRUKHIN	68	CNTR
40 ±70		BARDON	66	CNTR
23 ±40	[12]	LOBKOWICZ	66	CNTR

[12] This is the most conservative value given by LOBKOWICZ 66.

π^+ DECAY MODES

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the appropriate Search sections (Massive Neutrino Peak Search Test, A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+ \nu_\mu$		[*a*]	(99.98770±0.00004) %	
Γ_2	$\mu^+ \nu_\mu \gamma$		[*b*]	(2.00 ±0.25) $\times 10^{-4}$	
Γ_3	$e^+ \nu_e$		[*a*]	(1.230 ±0.004) $\times 10^{-4}$	
Γ_4	$e^+ \nu_e \gamma$		[*b*]	(1.61 ±0.23) $\times 10^{-7}$	
Γ_5	$e^+ \nu_e \pi^0$			(1.036 ±0.006) $\times 10^{-8}$	
Γ_6	$e^+ \nu_e e^+ e^-$			(3.2 ±0.5) $\times 10^{-9}$	
Γ_7	$e^+ \nu_e \nu \overline{\nu}$			< 5 $\times 10^{-6}$	90%
	Lepton Family number (*LF*) or Lepton number (*L*) violating modes				
Γ_8	$\mu^+ \overline{\nu}_e$	*L*	[*c*]	< 1.5 $\times 10^{-3}$	90%
Γ_9	$\mu^+ \nu_e$	*LF*	[*c*]	< 8.0 $\times 10^{-3}$	90%
Γ_{10}	$\mu^- e^+ e^+ \nu$	*LF*		< 1.6 $\times 10^{-6}$	90%

[a] Measurements of $\Gamma(e^+\nu_e)/\Gamma(\mu^+\nu_\mu)$ always include decays with γ's, and measurements of $\Gamma(e^+\nu_e\gamma)$ and $\Gamma(\mu^+\nu_\mu\gamma)$ never include low-energy γ's. Therefore, since no clean separation is possible, we consider the modes with γ's to be subreactions of the modes without them, and let $[\Gamma(e^+\nu_e) + \Gamma(\mu^+\nu_\mu)]/\Gamma_{\text{total}} = 100\%$.

[b] See the Particle Listings below for the energy limits used in this measurement; low-energy γ's are not included.

[c] Derived from an analysis of neutrino-oscillation experiments.

π^+ BRANCHING RATIOS

$\Gamma(e^+\nu_e)/\Gamma_{\text{total}}$ — Γ_3/Γ

See note [a] in the list of π^+ decay modes just above, and see also the next block of data.

VALUE (units 10^{-4})	*DOCUMENT ID*
1.230±0.004 OUR EVALUATION	

$[\Gamma(e^+\nu_e) + \Gamma(e^+\nu_e\gamma)]/[\Gamma(\mu^+\nu_\mu) + \Gamma(\mu^+\nu_\mu\gamma)]$ — $(\Gamma_3+\Gamma_4)/(\Gamma_1+\Gamma_2)$

See note [a] in the list of π^+ decay modes above. See NUMAO 92 for a discussion of e-μ universality.

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.230 ±0.004 OUR AVERAGE					
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO	Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR	Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR	Stopping π^+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.273 ±0.028	11k	[13] DICAPUA	64	CNTR	
1.21 ±0.07		ANDERSON	60	SPEC	

[13] DICAPUA 64 has been updated using the current mean life.

$\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{\text{total}}$ — Γ_2/Γ

Note that measurements here do not cover the full kinematic range.

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
2.0 ±0.24±0.08		[14] BRESSI	98	CALO	+	Stopping π^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.24±0.25	26	CASTAGNOLI	58	EMUL		$KE_\mu < 3.38$ MeV

[14] BRESSI 98 result is given for $E_\gamma > 1$ MeV only. Result agrees with QED expectation, 2.283×10^{-4} and does not confirm discrepancy of earlier experiment CASTAGNOLI 58.

$\Gamma(e^+\nu_e\gamma)/\Gamma_{\text{total}}$ — Γ_4/Γ

Note that measurements here do not cover the full kinematic range.

