$\pi^{\pm}$

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

We have omitted some results that have been superseded by later experiments.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 postive mass-squared for the muon neutrino, given the precise muon momentum measurements now available (DAUM 91 and ASSAMAGAN 94) 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*
139.56995±0.00035 OUR FIT					
139.56995±0.00035	[1] JECKELMANN	94	CNTR	−	π^- atom, Soln. B
• • • We do not use the following data for averages, fits, limits, etc. • • •					
139.56782±0.00037	[2] JECKELMANN	94	CNTR	−	π^- atom, Soln. A
139.56996±0.00067	[3] DAUM	91	SPEC	+	$\pi^+ \rightarrow \mu^+ \nu$
139.56752±0.00037	[4] JECKELMANN	86B	CNTR	−	Mesonic atoms
139.5704 ±0.0011	[3] ABELA	84	SPEC	+	See DAUM 91
139.5664 ±0.0009	[5] LU	80	CNTR	−	Mesonic atoms
139.5686 ±0.0020	CARTER	76	CNTR	−	Mesonic atoms
139.5660 ±0.0024	[5,6] MARUSHEN...	76	CNTR	−	Mesonic atoms

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

[2] 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.

[3] 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.

[4] 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.

[5] 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.

[6] 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		[7] DAUM	91	SPEC	+	$\pi^+ \rightarrow \mu^+ \nu$
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

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

*CITATION: L. Montanet et al., Physical Review D50, 1173 (1994) and 1995 off-year partial update for the 1996 edition (URL: http://pdg.lbl.gov/)

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

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 $> 0.02 \times 10^{-8}$ s have been omitted.

VALUE (10^{-8} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.6030±0.0024 OUR AVERAGE				
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	[8] KINSEY	66	CNTR	+

[8] 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	[9] LOBKOWICZ	66	CNTR

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

π^+ DECAY MODES

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

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\mu^+\nu_\mu$		[a]	(99.98770 ± 0.00004) %	
Γ_2	$\mu^+\nu_\mu\gamma$		[b]	$(1.24 \pm 0.25) \times 10^{-4}$	
Γ_3	$e^+\nu_e$		[a]	$(1.230 \pm 0.004) \times 10^{-4}$	
Γ_4	$e^+\nu_e\gamma$		[b]	$(1.61 \pm 0.23) \times 10^{-7}$	
Γ_5	$e^+\nu_e\pi^0$			$(1.025 \pm 0.034) \times 10^{-8}$	
Γ_6	$e^+\nu_e e^+ e^-$			$(3.2 \pm 0.5) \times 10^{-9}$	
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 Full 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

$\Gamma(e^+\nu_e)/\Gamma_{total}$ — 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	[10] DICAPUA	64	CNTR	
1.21 ±0.07		ANDERSON	60	SPEC	

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

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

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

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.24±0.25	26	CASTAGNOLI	58	EMUL	$KE_\mu < 3.38$ MeV

$\Gamma(e^+\nu_e\gamma)/\Gamma_{total}$ — 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		[11] 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	[12] STETZ	78	SPEC	$P_e > 56$ MeV/c
3.0	143	DEPOMMIER	63B	CNTR	$(KE)_{e^+\gamma} > 48$ MeV

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

[12] 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
1.025±0.034 OUR AVERAGE						
1.026±0.039	1224	[13] MCFARLANE	85	CNTR	+	Decay in flight
$1.00\ ^{+0.08}_{-0.10}$	332	DEPOMMIER	68	CNTR	+	
1.07 ±0.21	38	[14] BACASTOW	65	OSPK	+	
1.10 ±0.26		[14] BERTRAM	65	OSPK	+	
1.1 ±0.2	43	[14] DUNAITSEV	65	CNTR	+	
0.97 ±0.20	36	[14] BARTLETT	64	OSPK	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.15 ±0.22	52	[14] DEPOMMIER	63	CNTR	+	See DEPOMMIER 68

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

[14] 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 $R_{PCAC} = 0.068 \pm 0.004$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.46±0.16±0.07		7	[15] BARANOV	92	SPEC	Stopped π^+
< 4.8	90		KORENCHE...	76B	SPEC	
<34	90		KORENCHE...	71	OSPK	

[15] 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	COOPER	82	HLBC	Wideband ν beam

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

Forbidden by lepton family number conservation.

