# $\pi^{\pm}$

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

We have omitted some results that have been superseded by later experiments.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 $\pi^-$-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* |
|---|---|---|---|---|---|
| **139.57061±0.00024 OUR FIT** Error includes scale factor of 1.6. | | | | | |
| **139.57061±0.00023 OUR AVERAGE** Error includes scale factor of 1.5. See the ideogram below. | | | | | |
| 139.57077±0.00018 | [1] TRASSINELLI | 16 | CNTR | | X-ray transitions in pionic N2 |
| 139.57071±0.00053 | [2] LENZ | 98 | CNTR | − | pionic N2-atoms gas target |
| 139.56995±0.00035 | [3] JECKELMANN | 94 | CNTR | − | $\pi^-$ atom, Soln. B |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 139.57022±0.00014 | [4] ASSAMAGAN | 96 | SPEC | + | $\pi^+ \to \mu^+ \nu_\mu$ |
| 139.56782±0.00037 | [5] JECKELMANN | 94 | CNTR | − | $\pi^-$ atom, Soln. A |
| 139.56996±0.00067 | [6] DAUM | 91 | SPEC | + | $\pi^+ \to \mu^+ \nu$ |
| 139.56752±0.00037 | [7] JECKELMANN | 86B | CNTR | − | Mesonic atoms |
| 139.5704 ±0.0011 | [6] ABELA | 84 | SPEC | + | See DAUM 91 |
| 139.5664 ±0.0009 | [8] LU | 80 | CNTR | − | Mesonic atoms |
| 139.5686 ±0.0020 | CARTER | 76 | CNTR | − | Mesonic atoms |
| 139.5660 ±0.0024 | [8,9] MARUSHEN... | 76 | CNTR | − | Mesonic atoms |

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

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

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

[4] ASSAMAGAN 96 measures the $\mu^+$ momentum $p_\mu$ in $\pi^+ \to \mu^+ \nu_\mu$ decay at rest to be 29.79200 ± 0.00011 MeV/$c$. Combined with the $\mu^+$ mass and the assumption $m_{\nu_\mu} = 0$, this gives the $\pi^+$ mass above; if $m_{\nu_\mu} > 0$, $m_{\pi^+}$ given above is a lower limit.

Combined instead with $m_\mu$ and (assuming *CPT*) the $\pi^-$ mass of JECKELMANN 94, $p_\mu$ gives an upper limit on $m_{\nu_\mu}$ (see the $\nu_\mu$).

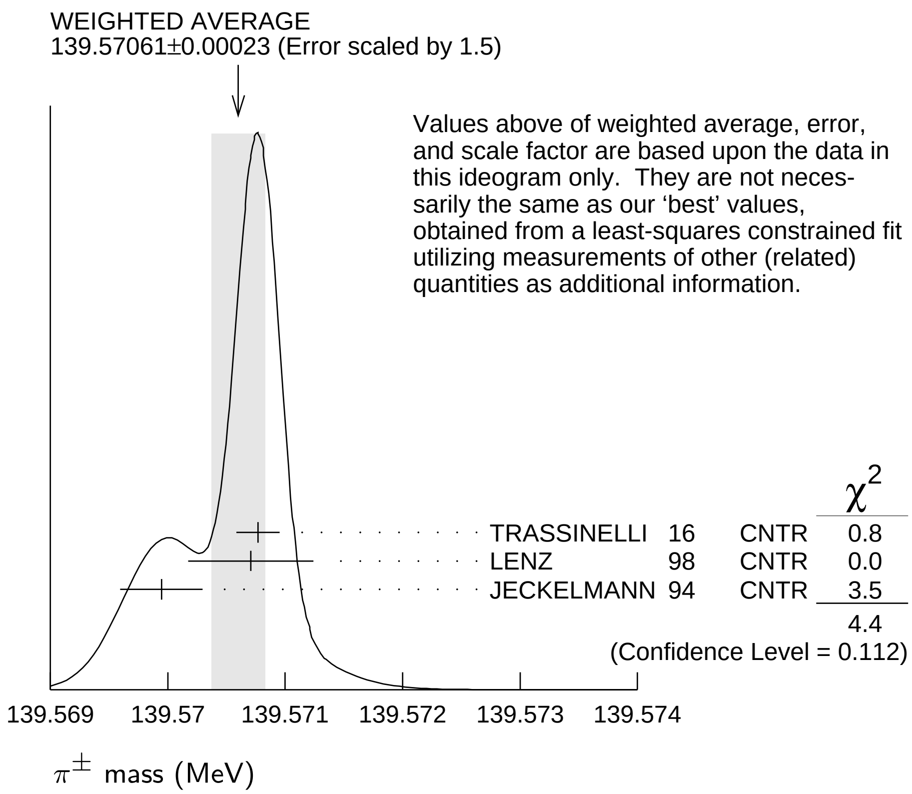
[5] JECKELMANN 94 Solution A (small 2-electron K-shell occupancy) in combination with either the DAUM 91 or ASSAMAGAN 94 pion decay muon momentum measurement yields a significantly negative $m^2_{\nu_\mu}$. It is accordingly not used in our fits.

