μ

$J = \frac{1}{2}$

μ MASS

The mass is known more precisely in u (atomic mass units) than in MeV (see the footnote to COHEN 87). The conversion from u to MeV, 1 u = 931.49432 ± 0.00028 MeV, involves the relatively poorly known electronic charge.

Where m_μ/m_e was measured, we have used the 1986 CODATA value for m_e = 0.51099906 ± 0.00000015 MeV.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
105.658389±0.000034	[1] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.65841 ±0.00033	[2] BELTRAMI	86	SPEC	−	Muonic atoms
105.658432±0.000064	[3] KLEMPT	82	CNTR	+	Incl. in MARIAM 82
105.658386±0.000044	[4] MARIAM	82	CNTR	+	
105.65856 ±0.00015	[5] CASPERSON	77	CNTR	+	
105.65836 ±0.00026	[6] CROWE	72	CNTR		
105.65865 ±0.00044	[7] CRANE	71	CNTR		

[1] The mass is known more precisely in u: m = 0.113428913 ± 0.000000017 u. COHEN 87 makes use of the other entries below.

[2] BELTRAMI 86 gives m_μ/m_e = 206.76830(64).

[3] KLEMPT 82 gives m_μ/m_e = 206.76835(11).

[4] MARIAM 82 gives m_μ/m_e = 206.768259(62).

[5] CASPERSON 77 gives m_μ/m_e = 206.76859(29).

[6] CROWE 72 gives m_μ/m_e = 206.7682(5).

[7] CRANE 71 gives m_μ/m_e = 206.76878(85).

μ MEAN LIFE τ

Measurements with an error > 0.001×10^{-6} s have been omitted.

VALUE (10^{-6} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO

A test of *CPT* invariance.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.000024±0.000078	BARDIN	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0008 ±0.0010	BAILEY	79	CNTR	Storage ring
1.000 ±0.001	MEYER	63	CNTR	Mean life μ^+/ μ^-

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

A test of *CPT* invariance. Calculated from the mean-life ratio, above.

VALUE	*DOCUMENT ID*
(2±8) × 10^{-5} OUR EVALUATION	

μ MAGNETIC MOMENT ANOMALY

$\mu_\mu/(e\hbar/2m_\mu)-1 = (g_\mu-2)/2$

For reviews of theory and experiments, see HUGHES 85, KINOSHITA 84, COMBLEY 81, FARLEY 79, and CALMET 77.

VALUE (units 10^{-6})	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1165.9230±0.0084	COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1165.910 ±0.011	[8] BAILEY	79	CNTR	+	Storage ring
1165.937 ±0.012	[8] BAILEY	79	CNTR	−	Storage ring
1165.923 ±0.0085	[8] BAILEY	79	CNTR	±	Storage ring
1165.922 ±0.009	[8] BAILEY	77	CNTR	±	Storage ring
1166.16 ±0.31	BAILEY	68	CNTR	±	Storage rings
1162.0 ±5.0	CHARPAK	62	CNTR	+	

[8] BAILEY 79 is final result. Includes BAILEY 77 data. We use μ/p magnetic moment ratio = 3.1833452 and recalculate the BAILEY 79 values. Third BAILEY 79 result is first two combined.

$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-8})	*DOCUMENT ID*	
−2.6±1.6	BAILEY	79

μ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (10^{-19} e cm)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.7±3.4	[9] BAILEY	78	CNTR	±	Storage ring
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.6±4.5	BAILEY	78	CNTR	+	Storage rings
0.8±4.3	BAILEY	78	CNTR	−	Storage rings

[9] This is the combination of the two BAILEY 78 results given below.

μ/p MAGNETIC MOMENT RATIO

This ratio is used to obtain a precise value of the muon mass. Measurements with an error > 0.00001 have been omitted.

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.18334547±0.00000047	[10] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.1833441 ±0.0000017	KLEMPT	82	CNTR	+	Precession strob
3.1833461 ±0.0000011	MARIAM	82	CNTR	+	HFS splitting
3.1833448 ±0.0000029	CAMANI	78	CNTR	+	See KLEMPT 82
3.1833403 ±0.0000044	CASPERSON	77	CNTR	+	HFS splitting
3.1833402 ±0.0000072	COHEN	73	RVUE		1973 CODATA value
3.1833467 ±0.0000082	CROWE	72	CNTR	+	Precession phase

[10] COHEN 87 (1986 CODATA) value was fitted using their own selection of the following data. Because their value is from a multiparameter fit, correlations with other quantities may be important and one cannot arrive at this result by any average of these data alone.

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^-\overline{\nu}_e\nu_\mu$			$\approx$ 100%	
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$		[a]	(1.4±0.4) %	
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$		[b]	(3.4±0.4) $\times 10^{-5}$	
	Lepton Family number (*LF*) violating modes				
Γ_4	$e^-\nu_e\overline{\nu}_\mu$	*LF*	[c]	< 1.2 %	90%
Γ_5	$e^-\gamma$	*LF*		< 4.9 $\times 10^{-11}$	90%
Γ_6	$e^-e^+e^-$	*LF*		< 1.0 $\times 10^{-12}$	90%
Γ_7	$e^-2\gamma$	*LF*		< 7.2 $\times 10^{-11}$	90%

[a] This only includes events with the γ energy > 10 MeV. Since the $e^-\overline{\nu}_e\nu_\mu$ and $e^-\overline{\nu}_e\nu_\mu\gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[*b*] See the Particle Listings below for the energy limits used in this measurement.

[*c*] A test of additive vs. multiplicative lepton family number conservation.