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
16.1±2.3		[15] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^-\overline{\nu}_e\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.6±0.7	226	[16] STETZ	78	SPEC	$P_e > 56$ MeV/c
3.0	143	DEPOMMIER	63B	CNTR	$(KE)_{e^+\gamma} > 48$ MeV

[15] BOLOTOV 90B is for $E_\gamma > 21$ MeV, $E_e > 70 - 0.8\,E_\gamma$.

[16] STETZ 78 is for an $e^-\gamma$ opening angle $> 132°$. Obtains 3.7 when using same cutoffs as DEPOMMIER 63B.

$\Gamma(e^+\nu_e\pi^0)/\Gamma_{total}$ Γ_5/Γ

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.036±0.006 OUR AVERAGE						
1.036±0.006		[17,18] POCANIC	04	PIBE	+	π decay at rest
1.026±0.039	1224	[19] MCFARLANE	85	CNTR	+	Decay in flight
$1.00\ ^{+0.08}_{-0.10}$	332	DEPOMMIER	68	CNTR	+	
1.07 ±0.21	38	[20] BACASTOW	65	OSPK	+	
1.10 ±0.26		[20] BERTRAM	65	OSPK	+	
1.1 ±0.2	43	[20] DUNAITSEV	65	CNTR	+	
0.97 ±0.20	36	[20] BARTLETT	64	OSPK	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.15 ±0.22	52	[20] DEPOMMIER	63	CNTR	+	See DEPOMMIER 68

[17] POCANIC 04 normalizes to $e^+\nu_e$ decays, using the PDG 2004 value B($\pi^+ \to e^+\nu_e$) = $(1.230 \pm 0.004) \times 10^{-4}$. We add their statistical (0.004×10^{-8}), systematic (0.004×10^{-8}) and systematic error due to the uncertainty of B($\pi^+ \to e^+\nu_e$) (0.003×10^{-8}) in quadrature.

[18] This result can be used to calculate V_{ud} from pion beta decay: $V_{ud}^{PIBETA} = 0.9728 \pm 0.0030$.

[19] MCFARLANE 85 combines a measured rate (0.394 ± 0.015)/s with 1982 PDG mean life.

[20] DEPOMMIER 68 says the result of DEPOMMIER 63 is at least 10% too large because of a systematic error in the π^0 detection efficiency, and that this may be true of all the previous measurements (also V. Soergel, private communication, 1972).

$\Gamma(e^+\nu_e e^+e^-)/\Gamma(\mu^+\nu_\mu)$ Γ_6/Γ_1

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
3.2 ±0.5 ±0.2		98	EGLI	89	SPEC	Uses $R_{\text{PCAC}} = 0.068 \pm 0.004$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.46±0.16±0.07		7	[21] BARANOV	92	SPEC	Stopped π^+
< 4.8	90		KORENCHE...	76B	SPEC	
<34	90		KORENCHE...	71	OSPK	

[21] This measurement by BARANOV 92 is of the structure-dependent part of the decay. The value depends on values assumed for ratios of form factors.

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma_{total}$ Γ_7/Γ

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN
<5	90	PICCIOTTO	88	SPEC

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{total}$ Γ_8/Γ

Forbidden by total lepton number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	[22] COOPER	82	HLBC	Wideband ν beam

[22] COOPER 82 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton number violation.

$\Gamma(\mu^+ \nu_e)/\Gamma_{total}$ **Γ_9/Γ**

Forbidden by lepton family number conservation.

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8.0	90	[23] COOPER	82	HLBC	Wideband ν beam

[23] COOPER 82 limit on ν_e observation is here interpreted as a limit on lepton family number violation.

$\Gamma(\mu^- e^+ e^+ \nu)/\Gamma_{total}$ **Γ_{10}/Γ**

Forbidden by lepton family number conservation.