[6] The DAUM 91 value includes the ABELA 84 result. The value is based on a measurement of the $\mu^+$ momentum for $\pi^+$ 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.

[7] 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.

[8] 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.

[9] This MARUSHENKO 76 value used at the authors' request to use the accepted set of calibration $\gamma$ 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 > $0.02 \times 10^{-8}$ 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 $\mu^+$'s |
| 2.60231±0.00050±0.00084 | NUMAO | 95 | SPEC | + | Surface $\mu^+$'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.

## $\pi$ ELECTRIC POLARIZABILITY $\alpha_\pi$

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 $\alpha_\pi = -\beta_\pi$.

## $\pi^+$ DECAY MODES

$\pi^-$ 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 ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|---|---|
| $\Gamma_1$ | $\mu^+ \nu_\mu$ | | [a] | (99.98770±0.00004) % | |
| $\Gamma_2$ | $\mu^+ \nu_\mu \gamma$ | | [b] | ( 2.00 ±0.25 ) $\times 10^{-4}$ | |
| $\Gamma_3$ | $e^+ \nu_e$ | | [a] | ( 1.230 ±0.004 ) $\times 10^{-4}$ | |
| $\Gamma_4$ | $e^+ \nu_e \gamma$ | | [b] | ( 7.39 ±0.05 ) $\times 10^{-7}$ | |
| $\Gamma_5$ | $e^+ \nu_e \pi^0$ | | | ( 1.036 ±0.006 ) $\times 10^{-8}$ | |
| $\Gamma_6$ | $e^+ \nu_e e^+ e^-$ | | | ( 3.2 ±0.5 ) $\times 10^{-9}$ | |
| $\Gamma_7$ | $e^+ \nu_e \nu \overline{\nu}$ | | | $<$ 5 $\times 10^{-6}$ | 90% |
| | **Lepton Family number (*LF*) or Lepton number (*L*) violating modes** | | | | |
| $\Gamma_8$ | $\mu^+ \overline{\nu}_e$ | *L* | [c] | $<$ 1.5 $\times 10^{-3}$ | 90% |
| $\Gamma_9$ | $\mu^+ \nu_e$ | *LF* | [c] | $<$ 8.0 $\times 10^{-3}$ | 90% |
| $\Gamma_{10}$ | $\mu^- e^+ e^+ \nu$ | *LF* | | $<$ 1.6 $\times 10^{-6}$ | 90% |

[a] Measurements of $\Gamma(e^+ \nu_e)/\Gamma(\mu^+ \nu_\mu)$ always include decays with $\gamma$'s, and measurements of $\Gamma(e^+ \nu_e \gamma)$ and $\Gamma(\mu^+ \nu_\mu \gamma)$ never include low-energy $\gamma$'s. Therefore, since no clean separation is possible, we consider the modes with $\gamma$'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 $\gamma$'s are not included.

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

# $\pi^+$ BRANCHING RATIOS

## $\Gamma(e^+\nu_e)/\Gamma_{total}$ — $\Gamma_3/\Gamma$

See note [a] in the list of $\pi^+$ 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 $\pi^+$ decay modes above. See NUMAO 92 for a discussion of $e$-$\mu$ 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 $\pi^+$ |
| 1.2346±0.0035±0.0036 | 120k | CZAPEK | 93 | CALO | | Stopping $\pi^+$ |
| 1.2265±0.0034±0.0044 | 190k | BRITTON | 92 | CNTR | | Stopping $\pi^+$ |
| 1.218 ±0.014 | 32k | BRYMAN | 86 | CNTR | | Stopping $\pi^+$ |
| • • • 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.

