$\pi^{\pm}$

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

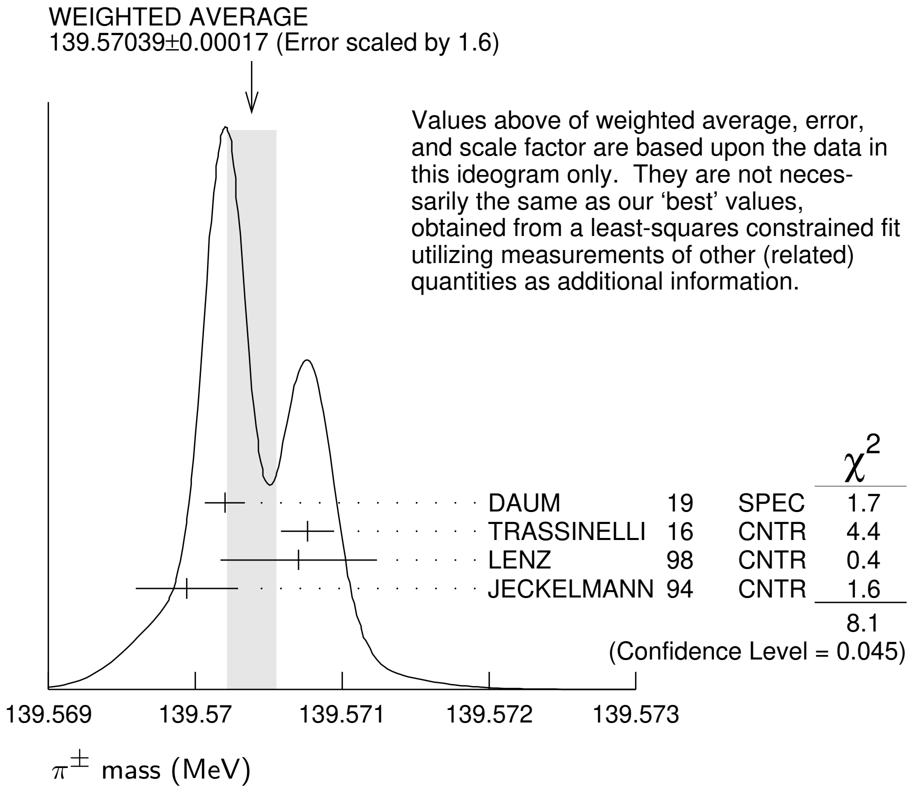
We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** 1 (1988).

$\pi^{\pm}$ 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*
139.57039±0.00018 OUR FIT	Error includes scale factor of 1.8.				
139.57039±0.00017 OUR AVERAGE	Error includes scale factor of 1.6. See the ideogram below.				
139.57021±0.00014	[1] DAUM	19	SPEC		$\pi^+ \to \mu^+ \nu_\mu$
139.57077±0.00018	[2] TRASSINELLI	16	CNTR		X-ray transitions in pionic N2
139.57071±0.00053	[3] LENZ	98	CNTR	$-$	pionic N2-atoms gas target
139.56995±0.00035	[4] JECKELMANN	94	CNTR	$-$	π^- atom, Soln. B
• • • We do not use the following data for averages, fits, limits, etc. • • •					
139.57022±0.00014	[5] ASSAMAGAN	96	SPEC	$+$	$\pi^+ \to \mu^+ \nu_\mu$
139.56782±0.00037	[6] JECKELMANN	94	CNTR	$-$	π^- atom, Soln. A
139.56996±0.00067	[7] DAUM	91	SPEC	$+$	$\pi^+ \to \mu^+ \nu$
139.56752±0.00037	[8] JECKELMANN	86B	CNTR	$-$	Mesonic atoms
139.5704 ±0.0011	[7] ABELA	84	SPEC	$+$	See DAUM 91
139.5664 ±0.0009	[9] LU	80	CNTR	$-$	Mesonic atoms
139.5686 ±0.0020	CARTER	76	CNTR	$-$	Mesonic atoms
139.5660 ±0.0024	[9,10] MARUSHEN...	76	CNTR	$-$	Mesonic atoms



[1] DAUM 19 value is based on their previous (1991+1996) measurements of the μ^+ momentum of 29.79200 ± 0.00011 MeV for π^+ decay at rest. It also uses m_μ = 105.6583745 ± 0.0000024 MeV, and assumes conservatively m_{ν_μ} = 2.0 ± 2.0 MeV. It is the most precise charged pion mass determination.

[2] TRASSINELLI 16 use the muonic oxygen line for online energy calibration of the pionic line.

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

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

[5] ASSAMAGAN 96 measures the μ^+ momentum p_μ in $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay at rest to be 29.79200 ± 0.00011 MeV/c. Combined with the μ^+ mass and the assumption m_{ν_μ} = 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).