VALUE (units 10^{-6})	CL%	DOCUMENT ID		TECN	CHG
<1.6	90	BARANOV	91B	SPEC	+
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.7	90	KORENCHE...	87	SPEC	+

π^+ — POLARIZATION OF EMITTED μ^+

$\pi^+ \to \mu^+ \nu$

Tests the Lorentz structure of leptonic charged weak interactions.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<(−0.9959)	90	[24] FETSCHER	84	RVUE	+	
−0.99±0.16		[25] ABELA	83	SPEC	−	μ X-rays

[24] FETSCHER 84 uses only the measurement of CARR 83.

[25] Sign of measurement reversed in ABELA 83 to compare with μ^+ measurements.

$\pi^\pm \to \ell^\pm \nu \gamma$ AND $K^\pm \to \ell^\pm \nu \gamma$ FORM FACTORS

Written by H.S. Pruys (Zürich University).

In the radiative decays $\pi^\pm \to \ell^\pm \nu \gamma$ and $K^\pm \to \ell^\pm \nu \gamma$, where ℓ is an e or a μ and γ is a real or virtual photon (e^+e^- pair), both the vector and the axial-vector weak hadronic currents contribute to the decay amplitude. Each current gives a structure-dependent term (SD_V and SD_A) from virtual hadronic states, and the axial-vector current also gives a contribution from inner bremsstrahlung (IB) from the lepton and meson. The IB amplitudes are determined by the meson decay constants f_π and f_K [1]. The SD_V and SD_A amplitudes are parameterized in terms of the vector form factor F_V and the axial-vector form factors F_A and R [1–4]:

$$M(\mathrm{SD}_V) = \frac{-eG_F\,V_{qq'}}{\sqrt{2}\,m_P} \epsilon^\mu\,\ell^\nu\,F_V\,\epsilon_{\mu\nu\sigma\tau}\,k^\sigma\,q^\tau\ ,$$

$$M(\mathrm{SD}_A) = \frac{-ie\,G_F V_{qq'}}{\sqrt{2}\,m_P}\,\epsilon^\mu\,\ell^\nu\,\{F_A\,[(s-t)g_{\mu\nu} - q_\mu\,k_\nu] + R\,t\,g_{\mu\nu}\}\ . \tag{1}$$

Here $V_{qq'}$ is the Cabibbo-Kobayashi-Maskawa mixing-matrix element; ϵ^μ is the polarization vector of the photon (or the effective vertex, $\epsilon^\mu = (e/t)\overline{u}(p_-)\gamma^\mu v(p_+)$, of the e^+e^- pair); $\ell^\nu = \overline{u}(p_\nu)\gamma^\nu(1-\gamma_5)v(p_\ell)$ is the lepton-neutrino current; q and k are the meson and photon four-momenta, with $s = q\cdot k$ and $t = k^2 (= (p_+ + p_-)^2)$; and P stands for π or K. In the analysis of data, the s and t dependence of the form factors is neglected, which is a good approximation for pions [2] but not for kaons [4]. The pion vector form factor F_V^π is related via CVC to the π^0 lifetime, $|F_V^\pi| = (1/\alpha)\sqrt{2\Gamma_{\pi^0}/\pi m_{\pi^0}}$ [1]. PCAC relates R to the electromagnetic radius of the meson [2,4], $R^P = \frac{1}{3} m_P f_P \langle r_P^2\rangle$. The calculation of the other form factors, F_A^π, F_V^K, and F_A^K, is model dependent [1,4].

When the photon is real, the partial decay rate can be given analytically [1,5]:

$$\frac{d^2\Gamma_{P\to\ell\nu\gamma}}{dxdy} = \frac{d^2\,(\Gamma_{\mathrm{IB}} + \Gamma_{\mathrm{SD}} + \Gamma_{\mathrm{INT}})}{dxdy}\ , \tag{2}$$

where $\Gamma_{\mathrm{IB}}, \Gamma_{\mathrm{SD}}$, and Γ_{INT} are the contributions from inner bremsstrahlung, structure-dependent radiation, and their interference, and the Γ_{SD} term is given by

$$\frac{d^2\Gamma_{\mathrm{SD}}}{dxdy} = \frac{\alpha}{8\pi}\Gamma_{P\to\ell\nu}\,\frac{1}{r(1-r)^2}\left(\frac{m_P}{f_P}\right)^2 \times \left[(F_V + F_A)^2\,\mathrm{SD}^+ + (F_V - F_A)^2\,\mathrm{SD}^-\right]\ . \tag{3}$$