μ^- BRANCHING RATIOS

$\Gamma(e^-\overline{\nu}_e\nu_\mu\gamma)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.014 ±0.004		CRITTENDEN	61	CNTR	γ KE > 10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	862	BOGART	67	CNTR	γ KE > 14.5 MeV
0.0033±0.0013		CRITTENDEN	61	CNTR	γ KE > 20 MeV
	27	ASHKIN	59	CNTR	

$\Gamma(e^-\overline{\nu}_e\nu_\mu e^+e^-)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.4±0.2±0.3	7443	[11] BERTL	85	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.2±1.5	7	[12] CRITTENDEN	61	HLBC	+	$E(e^+e^-)$>10 MeV
2	1	[13] GUREVICH	60	EMUL	+	
1.5±1.0	3	[14] LEE	59	HBC	+	

[11] BERTL 85 has transverse momentum cut p_T > 17 MeV/c. Systematic error was increased by us.

[12] CRITTENDEN 61 count only those decays where total energy of either (e^+, e^-) combination is >10 MeV.

[13] GUREVICH 60 interpret their event as either virtual or real photon conversion. e^+ and e^- energies not measured.

[14] In the three LEE 59 events, the sum of energies E(e^+) + E(e^-) + E(e^+) was 51 MeV, 55 MeV, and 33 MeV.

$\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{total}$ — Γ_4/Γ

Forbidden by the additive conservation law for lepton family number. A multiplicative law predicts this branching ratio to be 1/2. For a review see NEMETHY 81.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 0.012	90	[15] FREEDMAN	93	CNTR	+	ν oscillation search
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.018	90	KRAKAUER	91B	CALO	+	
< 0.05	90	[16] BERGSMA	83	CALO		$\overline{\nu}_\mu e \to \mu^-\overline{\nu}_e$
< 0.09	90	JONKER	80	CALO		See BERGSMA 83
−0.001±0.061		WILLIS	80	CNTR	+	
0.13 ±0.15		BLIETSCHAU	78	HLBC	±	Avg. of 4 values
< 0.25	90	EICHTEN	73	HLBC	+	

[15] FREEDMAN 93 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton family number violation.

[16] BERGSMA 83 gives a limit on the inverse muon decay cross-section ratio $\sigma(\overline{\nu}_\mu e^- \to \mu^-\overline{\nu}_e)/\sigma(\nu_\mu e^- \to \mu^-\nu_e)$, which is essentially equivalent to $\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{total}$ for small values like that quoted.

$\Gamma(e^-\gamma)/\Gamma_{total}$ — Γ_5/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 4.9	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<100	90	AZUELOS	83	CNTR	+	TRIUMF
< 17	90	KINNISON	82	SPEC	+	LAMPF
<100	90	SCHAAF	80	ELEC	+	SIN

$\Gamma(e^-e^+e^-)/\Gamma_{total}$ — Γ_6/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 1.0	90	[17] BELLGARDT	88	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 36	90	BARANOV	91	SPEC	+	ARES
< 35	90	BOLTON	88	CBOX	+	LAMPF
< 2.4	90	[17] BERTL	85	SPEC	+	SINDRUM
<160	90	[17] BERTL	84	SPEC	+	SINDRUM
<130	90	[17] BOLTON	84	CNTR		LAMPF

[17] These experiments assume a constant matrix element.

$\Gamma(e^-2\gamma)/\Gamma_{total}$ — Γ_7/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 7.2	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 840	90	[18] AZUELOS	83	CNTR	+	TRIUMF
<5000	90	[19] BOWMAN	78	CNTR		DEPOMMIER 77 data

[18] AZUELOS 83 uses the phase space distribution of BOWMAN 78.
[19] BOWMAN 78 assumes an interaction Lagrangian local on the scale of the inverse μ mass.

LIMIT ON $\mu^- \to e^-$ CONVERSION

Forbidden by lepton family number conservation.

$\sigma(\mu^- \, {}^{32}\text{S} \to e^- \, {}^{32}\text{S}) \, / \, \sigma(\mu^- \, {}^{32}\text{S} \to \nu_\mu \, {}^{32}\text{P}^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7 \times 10^{-11}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-10}$	90	BADERT...	77	STRC	SIN

$\sigma(\mu^- \text{Cu} \to e^- \text{Cu}) \, / \, \sigma(\mu^- \text{Cu} \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.6 \times 10^{-8}$	90	BRYMAN	72	SPEC

$\sigma(\mu^- \text{Ti} \to e^- \text{Ti}) / \sigma(\mu^- \text{Ti} \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.3 × 10^{-12}	90	[20] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.6 × 10^{-12}	90	AHMAD	88	TPC	TRIUMF
<1.6 × 10^{-11}	90	BRYMAN	85	TPC	TRIUMF

[20] DOHMEN 93 assumes $\mu^- \to e^-$ conversion leaves the nucleus in its ground state, a process enhanced by coherence and expected to dominate.

$\sigma(\mu^- \text{Pb} \to e^- \text{Pb}) / \sigma(\mu^- \text{Pb} \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.6 × 10^{-11}	90	HONECKER	96	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.9 × 10^{-10}	90	AHMAD	88	TPC	TRIUMF

LIMIT ON $\mu^- \to e^+$ CONVERSION

Forbidden by total lepton number conservation.

$\sigma(\mu^- \, {}^{32}\text{S} \to e^+ \, {}^{32}\text{Si}^*) / \sigma(\mu^- \, {}^{32}\text{S} \to \nu_\mu \, {}^{32}\text{P}^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9 × 10^{-10}	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5 × 10^{-9}	90	BADERT...	78	STRC	SIN

$\sigma(\mu^- \, {}^{127}\text{I} \to e^+ \, {}^{127}\text{Sb}^*) / \sigma(\mu^- \, {}^{127}\text{I} \to \text{anything})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3 × 10^{-10}	90	[21] ABELA	80	CNTR	Radiochemical tech.

[21] ABELA 80 is upper limit for $\mu^- e^+$ conversion leading to particle-stable states of ^{127}Sb. Limit for total conversion rate is higher by a factor less than 4 (G. Backenstoss, private communication).