## $\Gamma(\mu^+\nu_\mu\gamma)/\Gamma_{total}$ — $\Gamma_2/\Gamma$

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 $\pi^+$ |
| • • • 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 |

[1] BRESSI 98 result is given for $E_\gamma > 1$ MeV only. Result agrees with QED expectation, $2.283\times10^{-4}$ and does not confirm discrepancy of earlier experiment CASTAGNOLI 58.

## $\Gamma(e^+\nu_e\gamma)/\Gamma_{total}$ — $\Gamma_4/\Gamma$

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. • • • | | | | | |
| 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.

## $\Gamma(e^+\nu_e\pi^0)/\Gamma_{total}$ $\Gamma_5/\Gamma$

| *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 | + | $\pi$ 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. • • • | | | | | | |
| 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($\pi^+ \to e^+\nu_e$) $= (1.230 \pm 0.004) \times 10^{-4}$. We add their statistical ($0.004 \times 10^{-8}$), systematic ($0.004 \times 10^{-8}$) and systematic error due to the uncertainty of B($\pi^+ \to e^+\nu_e$) ($0.003 \times 10^{-8}$) 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 $\pi^0$ detection efficiency, and that this may be true of all the previous measurements (also V. Soergel, private communication, 1972).

## $\Gamma(e^+\nu_e e^+e^-)/\Gamma(\mu^+\nu_\mu)$ $\Gamma_6/\Gamma_1$

| *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 ± 0.004 |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| 0.46±0.16±0.07 | | 7 | [1] BARANOV | 92 | SPEC | Stopped $\pi^+$ |
| < 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.

## $\Gamma(e^+\nu_e\nu\overline{\nu})/\Gamma_{total}$ $\Gamma_7/\Gamma$

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

## $\Gamma(\mu^+\overline{\nu}_e)/\Gamma_{total}$ $\Gamma_8/\Gamma$

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 $\nu$ beam |

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

### $\Gamma(\mu^+ \nu_e)/\Gamma_{total}$ — $\Gamma_9/\Gamma$

Forbidden by lepton family number conservation.

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

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

### $\Gamma(\mu^- e^+ e^+ \nu)/\Gamma_{total}$ — $\Gamma_{10}/\Gamma$

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 | + |

## $\pi^+$ — POLARIZATION OF EMITTED $\mu^+$

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

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 | + | |
| $-0.99\pm0.16$ | | [2] ABELA | 83 | SPEC | − | $\mu$ X-rays |

[1] FETSCHER 84 uses only the measurement of CARR 83.
[2] Sign of measurement reversed in ABELA 83 to compare with $\mu^+$ measurements.

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## $\pi^\pm$ FORM FACTORS

### $F_V$, VECTOR FORM FACTOR

| VALUE | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **0.0254±0.0017 OUR AVERAGE** | | | | | |
| $0.0258\pm0.0017$ | 65k | [1] BYCHKOV | 09 | PIBE | $e^+ \nu \gamma$ at rest |
| $0.014\ \pm0.009$ | | [2] BOLOTOV | 90B | SPEC | 17 GeV $\pi^- \to e^- \overline{\nu}_e \gamma$ |
| $0.023\ ^{+0.015}_{-0.013}$ | 98 | EGLI | 89 | SPEC | $\pi^+ \to e^+ \nu_e e^+ e^-$ |

[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. • • • | | | | | |
| $0.0115\pm0.0004$ | 41k | [1,3] FRLEZ | 04 | PIBE | $\pi^+ \to e^+ \nu \gamma$ at rest |
| $0.0106\pm0.0060$ | | [1,4] BOLOTOV | 90B | SPEC | 17 GeV $\pi^- \to e^- \overline{\nu}_e \gamma$ |
| $0.021\ ^{+0.011}_{-0.013}$ | 98 | EGLI | 89 | SPEC | $\pi^+ \to e^+ \nu_e e^+ e^-$ |
| $0.0135\pm0.0016$ | | [1,4] BAY | 86 | SPEC | $\pi^+ \to e^+ \nu \gamma$ |
| $0.006\ \pm0.003$ | | [1,4] PIILONEN | 86 | SPEC | $\pi^+ \to e^+ \nu \gamma$ |
| $0.011\ \pm0.003$ | | [1,4,5] STETZ | 78 | SPEC | $\pi^+ \to e^+ \nu \gamma$ |