Here

$$\mathrm{SD}^+ = (x + y - 1 - r)\,[(x+y-1)(1-x) - r]\ ,$$

$$\mathrm{SD}^- = (1 - y + r)\,[(1-x)(1-y) + r]\ , \tag{4}$$

where $x = 2E_\gamma/m_P$, $y = 2E_\ell/m_P$, and $r = (m_\ell/m_P)^2$.

In $\pi^\pm \to e^\pm\nu\gamma$ and $K^\pm \to e^\pm\nu\gamma$ decays, the interference terms are small, and thus only the absolute values $|F_A+F_V|$ and $|F_A-F_V|$ can be obtained. In $K^\pm \to \mu^\pm\nu\gamma$ decay, the interference term is important, and thus the signs of F_V and F_A can be obtained. In $\pi^\pm \to \mu^\pm\nu\gamma$ decay, bremsstrahlung completely dominates. In $\pi^\pm \to e^\pm\nu e^+e^-$ and $K^\pm \to \ell^\pm\nu e^+e^-$ decays, all three form factors, F_V, F_A, and R, can be determined.

We give the $\pi^\pm$ form factors F_V, F_A, and R in the Listings below. In the $K^\pm$ Listings, we give the sum $F_A + F_V$ and difference $F_A - F_V$.

The electroweak decays of the pseudoscalar mesons are investigated to learn something about the unknown hadronic structure of these mesons, assuming a standard $V-A$ structure of the weak leptonic current. The experiments are quite difficult, and it is not meaningful to analyse the results using parameters for both the hadronic structure (decay constants, form factors) and the leptonic weak current (*e.g.*, to add pseudoscalar or tensor couplings to the $V-A$ coupling). Deviations from the $V-A$ interactions are much better studied in purely leptonic systems such as muon decay.

References

1. D.A. Bryman *et al.*, Phys. Reports **88**, 151 (1982). See also our note on “Pseudoscalar-Meson Decay Constants,” above.
2. A. Kersch and F. Scheck, Nucl. Phys. **B263**, 475 (1986).
3. W.T. Chu *et al.*, Phys. Rev. **166**, 1577 (1968).
4. D.Yu. Bardin and E.A. Ivanov, Sov. J. Part. Nucl. **7**, 286 (1976).
5. S.G. Brown and S.A. Bludman, Phys. Rev. **136**, B1160 (1964).

$\pi^\pm$ FORM FACTORS

F_V, VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.017±0.008 OUR AVERAGE					
0.014±0.009		[26] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^- \overline{\nu}_e \gamma$
$0.023^{+0.015}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$

[26] BOLOTOV 90B only determines the absolute value.

F_A, AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.0115±0.0005 OUR AVERAGE	Error includes scale factor of 1.2.					
0.0115±0.0004		[27,28] FRLEZ	04	PIBE	+	$\pi^+ \rightarrow e^+ \nu \gamma$ at rest
0.0106±0.0060		[27,29] BOLOTOV	90B	SPEC		17 GeV $\pi^- \rightarrow e^- \overline{\nu}_e \gamma$
0.0135±0.0016		[27,29] BAY	86	SPEC		$\pi^+ \rightarrow e^+ \nu \gamma$
0.006 ±0.003		[27,29] PIILONEN	86	SPEC		$\pi^+ \rightarrow e^+ \nu \gamma$
0.011 ±0.003		[27,29,30] STETZ	78	SPEC		$\pi^+ \rightarrow e^+ \nu \gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.021^{+0.011}_{-0.013}$	98	EGLI	89	SPEC		$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$

[27] Using the vector form factor from CVC prediction, $F_V = 0.0259 \pm 0.0005$.