$\sigma(\mu^- \text{Cu} \to e^+ \text{Co}) / \sigma(\mu^- \text{Cu} \to \nu_\mu \text{Ni})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.6 × 10^{-8}	90	BRYMAN	72	SPEC
<2.2 × 10^{-7}	90	CONFORTO	62	OSPK

$\sigma(\mu^- \text{Ti} \to e^+ \text{Ca}) / \sigma(\mu^- \text{Ti} \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.9 × 10^{-11}	90	[22] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.3 × 10^{-12}	90	[23] DOHMEN	93	SPEC	SINDRUM II
<1.7 × 10^{-10}	90	[24] AHMAD	88	TPC	TRIUMF

[22] This DOHMEN 93 limit assumes a giant resonance excitation of the daughter Ca nucleus (mean energy and width both 20 MeV).
[23] This DOHMEN 93 limit assumes the daughter Ca nucleus is left in the ground state. However, the probability of this is unknown.
[24] Assuming a giant-resonance-excitation model.

LIMIT ON MUONIUM → ANTIMUONIUM CONVERSION

Forbidden by lepton family number conservation.

$R_g = G_C \,/\, G_F$

The effective Lagrangian for the $\mu^+ e^- \rightarrow \mu^- e^+$ conversion is assumed to be

$$\mathcal{L} = 2^{-1/2}\ G_C\ [\overline{\psi}_\mu \gamma_\lambda\ (1-\gamma_5)\ \psi_e]\ [\overline{\psi}_\mu \gamma_\lambda\ (1-\gamma_5)\ \psi_e] + \text{h.c.}$$

The experimental result is then an upper limit on G_C/G_F, where G_F is the Fermi coupling constant.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.018	90	0	[25] ABELA	96	SPEC	+	μ^+ at 24 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.14	90	1	[26] GORDEEV	97	SPEC	+	JINR phasotron
< 6.9	90		NI	93	CBOX		LAMPF
< 0.16	90		MATTHIAS	91	SPEC		LAMPF
< 0.29	90		HUBER	90B	CNTR		TRIUMF
<20	95		BEER	86	CNTR		TRIUMF
<42	95		MARSHALL	82	CNTR		

[25] ABELA 96 quote both probability $P_{M\overline{M}} < 8 \times 10^{-9}$ at 90% CL and $R_g = G_C/G_F$.

[26] GORDEEV 97 quote limits on both $f = G_{MM}/GF$ and the probability $W_{MM} < 4.7 \times 10^{-7}$ (90%CL).

MUON DECAY PARAMETERS

Revised October 1997 by W. Fetscher and H.-J. Gerber (ETH Zürich).

Introduction: All measurements in direct muon decay, $\mu^- \rightarrow e^- + 2$ neutrals, and its inverse, $\nu_\mu + e^- \rightarrow \mu^- +$ neutral, are successfully described by the "V-A interaction", which is a particular case of a local, derivative-free, lepton-number-conserving, four fermion interaction [1]. As shown below, within this framework, the Standard Model assumptions, such as the V-A form and the nature of the neutrals (ν_μ and $\bar{\nu}_e$), and hence the doublet assignments $(\nu_e\ e^-)_L$ and $(\nu_\mu\ \mu^-)_L$, have been determined from experiments [2,3]. All considerations on muon decay are valid for the leptonic tau decays $\tau \rightarrow \ell + \nu_\tau + \bar{\nu}_e$ with the replacements $m_\mu \rightarrow m_\tau$, $m_e \rightarrow m_\ell$.

Parameters: The differential decay probability to obtain an $e^\pm$ with (reduced) energy between x and $x + dx$, emitted in the direction $\widehat{z}$ at an angle between ϑ and $\vartheta + d\vartheta$ with respect to the muon polarization vector $\vec{P}_\mu$, and with its spin pointing in the arbitrary direction $\widehat{\zeta}$, neglecting radiative corrections, is given by

$$\begin{aligned}\frac{d^2\Gamma}{dx\; d\cos\vartheta} =& \frac{m_\mu}{4\pi^3}\, W_{e\mu}^4\, G_F^2\, \sqrt{x^2 - x_0^2} \\ & \times \left(F_{IS}(x) \pm P_\mu \cos\vartheta\; F_{AS}(x)\right) \\ & \times \left[1 + \vec{P}_e(x,\vartheta)\cdot\widehat{\zeta}\right] \;. \end{aligned} \qquad (1)$$

Here, $W_{e\mu} = \max(E_e) = (m_\mu^2 + m_e^2)/2m_\mu$ is the maximum $e^\pm$ energy, $x = E_e/W_{e\mu}$ is the reduced energy, $x_0 = m_e/W_{e\mu} = 9.67\times 10^{-3}$, and $P_\mu = |\vec{P}_\mu|$ is the degree of muon polarization. $\widehat{\zeta}$ is the direction in which a perfect polarization-sensitive electron detector is most sensitive. The isotropic part of the spectrum, $F_{IS}(x)$, the anisotropic part $F_{AS}(x)$ and the electron polarization, $\vec{P}_e(x,\vartheta)$, may be parametrized by the Michel parameters [1,4] ρ, η, ξ, δ, *etc.* These are bilinear combinations of the coupling constants $g^\gamma_{\varepsilon\mu}$, which occur in the matrix element (given below).

If the masses of the neutrinos as well as x_0^2 are neglected, the energy and angular distribution of the electron in the rest frame of a muon ($\mu^\pm$) measured by a polarization insensitive detector, is given by

$$\begin{aligned}\frac{d^2\Gamma}{dx\; d\cos\vartheta} \sim x^2\cdot\Big\{& 3(1-x) + \frac{2\rho}{3}(4x-3) + 3\eta\; x_0(1-x)/x \\ & \pm P_\mu\cdot\xi\cdot\cos\vartheta\left[1 - x + \frac{2\delta}{3}(4x-3)\right]\Big\} \;. \end{aligned}$$

Here, ϑ is the angle between the electron momentum and the muon spin, and $x \equiv 2E_e/m_\mu$. For the Standard Model coupling, we obtain $\rho = \xi\delta = 3/4$, $\xi = 1$, $\eta = 0$ and the differential decay rate is

$$\frac{d^2\Gamma}{dx \;\; d\cos\vartheta} \;=\; \frac{G_F^2 m_\mu^5}{192\pi^3} \;\left[3 - 2x \pm P_\mu \cos\vartheta(2x-1)\right] \; x^2 \quad .$$

The coefficient in front of the square bracket is the total decay rate.