[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 $0.0117 \pm 0.0017$, 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 |

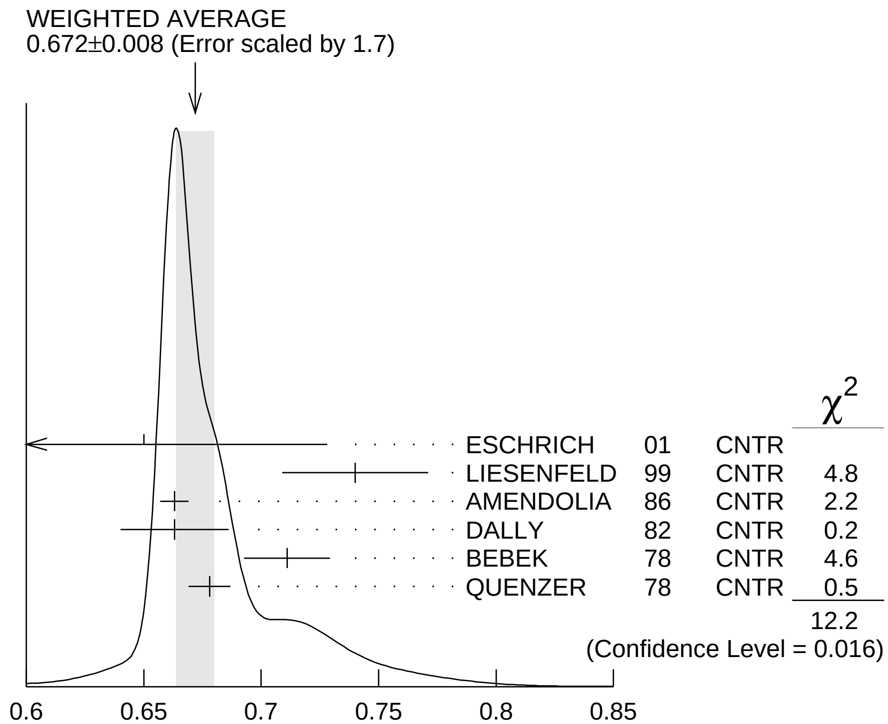
## *R*, SECOND AXIAL-VECTOR FORM FACTOR

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

# $\pi^{\pm}$ 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 | $\pi e \to \pi e$ |
| 0.740±0.031 | LIESENFELD | 99 | CNTR | $e p \to e \pi^+ n$ |
| 0.663±0.006 | AMENDOLIA | 86 | CNTR | $\pi e \to \pi e$ |
| 0.663±0.023 | DALLY | 82 | CNTR | $\pi e \to \pi e$ |
| 0.711±0.009±0.016 | BEBEK | 78 | CNTR | $e N \to e \pi N$ |
| 0.678±0.004±0.008 | QUENZER | 78 | CNTR | $e^+ e^- \to \pi^+ \pi^-$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.661±0.012 | [1] BIJNENS | 98 | CNTR | $\chi$PT extraction |
| 0.660±0.024 | AMENDOLIA | 84 | CNTR | $\pi e \to \pi e$ |
| $0.78\ ^{+0.09}_{-0.10}$ | ADYLOV | 77 | CNTR | $\pi e \to \pi e$ |
| $0.74\ ^{+0.11}_{-0.13}$ | BARDIN | 77 | CNTR | $e p \to e \pi^+ n$ |
| 0.56 ±0.04 | DALLY | 77 | CNTR | $\pi e \to \pi e$ |

[1] 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** 1 (1988).


| | | | | |
|---|---|---|---|---|
| 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.A. Aguilar-Arevalo *et al.* | (PiENu Collab.) |
| HOLSTEIN | 14 | ARNPS 64 51 | B. Holstein, S. Scherer | (MASA, MANZ) |
| 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. | | |

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| 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) |