[28] The sign of $\gamma = F_A / F_V$ is determined to be positive.

[29] Only the absolute value of F_A is determined.

[30] The result of STETZ 78 has a two-fold ambiguity. We take the solution compatible with later determinations.

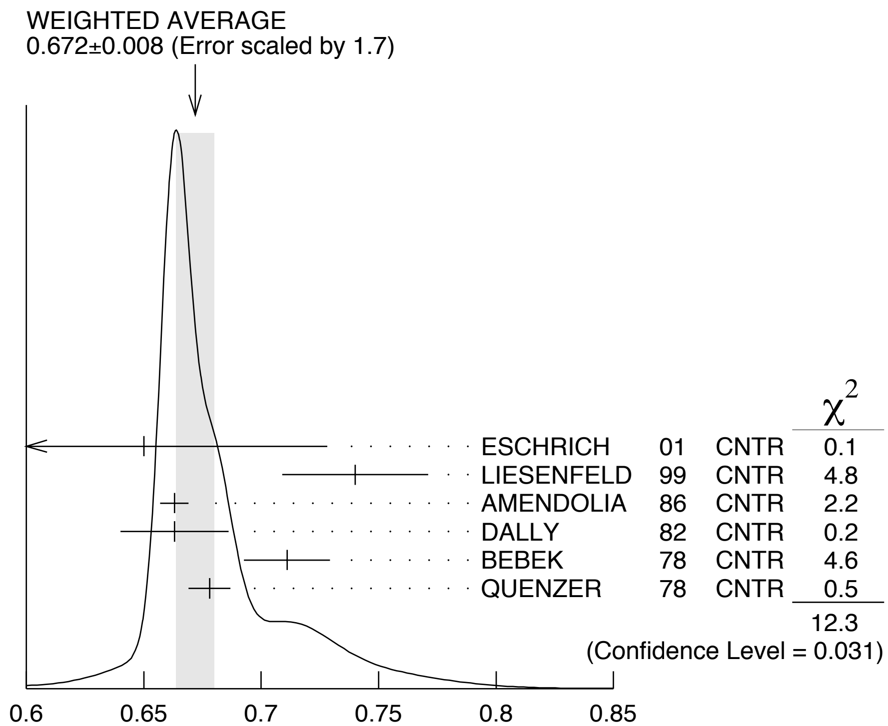
R, SECOND AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.059^{+0.009}_{-0.008}}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$

$\pi^\pm$ CHARGE RADIUS

VALUE (fm)	DOCUMENT ID		TECN	COMMENT
0.672±0.008 OUR AVERAGE	Error includes scale factor of 1.7. See the ideogram below.			
0.65 ±0.05 ±0.06	ESCHRICH	01	CNTR	$\pi e \rightarrow \pi e$
0.740±0.031	LIESENFELD	99	CNTR	$e p \rightarrow e \pi^+ n$
0.663±0.006	AMENDOLIA	86	CNTR	$\pi e \rightarrow \pi e$
0.663±0.023	DALLY	82	CNTR	$\pi e \rightarrow \pi e$
0.711±0.009±0.016	BEBEK	78	CNTR	$e N \rightarrow e \pi N$
0.678±0.004±0.008	QUENZER	78	CNTR	$e^+ e^- \rightarrow \pi^+ \pi^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.661±0.012	[31] BIJNENS	98	CNTR	χPT extraction
0.660±0.024	AMENDOLIA	84	CNTR	$\pi e \rightarrow \pi e$
$0.78^{+0.09}_{-0.10}$	ADYLOV	77	CNTR	$\pi e \rightarrow \pi e$
$0.74^{+0.11}_{-0.13}$	BARDIN	77	CNTR	$e p \rightarrow e \pi^+ n$
0.56 ±0.04	DALLY	77	CNTR	$\pi e \rightarrow \pi e$

[31] BIJNENS 98 fits existing data.