If only the neutrino masses are neglected, and if the $e^\pm$ polarization is detected, then the functions in Eq. (1) become

$$\begin{aligned}
F_{IS}(x) &= x(1-x) + \tfrac{2}{9}\;\rho(4x^2 - 3x - x_0^2) + \eta \cdot x_0(1-x) \\
F_{AS}(x) &= \tfrac{1}{3}\xi\;\sqrt{x^2 - x_0^2} \\
&\qquad \times \left[1 - x + \tfrac{2}{3}\delta\Big(4x - 3 + \Big(\sqrt{1-x_0^2} - 1\Big)\Big)\right] \\
\vec{P}_e(x,\vartheta) &= P_{T_1}\;\widehat{x} + P_{T_2}\widehat{y} + P_L\;\widehat{z}\;.
\end{aligned}$$

Here $\widehat{x}$, $\widehat{y}$, and $\widehat{z}$ are orthogonal unit vectors defined as follows:

$\widehat{z}$	is along the e momentum
$\widehat{y} = [\widehat{z} \times \vec{P_\mu}]/\lvert[\widehat{z} \times \vec{P_\mu}]\rvert$	is transverse to the e momentum and perpendicular to the "decay plane"
$\widehat{x} = \widehat{y} \times \widehat{z}$	is transverse to the e momentum and in the "decay plane."

The components of $\vec{P}_e$ then are given by

$$\begin{aligned}
P_{T_1}(x,\vartheta) &= P_\mu \sin\vartheta\;F_{T_1}(x)/\left(F_{IS}(x) \pm P_\mu \cos\vartheta\;F_{AS}(x)\right) \\
P_{T_2}(x,\vartheta) &= P_\mu \sin\vartheta\;F_{T_2}(x)/\left(F_{IS}(x) \pm P_\mu\;cos\vartheta\;F_{AS}(x)\right) \\
P_L(x,\vartheta) &= \pm F_{IP}(x) + P_\mu \cos\vartheta \\
&\qquad \times F_{AP}(x)/\left(F_{IS}(x) \pm P_\mu \cos\vartheta\;F_{AS}(x)\right)\;,
\end{aligned}$$

where

$$F_{T_1}(x) = \tfrac{1}{12}\left\{-2\left[\xi'' + 12(\rho - \tfrac{3}{4})\right](1-x)x_0 \right.$$
$$\left. -3\eta(x^2 - x_0^2) + \eta''(-3x^2 + 4x - x_0^2)\right\}$$

$$F_{T_2}(x) = \tfrac{1}{3}\sqrt{x^2 - x_0^2}\left\{3\frac{\alpha'}{A}(1-x) + 2\frac{\beta'}{A}\sqrt{1-x_0^2}\right\}$$

$$F_{IP}(x) = \tfrac{1}{54}\sqrt{x^2 - x_0^2}\left\{9\xi'\left(-2x + 2 + \sqrt{1-x_0^2}\right)\right.$$
$$\left. + 4\xi(\delta - \tfrac{3}{4})(4x - 4 + \sqrt{1-x_0^2})\right\}$$

$$F_{AP}(x) = \tfrac{1}{6}\left\{\xi''(2x^2 - x - x_0^2) + 4(\rho - \tfrac{3}{4})\left(4x^2 - 3x - x_0^2\right)\right.$$
$$\left. + 2\eta''(1-x)x_0\right\} \ .$$

For the experimental values of the parameters ρ, ξ, ξ', ξ', δ, η, η', α/A, β/A, α'/A, β'/A, which are not all independent, see the Data Listings below. Experiments in the past have also been analyzed using the parameters a, b, c, a', b', c', α/A, β/A, α'/A, β'/A (and $\eta = (\alpha - 2\beta)/2A$), as defined by Kinoshita and Sirlin [5]. They serve as a model-independent summary of all possible measurements on the decay electron (see Listings below). The relations between the two sets of parameters are

$$\rho - \tfrac{3}{4} \ = \ \tfrac{3}{4}(-a + 2c)/A \ ,$$

$$\eta = (\alpha - 2\beta)/A \ ,$$

$$\eta'' = (3\alpha + 2\beta)/A \ ,$$

$$\delta - \tfrac{3}{4} \ = \ \tfrac{9}{4} \ \cdot \ \frac{(a' - 2c')/A}{1 - [a + 3a' + 4(b + b') + 6c - 14c']/A} \ ,$$

$$1 - \xi\frac{\delta}{\rho} \ = \ 4 \ \frac{[(b + b') + 2(c - c')]/A}{1 - (a - 2c)/A} \ ,$$

$$1 - \xi' \ = \ [(a + a') + 4(b + b') + 6(c + c')]/A \ ,$$

$$1 - \xi'' \ = \ (-2a + 20c)/A \ ,$$

where

$$A \;=\; a \;+\; 4b \;+\; 6c\;.$$

The differential decay probability to obtain a *left-handed* ν_e with (reduced) energy between y and $y + dy$, neglecting radiative corrections as well as the masses of the electron and of the neutrinos, is given by [6]

$$\frac{d\Gamma}{dy} \;=\; \frac{m_\mu^5\; G_F}{16\pi^3}\;\cdot\; Q_L^{\nu_e}\;\cdot y^2\Big\{(1-y) - \omega_L\cdot(y-\tfrac{3}{4})\Big\}\;.$$

Here, $y = 2\;E_{\nu_e}/m_\mu$. $Q_L^{\nu_e}$ and ω_L are parameters. ω_L is the neutrino analog of the spectral shape parameter ρ of Michel. Since in the Standard Model, $Q_L^{\nu_e} = 1,\; \omega_L = 0$, the measurement of $d\Gamma/dy$ has allowed a null-test of the Standard Model (see Listings below).