[6] 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.

[7] 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_μ = 105.658389 ± 0.000034 MeV, and assumes that $m_{\nu_\mu} = 0$. The last assumption means that in fact the value is a lower limit.

[8] 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.

[9] 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.

[10] 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		[1] 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

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

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

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	[1] 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	[2] KINSEY	66	CNTR	+	

[1] KOPTEV 95 combines the statistical and systematic errors; the statistical error dominates.

[2] Systematic errors in the calibration of this experiment are discussed by NORDBERG 67.

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

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	[1] LOBKOWICZ	66	CNTR

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

π ELECTRIC POLARIZABILITY α_π

See HOLSTEIN 14 for a general review on hadron polarizability.

VALUE (10^{-4} fm^3)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.0±0.6±0.7	63k	[1] ADOLPH	15A	SPEC	$\pi^- \gamma \to \pi^- \gamma$ Compton scatt.

[1] Value is derived assuming $\alpha_\pi = -\beta_\pi$.

π^+ DECAY MODES

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

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

	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) × 10^{-4}	
Γ_3	$e^+ \nu_e$		[a]	(1.230 ±0.004) × 10^{-4}	
Γ_4	$e^+ \nu_e \gamma$		[b]	(7.39 ±0.05) × 10^{-7}	
Γ_5	$e^+ \nu_e \pi^0$			(1.036 ±0.006) × 10^{-8}	
Γ_6	$e^+ \nu_e e^+ e^-$			(3.2 ±0.5) × 10^{-9}	
Γ_7	$\mu^+ \nu_\mu \nu \overline{\nu}$			$<$ 9 × 10^{-6}	90%
Γ_8	$e^+ \nu_e \nu \overline{\nu}$			$<$ 1.6 × 10^{-7}	90%
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
Γ_9	$\mu^+ \overline{\nu}_e$	*L*	[c]	$<$ 1.5 × 10^{-3}	90%
Γ_{10}	$\mu^+ \nu_e$	*LF*	[c]	$<$ 8.0 × 10^{-3}	90%
Γ_{11}	$\mu^- e^+ e^+ \nu$	*LF*		$<$ 1.6 × 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. See also the note on "Decay Constants of Charged Pseudoscalar Mesons" in the D_s^+ Listings.

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. See also the note on "Decay Constants of Charged Pseudoscalar Mesons" in the D_s^+ Listings.

VALUE (units 10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.2327±0.0023 OUR AVERAGE						
1.2344±0.0023±0.0019	400k	AGUILAR-AR...	15	CNTR	+	Stopping π^+
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	[1] DICAPUA	64	CNTR		
1.21 ±0.07		ANDERSON	60	SPEC		

[1] 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		[1] 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		$\text{KE}_\mu < 3.38$ MeV

[1] 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

The very different values reflect the very different kinematic ranges covered (bigger range, bigger value). And none of them covers the whole kinematic range.

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
73.86±0.54	65k	[1] BYCHKOV	09	PIBE	$e^+\nu\gamma$ at rest

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

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
16.1 ±2.3		[2] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^-\overline{\nu}_e\gamma$
5.6 ±0.7	226	[3] STETZ	78	SPEC	$P_e > 56$ MeV/c
3.0	143	DEPOMMIER	63B	CNTR	$(KE)_{e^+\gamma} > 48$ MeV

[1] This BYCHKOV 09 value is for $E_\gamma > 10$ MeV and $\Theta_{e^+\gamma} > 40^\circ$.

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

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

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

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.036±0.006 OUR AVERAGE						
1.036±0.006	64k	[1,2] POCANIC	04	PIBE	+	π decay at rest
1.026±0.039	1224	[3] MCFARLANE	85	CNTR	+	Decay in flight
$1.00\ {}^{+0.08}_{-0.10}$	332	DEPOMMIER	68	CNTR	+	
1.07 ±0.21	38	[4] BACASTOW	65	OSPK	+	
1.10 ±0.26		[4] BERTRAM	65	OSPK	+	
1.1 ±0.2	43	[4] DUNAITSEV	65	CNTR	+	
0.97 ±0.20	36	[4] BARTLETT	64	OSPK	+	

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

VALUE (units 10^{-8})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.15 ±0.22	52	[4] DEPOMMIER	63	CNTR	+	See DEPOMMIER 68

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

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

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

[4] 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. • • •

VALUE (units 10^{-9})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.46±0.16±0.07		7	[1] BARANOV	92	SPEC	Stopped π^+
$<$ 4.8	90		KORENCHE...	76B	SPEC	
$<$34	90		KORENCHE...	71	OSPK	

[1] 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.