$\pi^{\pm}$ charge radius

$\pi^{\pm}$ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

FRLEZ	04	PRL 93 181804	E. Frlez *et al.*	(PIBETA Collab.)
POCANIC	04	PRL 93 181803	D. Pocanic *et al.*	(PIBETA Collab.)
ESCHRICH	01	PL B522 233	I. Eschrich *et al.*	(FNAL SELEX Collab.)
LIESENFELD	99	PL B468 20	A. Liesenfeld *et al.*	
BIJNENS	98	JHEP 05 014	J. Bijnens *et al.*	
BRESSI	98	NP B513 555	G. Bressi *et al.*	
LENZ	98	PL B416 50	S. Lenz *et al.*	
ASSAMAGAN	96	PR D53 6065	K.A. Assamagan *et al.*	(PSI, ZURI, VILL+)
KOPTEV	95	JETPL 61 877	V.P. Koptev *et al.*	(PNPI)
		Translated from ZETFP 61 865.		
NUMAO	95	PR D52 4855	T. Numao *et al.*	(TRIU, BRCO)
ASSAMAGAN	94	PL B335 231	K.A. Assamagan *et al.*	(PSI, ZURI, VILL+)
JECKELMANN	94	PL B335 326	B. Jeckelmann, P.F.A. Goudsmit, H.J. Leisi	(WABRN+)
CZAPEK	93	PRL 70 17	G. Czapek *et al.*	(BERN, VILL)
BARANOV	92	SJNP 55 1644	V.A. Baranov *et al.*	(JINR)
		Translated from YAF 55 2940.		
BRITTON	92	PRL 68 3000	D.I. Britton *et al.*	(TRIU, CARL)
Also		PR D49 28	D.I. Britton *et al.*	(TRIU, CARL)
NUMAO	92	MPL A7 3357	T. Numao	(TRIU)
BARANOV	91B	SJNP 54 790	V.A. Baranov *et al.*	(JINR)
		Translated from YAF 54 1298.		