Matrix element: All results in direct muon decay (energy spectra of the electron and of the neutrinos, polarizations, and angular distributions) and in inverse muon decay (the reaction cross section) at energies well below $m_W c^2$ may be parametrized in terms of amplitudes $g^\gamma_{\varepsilon\mu}$ and the Fermi coupling constant G_F, using the matrix element

$$\frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T\\ \varepsilon,\mu=R,L}} g^\gamma_{\varepsilon\mu}\langle\bar{e}_\varepsilon|\Gamma^\gamma|(\nu_e)_n\rangle\langle\bar{\nu}_\mu)_m|\Gamma_\gamma|\mu_\mu\rangle. \qquad (2)$$

We use the notation of Fetscher *et al.* [2], who in turn use the sign conventions and definitions of Scheck [7]. Here, $\gamma = S, V, T$ indicates a scalar, vector, or tensor interaction; and $\varepsilon, \mu = R, L$ indicate a right- or left-handed chirality of the electron or muon. The chiralities n and m of the ν_e and $\bar{\nu}_\mu$ are then determined by the values of γ, ε and μ. The particles are represented by fields of definite chirality [8].

As shown by Langacker and London [9], explicit lepton-number nonconservation still leads to a matrix element equivalent to Eq. (2). They conclude that it is not possible, even in principle, to test lepton-number conservation in (leptonic) muon decay if the final neutrinos are massless and are not observed.

The ten complex amplitudes $g^{\gamma}_{\varepsilon\mu}$ (g^{T}_{RR} and g^{T}_{LL} are identically zero) and G_F constitute 19 independent (real) parameters to be determined by experiment. The Standard Model interaction corresponds to one single amplitude g^{V}_{LL} being unity and all the others being zero.

The (direct) muon decay experiments are compatible with an arbitrary mix of the scalar and vector amplitudes g^{S}_{LL} and g^{V}_{LL} – in the extreme even with purely scalar $g^{S}_{LL} = 2$, $g^{V}_{LL} = 0$. The decision in favour of the Standard Model comes from the quantitative observation of inverse muon decay, which would be forbidden for pure g^{S}_{LL} [2].

Experimental determination of V−A: In order to determine the amplitudes $g^{\gamma}_{\varepsilon\mu}$ uniquely from experiment, the following set of equations, where the left-hand sides represent experimental results, has to be solved.

$$
\begin{aligned}
a &= 16(|g^V_{RL}|^2 + |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 + |g^S_{LR} + 6g^T_{LR}|^2 \\
a' &= 16(|g^V_{RL}|^2 - |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 - |g^S_{LR} + 6g^T_{LR}|^2 \\
\alpha &= 8\mathrm{Re}\left\{g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})\right\} \\
\alpha' &= 8\mathrm{Im}\left\{g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL}) - g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR})\right\} \\
b &= 4(|g^V_{RR}|^2 + |g^V_{LL}|^2) + |g^S_{RR}|^2 + |g^S_{LL}|^2 \\
b' &= 4(|g^V_{RR}|^2 - |g^V_{LL}|^2) + |g^S_{RR}|^2 - |g^S_{LL}|^2 \\
\beta &= -4\mathrm{Re}\left\{g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR}\right\}
\end{aligned}
$$

$$\beta' = 4\mathrm{Im}\left\{g^V_{RR}g^{S*}_{LL} - g^V_{LL}g^{S*}_{RR}\right\}$$
$$c = \tfrac{1}{2}\left\{|g^S_{RL} - 2g^T_{RL}|^2 + |g^S_{LR} - 2g^T_{LR}|^2\right\}$$
$$c' = \tfrac{1}{2}\left\{|g^S_{RL} - 2g^T_{RL}|^2 - |g^S_{LR} - 2g^T_{LR}|^2\right\}$$

and

$$Q^{\nu_e}_L = 1 - \left\{\tfrac{1}{4}|g^S_{LR}|^2 + \tfrac{1}{4}|g^S_{LL}|^2 + |g^V_{RR}|^2 + |g^V_{RL}|^2 + 3|g^T_{LR}|^2\right\}$$
$$\omega_L = \tfrac{3}{4}\ \frac{\{|g^S_{RR}|^2 + 4|g^V_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2\}}{|g^S_{RL}|^2 + |g^S_{RR}|^2 + 4|g^V_{LL}|^2 + 4|g^V_{LR}|^2 + 12|g^T_{RL}|^2\}}\ .$$

It has been noted earlier by C. Jarlskog [10], that certain experiments observing the decay electron are especially informative if the yield the V-A values. The complete solution is now found as follows. Fetscher *et al.* [2] introduced four probabilities $Q_{\varepsilon\mu}(\varepsilon,\mu = R, L)$ for the decay of a μ-handed muon into an ε-handed electron and showed that there exist upper bounds on Q_{RR}, Q_{LR}, and Q_{RL}, and a lower bound on Q_{LL}. These probabilities are given in terms of the $g^\gamma_{\varepsilon\mu}$'s by

$$Q_{\varepsilon\mu} = \tfrac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1-\delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2\ , \qquad (3)$$

where $\delta_{\varepsilon\mu} = 1$ for $\varepsilon = \mu$, and $\delta_{\varepsilon\mu} = 0$ for $\varepsilon \neq \mu$. They are related to the parameters $a,\ b,\ c,\ a', b'$, and c' by

$$Q_{RR} = 2(b + b')/A\ ,$$
$$Q_{LR} = [(a - a') + 6(c - c')]/2A\ ,$$
$$Q_{RL} = [(a + a') + 6(c + c')]/2A\ ,$$
$$Q_{LL} = 2(b - b')/A\ ,$$

with $A = 16$. In the Standard Model, $Q_{LL} = 1$ and the others are zero.