$\Gamma(\mu^+\nu_\mu\nu\overline{\nu})/\Gamma(\mu^+\nu_\mu)$ Γ_7/Γ_1

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<8.6 \times 10^{-6}$	90	9.1M	AGUILAR-AR...	20A	SPEC	fit E_μ spectrum

$\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma_{\text{total}}$ Γ_8/Γ

VALUE	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<1.6 \times 10^{-7}$	90	1.3M	AGUILAR-AR...	20A	SPEC	fit E_e spectrum
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<5 \times 10^{-6}$	90		PICCIOTTO	88	SPEC	

$\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_9/Γ

Forbidden by total lepton number conservation. See the note on "Decay Constants of Charged Pseudoscalar Mesons" in the D_s^+ Listings.

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.5	90	[1] COOPER	82	HLBC	Wideband ν beam

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

$\Gamma(\mu^+\nu_e)/\Gamma_{\text{total}}$ Γ_{10}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<8.0	90	[1] COOPER	82	HLBC	Wideband ν beam

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

$\Gamma(\mu^- e^+ e^+ \nu)/\Gamma_{\text{total}}$ Γ_{11}/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	[1] FETSCHER	84	RVUE	+	
-0.99 ± 0.16		[2] ABELA	83	SPEC	−	μ *X*-rays

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

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

See the related review(s):

Form Factors for Semileptonic Kaon ($K_{\ell 3}$), Radiative Pion ($\pi_{\ell 2\gamma}$) and Kaon ($K_{\ell 2\gamma}$) Decays

$\pi^\pm$ FORM FACTORS

F_V, VECTOR FORM FACTOR

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.0254±0.0017 OUR AVERAGE					
0.0258±0.0017	65k	[1] BYCHKOV	09	PIBE	$e^+ \nu \gamma$ at rest
0.014 ±0.009		[2] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^- \overline{\nu}_e \gamma$
0.023 $^{+0.015}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$

[1] The BYCHKOV 09 F_A and F_V results are highly (anti-)correlated: $F_A + 1.0286\ F_V = 0.03853 \pm 0.00014$.

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

F_A, AXIAL-VECTOR FORM FACTOR

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.0119±0.0001	65k	[1,2] BYCHKOV	09	PIBE	$e^+ \nu \gamma$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0115±0.0004	41k	[1,3] FRLEZ	04	PIBE	$\pi^+ \rightarrow e^+ \nu \gamma$ at rest
0.0106±0.0060		[1,4] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^- \overline{\nu}_e \gamma$
0.021 $^{+0.011}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+ \nu_e e^+ e^-$
0.0135±0.0016		[1,4] BAY	86	SPEC	$\pi^+ \rightarrow e^+ \nu \gamma$
0.006 ±0.003		[1,4] PIILONEN	86	SPEC	$\pi^+ \rightarrow e^+ \nu \gamma$
0.011 ±0.003		[1,4,5] STETZ	78	SPEC	$\pi^+ \rightarrow e^+ \nu \gamma$

[1] These values come from fixing the vector form factor at the CVC prediction, $F_V = 0.0259 \pm 0.0005$.

[2] When F_V is released, the BYCHKOV 09 F_A is 0.0117 ± 0.0017, and F_A and F_V results are highly (anti-)correlated: $F_A + 1.0286\ F_V = 0.03853 \pm 0.00014$.

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

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

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

VECTOR FORM FACTOR SLOPE PARAMETER *a*

This is *a* in $F_V(q^2) = F_V(0)\ (1 + a\ q^2)$

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.10±0.06	65k	BYCHKOV	09	PIBE	$e^+ \nu \gamma$ at rest

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

The charge radius of the pion $\sqrt{\langle r^2_\pi \rangle}$ is defined in relation to the form factor of the pion electromagnetic vertex, called vector form factor VFF, F^V_π. The VFF is a function of the squared four-momentum transfer *t*, or of the squared c.m. energy *s*, depending on the channel in which the photon exchange takes place. In both cases, it is related to the slope of the VFF at zero, namely

$$\langle r^2_\pi \rangle = 6\ \frac{dF^V_\pi(q)}{dq}(q{=}0) \text{ where } q = t,\ s.$$

The quantity cannot be measured directly. It can be extracted from the cross sections of three processes: pion electroproduction, $e N \rightarrow e N \pi$, and pion electron scattering $e \pi \rightarrow e \pi$, for the t channel, and positron electron annihilation into two charged pions, $e^+ e^- \rightarrow \pi^+ \pi^-$, for the s channel. We encode all measurements, but we do not use electroproduction data in averaging because the extraction of the pion radius involves, in this case, theoretical uncertainties that cannot be controlled at the needed level of accuracy. In case of analyses based on the same data set, as ANANTHANARAYAN 17 and COLANGELO 19, which cannot be averaged, we combine the results into a common value, with the uncertainty range chosen to cover both analyses. Note that for consistency the form factor needs to be defined in both channels with the vacuum polarisation removed. For details see COLANGELO 19 or Appendix B of ANANTHANARAYAN 16A.