DAUM	91	PL B265 425	M. Daum *et al.*	(VILL)
BOLOTOV	90B	PL B243 308	V.N. Bolotov *et al.*	(INRM)
EGLI	89	PL B222 533	S. Egli *et al.*	(SINDRUM Collab.)
Also		PL B175 97	S. Egli *et al.*	(AACH3, ETH, SIN, ZURI)
PDG	88	PL B204	G.P. Yost *et al.*	(LBL+)
PICCIOTTO	88	PR D37 1131	C.E. Picciotto *et al.*	(TRIU, CNRC)
COHEN	87	RMP 59 1121	E.R. Cohen, B.N. Taylor	(RISC, NBS)
KORENCHE...	87	SJNP 46 192	S.M. Korenchenko *et al.*	(JINR)
		Translated from YAF 46 313.		
AMENDOLIA	86	NP B277 168	S.R. Amendolia *et al.*	(CERN NA7 Collab.)
BAY	86	PL B174 445	A. Bay *et al.*	(LAUS, ZURI)
BRYMAN	86	PR D33 1211	D.A. Bryman *et al.*	(TRIU, CNRC)
Also		PRL 50 7	D.A. Bryman *et al.*	(TRIU, CNRC)
JECKELMANN	86B	NP A457 709	B. Jeckelmann *et al.*	(ETH, FRIB)
Also		PRL 56 1444	B. Jeckelmann *et al.*	(ETH, FRIB)
PIILONEN	86	PRL 57 1402	L.E. Piilonen *et al.*	(LANL, TEMP, CHIC)
MCFARLANE	85	PR D32 547	W.K. McFarlane *et al.*	(TEMP, LANL)
ABELA	84	PL 146B 431	R. Abela *et al.*	(SIN)
Also		PL 74B 126	M. Daum *et al.*	(SIN)
Also		PR D20 2692	M. Daum *et al.*	(SIN)
AMENDOLIA	84	PL 146B 116	S.R. Amendolia *et al.*	(CERN NA7 Collab.)
FETSCHER	84	PL 140B 117	W. Fetscher	(ETH)
ABELA	83	NP A395 413	R. Abela *et al.*	(BASL, KARLK, KARLE)
CARR	83	PRL 51 627	J. Carr *et al.*	(LBL, NWES, TRIU)
COOPER	82	PL 112B 97	A.M. Cooper *et al.*	(RL)
DALLY	82	PRL 48 375	E.B. Dally *et al.*	
LU	80	PRL 45 1066	D.C. Lu *et al.*	(YALE, COLU, JHU)
BEBEK	78	PR D17 1693	C.J. Bebek *et al.*	
QUENZER	78	PL 76B 512	A. Quenzer *et al.*	(LALO)
STETZ	78	NP B138 285	A.W. Stetz *et al.*	(LBL, UCLA)
ADYLOV	77	NP B128 461	G.T. Adylov *et al.*	
BARDIN	77	NP B120 45	G. Bardin *et al.*	
DALLY	77	PRL 39 1176	E.B. Dally *et al.*	
CARTER	76	PRL 37 1380	A.L. Carter *et al.*	(CARL, CNRC, CHIC+)
KORENCHE...	76B	JETP 44 35	S.M. Korenchenko *et al.*	(JINR)
		Translated from ZETF 71 69.		
MARUSHEN...	76	JETPL 23 72	V.I. Marushenko *et al.*	(PNPI)
		Translated from ZETFP 23 80.		
Also		Private Comm.	R.E. Shafer	(FNAL)
Also		Private Comm.	A. Smirnov	(PNPI)
DUNAITSEV	73	SJNP 16 292	A.F. Dunaitsev *et al.*	(SERP)
		Translated from YAF 16 524.		
AYRES	71	PR D3 1051	D.S. Ayres *et al.*	(LRL, UCSB)
Also		PR 157 1288	D.S. Ayres *et al.*	(LRL)
Also		PRL 21 261	D.S. Ayres *et al.*	(LRL, UCSB)
Also		Thesis UCRL 18369	D.S. Ayres	(LRL)
Also		PRL 23 1267	A.J. Greenberg *et al.*	(LRL, UCSB)
KORENCHE...	71	SJNP 13 189	S.M. Korenchenko *et al.*	(JINR)
		Translated from YAF 13 339.		
BOOTH	70	PL 32B 723	P.S.L. Booth *et al.*	(LIVP)
DEPOMMIER	68	NP B4 189	P. Depommier *et al.*	(CERN)
PETRUKHIN	68	JINR P1 3862	V.I. Petrukhin *et al.*	(JINR)
HYMAN	67	PL 25B 376	L.G. Hyman *et al.*	(ANL, CMU, NWES)
NORDBERG	67	PL 24B 594	M.E. Nordberg, F. Lobkowicz, R.L. Burman	(ROCH)
BARDON	66	PRL 16 775	M. Bardon *et al.*	(COLU)
KINSEY	66	PR 144 1132	K.F. Kinsey, F. Lobkowicz, M.E. Nordberg	(ROCH)
LOBKOWICZ	66	PRL 17 548	F. Lobkowicz *et al.*	(ROCH, BNL)
BACASTOW	65	PR 139B 407	R.B. Bacastow *et al.*	(LRL, SLAC)
BERTRAM	65	PR 139B 617	W.K. Bertram *et al.*	(MICH, CMU)
DUNAITSEV	65	JETP 20 58	A.F. Dunaitsev *et al.*	(JINR)
		Translated from ZETF 47 84.		
ECKHAUSE	65	PL 19 348	M. Eckhause *et al.*	(WILL)
BARTLETT	64	PR 136B 1452	D. Bartlett *et al.*	(COLU)
DICAPUA	64	PR 133B 1333	M. di Capua *et al.*	(COLU)
Also		Private Comm.	L. Pondrom	(WISC)
DEPOMMIER	63	PL 5 61	P. Depommier *et al.*	(CERN)
DEPOMMIER	63B	PL 7 285	P. Depommier *et al.*	(CERN)
ANDERSON	60	PR 119 2050	H.L. Anderson *et al.*	(EFI)
CASTAGNOLI	58	PR 112 1779	C. Castagnoli, M. Muchnik	(ROMA)