Since the upper bounds on Q_{RR}, Q_{LR}, and Q_{RL} are found to be small, and since the helicity of the ν_μ in pion decay is known from experiment [11,12] to very high precision to be -1 [13], the cross section S of *inverse* muon decay, normalized to the V-A value, yields [2]

$$|g^S_{LL}|^2 \leq 4(1-S) \tag{4}$$

and

$$|g^V_{LL}|^2 \ = \ S \ . \tag{5}$$

Thus the Standard Model assumption of a pure V-A leptonic charged weak interaction of e and μ is derived (within errors) from experiments at energies far below mass of the $W^\pm$: Eq. (5) gives a lower limit for V-A, and Eqs. (3) and (4) give upper limits for the other four-fermion interactions. The existence of such upper limits may also be seen from $Q_{RR}+Q_{RL} = (1-\xi')/2$ and $Q_{RR}+Q_{LR} = \frac{1}{2}(1+\xi/3-16 \ \xi\delta/9)$. Table 1 gives the current experimental limits on the magnitudes of the $g^\gamma_{\varepsilon\mu}$'s.

Limits on the "charge retention" coordinates, as used in the older literature (*e.g.*, Ref. 16), are given by Burkard *et al.* [17].

Table 1. Coupling constants $g^\gamma_{\varepsilon\mu}$. Ninety-percent confidence level experimental limits. The limits on $|g^S_{LL}|$ and $|g^V_{LL}|$ are from Ref. 14, and the others are from Ref. 15. The experimental uncertainty on the muon polarization in pion decay is included.

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.550$	$\lvert g^V_{LL}\rvert > 0.960$	$\lvert g^T_{LL}\rvert \equiv 0$

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15. B. Balke *et al.*, Phys. Rev. **D37**, 587 (1988).
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μ DECAY PARAMETERS

ρ PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7518±0.0026		DERENZO	69	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.762 ±0.008	170k	[27] FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.760 ±0.009	280k	[27] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.7503±0.0026	800k	[27] PEOPLES	66	ASPK	+	20–53 MeV e^+

[27] η constrained = 0. These values incorporated into a two parameter fit to ρ and η by DERENZO 69.

η PARAMETER

$(V-A)$ theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.007±0.013 OUR AVERAGE						
−0.007±0.013	5.3M	[28] BURKARD	85B	FIT	+	9–53 MeV e^+
−0.12 ±0.21	6346	DERENZO	69	HBC	+	1.6–6.8 MeV e^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.012±0.015±0.003	5.3M	[29] BURKARD	85B	CNTR	+	9–53 MeV e^+
0.011±0.081±0.026	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+
−0.7 ±0.5	170k	[30] FRYBERGER	68	ASPK	+	25–53 MeV e^+
−0.7 ±0.6	280k	[30] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.05 ±0.5	800k	[30] PEOPLES	66	ASPK	+	20–53 MeV e^+
−2.0 ±0.9	9213	[31] PLANO	60	HBC	+	Whole spectrum

[28] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[29] $\alpha = \alpha' = 0$ assumed.
[30] ρ constrained = 0.75.
[31] Two parameter fit to ρ and η; PLANO 60 discounts value for η.

δ PARAMETER

$(V-A)$ theory predicts $\delta = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7486±0.0026±0.0028		[32] BALKE	88	SPEC	+	Surface μ^+'s
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[33] VOSSLER	69			
0.752 ±0.009	490k	FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.782 ±0.031		KRUGER	61			
0.78 ±0.05	8354	PLANO	60	HBC	+	Whole spectrum

[32] BALKE 88 uses $\rho = 0.752 \pm 0.003$.
[33] VOSSLER 69 has measured the asymmetry below 10 MeV. See comments about radiative corrections in VOSSLER 69.

$|(\xi$ PARAMETER$)\times(\mu$ LONGITUDINAL POLARIZATION$)|$

$(V-A)$ theory predicts $\xi = 1$, longitudinal polarization = 1.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0027±0.0079±0.0030		BELTRAMI	87	CNTR		SIN, π decay in flight
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.0013±0.0030±0.0053		[34] IMAZATO	92	SPEC	+	$K^+ \to \mu^+ \nu_\mu$
0.975 ±0.015		AKHMANOV	68	EMUL		140 kG
0.975 ±0.030	66k	GUREVICH	64	EMUL		See AKHMANOV 68
0.903 ±0.027		[35] ALI-ZADE	61	EMUL	+	27 kG
0.93 ±0.06	8354	PLANO	60	HBC	+	8.8 kG
0.97 ±0.05	9k	BARDON	59	CNTR		Bromoform target

[34] The corresponding 90% confidence limit from IMAZATO 92 is $|\xi P_\mu| > 0.990$. This measurement is of K^+ decay, not π^+ decay, so we do not include it in an average, nor do we yet set up a separate data block for K results.
[35] Depolarization by medium not known sufficiently well.

ξ × (μ LONGITUDINAL POLARIZATION) × δ / ρ

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.99682	90	[36] JODIDIO	86	SPEC	+	TRIUMF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.9966	90	[37] STOKER	85	SPEC	+	μ-spin rotation
>0.9959	90	CARR	83	SPEC	+	11 kG

[36] JODIDIO 86 includes data from CARR 83 and STOKER 85. The value here is from the erratum.

[37] STOKER 85 find ($\xi P_\mu \delta/\rho$) >0.9955 and >0.9966, where the first limit is from new μ spin-rotation data and the second is from combination with CARR 83 data. In $V-A$ theory, $(\delta/\rho) = 1.0$.