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

$\Gamma(\mu^- e^+ e^+ \nu)/\Gamma_{total}$ — 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^+

$\pi^+ \rightarrow \mu^+\nu$

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	[16] FETSCHER	84	RVUE	+	
-0.99 ± 0.16		[17] ABELA	83	SPEC	−	μ X-rays

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

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

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$\pi^\pm$ FORM FACTORS

F_V, VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.017±0.008 OUR AVERAGE					
0.014 ± 0.009		[18] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^-\overline{\nu}_e\gamma$
$0.023^{+0.015}_{-0.013}$	98	EGLI	89	SPEC	$\pi^+ \rightarrow e^+\nu_e e^+ e^-$

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

F_A, AXIAL-VECTOR FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.0116±0.0016 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.				
0.0106 ± 0.0060		[19] BOLOTOV	90B	SPEC	17 GeV $\pi^- \rightarrow e^-\overline{\nu}_e\gamma$
0.0135 ± 0.0016		[19] BAY	86	SPEC	$\pi^+ \rightarrow e^+\nu\gamma$
$0.006\ \pm0.003$		[19] PIILONEN	86	SPEC	$\pi^+ \rightarrow e^+\nu\gamma$
$0.011\ \pm0.003$		[19,20] 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	$\pi^+ \rightarrow e^+\nu_e e^+ e^-$

[19] Using the vector form factor from CVC prediction $F_V = 0.0259 \pm 0.0005$. Only the absolute value of F_A is determined.

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

$\pi^{\pm}$ axial-vector form factor

R, SECOND AXIAL-VECTOR FORM FACTOR

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

$\pi^{\pm}$ 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).

ASSAMAGAN	94	PL B335 231	+Broennimann, Daum+	(PSI, ZURI, VILL, VIRG)
JECKELMANN	94	PL B335 326	+Goudsmit, Leisi	(WABRN, VILL)
CZAPEK	93	PRL 70 17	+Federspiel, Flueckiger, Frei+	(BERN, VILL)
BARANOV	92	SJNP 55 1644	+Vanko, Glazov, Evtukhovich+	(JINR)
		Translated from YAF 55 2940.		
BRITTON	92	PRL 68 3000	+Ahmad, Bryman, Burnham+	(TRIU, CARL)
Also	94	PR D49 28	Britton, Ahmad, Bryman+	(TRIU, CARL)
NUMAO	92	MPL A7 3357		(TRIU)
BARANOV	91B	SJNP 54 790	+Kisel, Korenchenko, Kuchinskii+	(JINR)
		Translated from YAF 54 1298.		
DAUM	91	PL B265 425	+Frosch, Herter, Janousch, Kettle	(VILL)
BOLOTOV	90B	PL B243 308	+Gninenko, Djilkibaev, Isakov+	(INRM)
EGLI	89	PL B222 533	+Engfer, Grab, Hermes, Kraus+	(SINDRUM Collab.)
Also	86	PL B175 97	Egli, Engfer, Grab, Hermes+	(AACH3, ETH, SIN, ZURI)
PDG	88	PL B204	Yost, Barnett+	(LBL+)
PICCIOTTO	88	PR D37 1131	+Ahmad, Britton, Bryman, Clifford+	(TRIU, CNRC)
COHEN	87	RMP 59 1121	+Taylor	(RISC, NBS)
KORENCHE...	87	SJNP 46 192	Korenchenko, Kostin, Mzhaviya+	(JINR)
		Translated from YAF 46 313.		
BAY	86	PL B174 445	+Ruegger, Gabioud, Joseph, Loude+	(LAUS, ZURI)
BRYMAN	86	PR D33 1211	+Dubois, Macdonald, Numao+	(TRIU, CNRC)
Also	83	PRL 50 7	Bryman, Dubois, Numao, Olaniya+	(TRIU, CNRC)
JECKELMANN	86B	NP A457 709	+Beer, Chambrier, Elsenhans+	(ETH, FRIB)
Also	86	PRL 56 1444	Jeckelmann, Nakada, Beer+	(ETH, FRIB)
PIILONEN	86	PRL 57 1402	+Bolton, Cooper, Frank+	(LANL, TEMP, CHIC)
MCFARLANE	85	PR D32 547	+Auerbach, Gaille+	(TEMP, LANL)
ABELA	84	PL 146B 431	+Daum, Eaton, Frosch, Jost, Kettle+	(SIN)
Also	78	PL 74B 126	Daum, Eaton, Frosch, Hirschmann+	(SIN)
Also	79	PR D20 2692	Daum, Eaton, Frosch, Hirschmann+	(SIN)
FETSCHER	84	PL 140B 117		(ETH)
ABELA	83	NP A395 413	+Backenstoss, Kunold, Simons+	(BASL, KARLK, KARLE)
CARR	83	PRL 51 627	+Gidal, Gobbi, Jodidio, Oram+	(LBL, NWES, TRIU)
COOPER	82	PL 112B 97	+Guy, Michette, Tyndel, Venus	(RL)
LU	80	PRL 45 1066	+Delker, Dugan, Wu, Caffrey+	(YALE, COLU, JHU)
STETZ	78	NP B138 285	+Carroll, Ortendahl, Perez-Mendez+	(LBL, UCLA)
CARTER	76	PRL 37 1380	+Dixit, Sundaresan+	(CARL, CNRC, CHIC, CIT)
KORENCHE...	76B	JETP 44 35	Korenchenko, Kostin, Micelmacher+	(JINR)
		Translated from ZETF 71 69.		
MARUSHEN...	76	JETPL 23 72	Marushenko, Mezentsev, Petrunin+	(PNPI)
		Translated from ZETFP 23 80.		
Also	76	Private Comm.	Shafer	(FNAL)
Also	78	Private Comm.	Smirnov	(PNPI)
DUNAITSEV	73	SJNP 16 292	+Prokoshkin, Razuvaev+	(SERP)
		Translated from YAF 16 524.		