VALUE (fm)			*DOCUMENT ID*		*TECN*	*COMMENT*
0.659	**±0.004**	**OUR AVERAGE**				
0.656	±0.005		[1] PDG	19	FIT	
0.65	±0.05	±0.06	ESCHRICH	01	CNTR	$\pi e \rightarrow \pi e$
0.663	±0.006		AMENDOLIA	86	CNTR	$\pi e \rightarrow \pi e$
0.663	±0.023		DALLY	82	CNTR	$\pi e \rightarrow \pi e$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.640	±0.007		[2] CUI	21A	FIT	Fit existing data
0.655	±0.004		[3] COLANGELO	19	FIT	Fit existing data
0.657	±0.003		[4] ANANTHANA..	17	FIT	Fit existing data
0.6603	±0.0005	±0.0004	[5] HANHART	17	FIT	Fit existing data
0.740	±0.031		[6] LIESENFELD	99	CNTR	$e p \rightarrow e \pi^+ n$
0.661	±0.012		[7] BIJNENS	98	CNTR	χPT extraction
0.660	±0.024		AMENDOLIA	84	CNTR	$\pi e \rightarrow \pi e$
0.711	±0.009	±0.016	[6] BEBEK	78	CNTR	$e N \rightarrow e \pi N$
0.678	±0.004	±0.008	[8] QUENZER	78	CNTR	$e^+ e^- \rightarrow \pi^+ \pi^-$
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	$\pi e \rightarrow \pi e$

[1] This value combines the measurements of ANANTHANARAYAN 17 and COLANGELO 19 which are based on the same data set. The uncertainty range is chosen to cover both results.

[2] CUI 21A perform a fit including spacelike data only. Employ a new mathematical procedure based on interpolation via continued fractions augmented by statistical sampling. Also do not impose the charge conserving normalization condition F(0) = 1.

[3] COLANGELO 19 fit existing F_V data, using an extended Omnes dispersive representation. This analysis is based on the same data set of ANANTHANARAYAN 17 . Accordingly, they cannot be averaged. We combine the results into a common value, with the uncertainty range chosen to cover the uncertainty ranges of both analyses.

[4] ANANTHANARAYAN 17 fit existing F_V data, using a mixed phase-modulus dispersive representation. This analysis is based on the same data set of COLANGELO 19. Accordingly, they cannot be averaged. We combine the results into a common value, with the uncertainty range chosen to cover the uncertainty ranges of both analyses.

[5] According to the authors the uncertainty could be underestimated. The value quoted omits the BaBar data AUBERT 09.

[6] The extractions could contain an additional theoretical uncertainty which cannot be sufficiently quantified.

[7] BIJNENS 98 fits existing data.

[8] The extraction is based on a parametrization that does not have correct analytic properties.

$\pi^\pm$ 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** 1 (1988).

CUI	21A	PL B822 136631	Z.-F. Cui *et al.*	(NJU, ECT, HZDR)
AGUILAR-AR...	20A	PR D102 012001	A. Aguilar-Arevalo *et al.*	(PIENU Collab.)
COLANGELO	19	JHEP 1902 006	G. Colangelo, M. Hoferichter, P. Stoffer	(BERN+)
DAUM	19	PL B796 11	M. Daum, R. Frosch, P.-R. Kettle	(PSI)
PDG	19	RPP 2019 at pdg.lbl.gov	M. Tanabashi *et al.*	(PDG Collab.)
ANANTHANA...	17	PRL 119 132002	B. Ananthanarayan, I. Caprini, D. Das	
HANHART	17	EPJ C77 98	C. Hanhart *et al.*	
ANANTHANA...	16A	PR D93 116007	B. Ananthanarayan *et al.*	
TRASSINELLI	16	PL B759 583	M. Trassinelli *et al.*	
ADOLPH	15A	PRL 114 062002	C. Adolph *et al.*	(COMPASS Collab.)
AGUILAR-AR...	15	PRL 115 071801	A. Aguilar-Arevalo *et al.*	(PIENU Collab.)
HOLSTEIN	14	ARNPS 64 51	B. Holstein, S. Scherer	(MASA, MAINZ)
AUBERT	09	PR D79 011102	B. Aubert *et al.*	(BABAR Collab.)
BYCHKOV	09	PRL 103 051802	M. Bychkov *et al.*	(PSI PIBETA Collab.)
FRLEZ	04	PRL 93 181804	E. Frlez *et al.*	(PSI PIBETA Collab.)
POCANIC	04	PRL 93 181803	D. Pocanic *et al.*	(PSI 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 9805 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 1	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 139 B407	R.B. Bacastow *et al.*	(LRL, SLAC)
BERTRAM	65	PR 139 B617	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 136 B1452	D. Bartlett *et al.*	(COLU)
DICAPUA	64	PR 133 B1333	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)