ξ' = LONGITUDINAL POLARIZATION OF e^+

($V-A$) theory predicts the longitudinal polarization = ±1 for $e^\pm$, respectively. We have flipped the sign for e^- so our programs can average.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00 ±0.04 OUR AVERAGE						
0.998±0.045	1M	BURKARD	85	CNTR	+	Bhabha + annihil
0.89 ±0.28	29k	SCHWARTZ	67	OSPK	−	Moller scattering
0.94 ±0.38		BLOOM	64	CNTR	+	Brems. transmiss.
1.04 ±0.18		DUCLOS	64	CNTR	+	Bhabha scattering
1.05 ±0.30		BUHLER	63	CNTR	+	Annihilation

ξ'' PARAMETER

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.65±0.36	326k	[38] BURKARD	85	CNTR	+	Bhabha + annihil

[38] BURKARD 85 measure $(\xi''-\xi\xi')/\xi$ and ξ' and set $\xi = 1$.

TRANSVERSE e^+ POLARIZATION IN PLANE OF μ SPIN, e^+ MOMENTUM

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.016±0.021±0.01	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

TRANSVERSE e^+ POLARIZATION NORMAL TO PLANE OF μ SPIN, e^+ MOMENTUM

Zero if T invariance holds.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.007±0.022±0.007	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

α/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.4± 4.3		[39] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
15 ±50 ±14	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[39] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

α'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
$-$ 0.2± 4.3		[40] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
-47 ±50 ±14	5.3M	[41] BURKARD	85B	CNTR	+	9–53 MeV e^+

[40] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[41] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

β/A

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.9± 6.2		[42] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2 ±17 ±6	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[42] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

β'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.5± 6.3		[43] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
17 ±17 ±6	5.3M	[44] BURKARD	85B	CNTR	+	9–53 MeV e^+

[43] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[44] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

a/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<15.9	90	[45] BURKARD	85B	FIT

[45] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

a'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.3±4.1	[46] BURKARD	85B	FIT

[46] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$(b'+b)/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.04	90	[47] BURKARD	85B	FIT

[47] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.4	90	[48] BURKARD	85B	FIT

[48] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.5 ± 2.0	[49] BURKARD	85B	FIT

[49] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$\overline{\eta}$ PARAMETER

$(V-A)$ theory predicts $\overline{\eta} = 0$. $\overline{\eta}$ affects spectrum of radiative muon decay.

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
0.02 ±0.08 OUR AVERAGE					
-0.014 ± 0.090	EICHENBER...	84	ELEC	+	ρ free
$+0.09 \pm 0.14$	BOGART	67	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
-0.035 ± 0.098	EICHENBER...	84	ELEC	+	ρ=0.75 assumed

μ REFERENCES

GORDEEV	97	PAN 60 1164	V.A. Gordeev+	(PNPI)
		Translated from YAF 60 1291.		
ABELA	96	PRL 77 1950	+Bagaturia+	(PSI, ZURI, HEIDH, TBIL, YALE+)
HONECKER	96	PRL 76 200	+Dohmen, Haan, Junker+	(SINDRUM II Collab.)
DOHMEN	93	PL B317 631	+Groth, Heer+	(PSI SINDRUM-II Collab.)
FREEDMAN	93	PR D47 811	+Fujikawa, Napolitano, Nelson+	(LAMPF E645 Collab.)
NI	93	PR D48 1976	+Arnold, Chmely+	(LAMPF Crystal-Box Collab.)
IMAZATO	92	PRL 69 877	+Kawashima, Tanaka+	(KEK, INUS, TOKY, TOKMS)
BARANOV	91	SJNP 53 802	+Vanko, Glazov, Evtukhovich+	(JINR)
		Translated from YAF 53 1302.		