AYRES	71	PR D3 1051	+Cormack, Greenberg, Kenney+	(LRL, UCSB)
Also	67	PR 157 1288	Ayres, Caldwell, Greenberg, Kenney, Kurz+	(LRL)
Also	68	PRL 21 261	Ayres, Cormack, Greenberg+	(LRL, UCSB)
Also	69	Thesis UCRL 18369	Ayres	(LRL)
Also	69	PRL 23 1267	Greenberg, Ayres, Cormack+	(LRL, UCSB)
KORENCHE...	71	SJNP 13 189	Korenchenko, Kostin, Micelmacher+	(JINR)
		Translated from YAF 13 339.		
BOOTH	70	PL 32B 723	+Johnson, Williams, Wormald	(LIVP)
DEPOMMIER	68	NP B4 189	+Duclos, Heintze, Kleinknecht+	(CERN)
PETRUKHIN	68	JINR P1 3862	+Rykalin, Khazins, Cisek	(JINR)
HYMAN	67	PL 25B 376	+Loken, Pewitt, McKenzie+	(ANL, CMU, NWES)
NORDBERG	67	PL 24B 594	+Lobkowicz, Burman	(ROCH)
BARDON	66	PRL 16 775	+Dore, Dorfan, Krieger+	(COLU)
KINSEY	66	PR 144 1132	+Lobkowicz, Nordberg	(ROCH)
LOBKOWICZ	66	PRL 17 548	+Melissinos, Nagashima+	(ROCH, BNL)
BACASTOW	65	PR 139B 407	+Ghesquiere, Wiegand, Larsen	(LRL, SLAC)
BERTRAM	65	PR 139B 617	+Meyer, Carrigan+	(MICH, CMU)
DUNAITSEV	65	JETP 20 58	+Petrukhin, Prokoshkin+	(JINR)
		Translated from ZETF 47 84.		
ECKHAUSE	65	PL 19 348	+Harris, Shuler+	(WILL)
BARTLETT	64	PR 136B 1452	+Devons, Meyer, Rosen	(COLU)
DICAPUA	64	PR 133B 1333	+Garland, Pondrom, Strelzoff	(COLU)
Also	86	Private Comm.	Pondrom	(WISC)
DEPOMMIER	63	PL 5 61	+Heintze, Rubbia, Soergel	(CERN)
DEPOMMIER	63B	PL 7 285	+Heintze, Rubbia, Soergel	(CERN)
ANDERSON	60	PR 119 2050	+Fujii, Miller+	(EFI)
CASTAGNOLI	58	PR 112 1779	+Muchnik	(ROMA)