KRAKAUER 91B PL B263 534 +Talaga, Allen, Chen, Doe+ (UMD, UCI, LANL)
MATTHIAS 91 PRL 66 2716 +Ahn+ (YALE, HEIDP, WILL, GSI, VILL, BNL)
Also 91B PRL 67 932 erratum Matthias, Ahn+ (YALE, HEIDP, WILL, GSI, VILL, BNL)
HUBER 90B PR D41 2709 + (WYOM, VICT, ARIZ, ROCH, TRIU, SFRA, BRCO)
AHMAD 88 PR D38 2102 +Azuelos+ (TRIU, VICT, VPI, BRCO, MONT, CNRC)
Also 87 PRL 59 970 Ahmad+ (TRIU, VPI, VICT, BRCO, MONT, CNRC)
BALKE 88 PR D37 587 +Gidal, Jodidio+ (LBL, UCB, COLO, NWES, TRIU)
BELLGARDT 88 NP B299 1 +Otter, Eichler+ (SINDRUM Collab.)
BOLTON 88 PR D38 2077 +Cooper, Frank, Hallin+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 56 2461 Bolton, Bowman, Cooper+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 57 3241 Grosnick, Wright, Bolton+ (CHIC, LANL, STAN, TEMP)
BELTRAMI 87 PL B194 326 +Burkard, Von Dincklage+ (ETH, SIN, MANZ)
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
BEER 86 PRL 57 671 +Marshall, Mason+ (VICT, TRIU, WYOM)
BELTRAMI 86 NP A451 679 +Aas, Beer, Dechambrier, Goudsmit+ (ETH, FRIB)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
BERTL 85 NP B260 1 +Egli, Eichler+ (SINDRUM Collab.)
BRYMAN 85 PRL 55 465 + (TRIU, CNRC, BRCO, LANL, CHIC, CARL+)
BURKARD 85 PL 150B 242 +Corriveau, Egger+ (ETH, SIN, MANZ)
BURKARD 85B PL 160B 343 +Corriveau, Egger+ (ETH, SIN, MANZ)
Also 81B PR D24 2004 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
Also 83B PL 129B 260 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
HUGHES 85 CNPP 14 341 +Kinoshita (YALE, CORN)
STOKER 85 PRL 54 1887 +Balke, Carr, Gidal+ (LBL, NWES, TRIU)
BARDIN 84 PL 137B 135 +Duclos, Magnon+ (SACL, CERN, BGNA, FIRZ)
BERTL 84 PL 140B 299 +Eichler, Felawka+ (SINDRUM Collab.)
BOLTON 84 PRL 53 1415 +Bowman, Carlini+ (LANL, CHIC, STAN, TEMP)
EICHENBER... 84 NP A412 523 Eichenberger, Engfer, VanderSchaff (ZURI)
GIOVANETTI 84 PR D29 343 +Dey, Eckhause, Hart+ (WILL)
KINOSHITA 84 PRL 52 717 +Nizic, Okamoto (CORN)
AZUELOS 83 PRL 51 164 +Depommier, Leroy, Martin+ (MONT, TRIU, BRCO)
Also 77 PRL 39 1113 Depommier+ (MONT, BRCO, TRIU, VICT, MELB)
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
KINNISON 82 PR D25 2846 +Anderson, Matis, Wright+ (EFI, STAN, LANL)
Also 79 PRL 42 556 Bowman, Cooper, Hamm+ (LASL, EFI, STAN)
KLEMPT 82 PR D25 652 +Schulze, Wolf, Camani, Gygax+ (MANZ, ETH)
MARIAM 82 PRL 49 993 +Beer, Bolton, Egan, Gardner+ (YALE, HEIDH, BERN)
MARSHALL 82 PR D25 1174 +Warren, Oram, Kiefl (BRCO)
COMBLEY 81 PRPL 68 93 +Farley, Picasso (SHEF, RMCS, CERN)
NEMETHY 81 CNPP 10 147 +Hughes (LBL, YALE)
ABELA 80 PL 95B 318 +Backenstoss, Simons, Wuest+ (BASL, KARLK, KARLE)
BADERT... 80 LNC 28 401 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
Also 82 NP A377 406 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
JONKER 80 PL 93B 203 +Panman, Udo, Allaby+ (CHARM Collab.)
SCHAAF 80 NP A340 249 +Engfer, Povel, Dey+ (ZURI, ETH, SIN)
Also 77 PL 72B 183 Povel, Dey, Walter, Pfeiffer+ (ZURI, ETH, SIN)
WILLIS 80 PRL 44 522 +Hughes+ (YALE, LBL, LASL, SACL, SIN, CNRC+)
Also 80B PRL 45 1370 Willis+ (YALE, LBL, LASL, SACL, SIN, CNRC+)
BAILEY 79 NP B150 1 (CERN, DARE, MANZ)
FARLEY 79 ARNPS 29 243 +Picasso (RMCS, CERN)
BADERT... 78 PL 79B 371 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
BAILEY 78 JPG 4 345 (DARE, BERN, SHEF, MANZ, RMCS, CERN, BIRM)
Also 79 NP B150 1 Bailey (CERN, DARE, MANZ)
BLIETSCHAU 78 NP B133 205 +Deden, Hasert, Krenz+ (Gargamelle Collab.)
BOWMAN 78 PRL 41 442 +Cheng, Li, Matis (LASL, IAS, CMU, EFI)
CAMANI 78 PL 77B 326 +Gygax, Klempt, Schenck, Schulze+ (ETH, MANZ)
BADERT... 77 PRL 39 1385 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
BAILEY 77 PL 67B 225 + (CERN Muon Storage Ring Collab.)
Also 77C PL 68B 191 Bailey+ (CERN, DARE, BERN, SHEF, MANZ+)
Also 75 PL 55B 420 Bailey+ (CERN Muon Storage Ring Collab., BIRM)
CALMET 77 RMP 49 21 +Narison, Perrottet+ (CPPM)
CASPERSON 77 PRL 38 956 +Crane+ (BERN, HEIDH, LASL, WYOM, YALE)
DEPOMMIER 77 PRL 39 1113 + (MONT, BRCO, TRIU, VICT, MELB)
BALANDIN 74 JETP 40 811 +Grebenyuk, Zinov, Konin, Ponomarev (JINR)
Translated from ZETF 67 1631.

COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
DUCLOS	73	PL 47B 491	+Magnon, Picard	(SACL)
EICHTEN	73	PL 46B 281	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BRYMAN	72	PRL 28 1469	+Blecher, Gotow, Powers	(VPI)
CROWE	72	PR D5 2145	+Hague, Rothberg, Schenck+	(LBL, WASH)
CRANE	71	PRL 27 474	+Casperson, Crane, Egan, Hughes+	(YALE)
DERENZO	69	PR 181 1854		(EFI)
VOSSLER	69	NC 63A 423		(EFI)
AKHMANOV	68	SJNP 6 230	+Gurevich, Dobretsov, Makarina+	(KIAE)
		Translated from YAF 6 316.		
BAILEY	68	PL 28B 287	+Bartl, VonBochmann, Brown, Farley+	(CERN)
Also	72	NC 9A 369	Bailey, Bartl, VonBochmann, Brown+	(CERN)
FRYBERGER	68	PR 166 1379		(EFI)
BOGART	67	PR 156 1405	+Dicapua, Nemethy, Strelzoff	(COLU)
SCHWARTZ	67	PR 162 1306		(EFI)
SHERWOOD	67	PR 156 1475		(EFI)
PEOPLES	66	Nevis 147 unpub.		(COLU)
BLOOM	64	PL 8 87	+Dick, Feuvrais, Henry, Macq, Spighel	(CERN)
DUCLOS	64	PL 9 62	+Heintze, DeRujula, Soergel	(CERN)
GUREVICH	64	PL 11 185	+Makarina+	(KIAE)
BUHLER	63	PL 7 368	+Cabibbo, Fidecaro, Massam, Muller+	(CERN)
MEYER	63	PR 132 2693	+Anderson, Bleser, Lederman+	(COLU)
CHARPAK	62	PL 1 16	+Farley, Garwin+	(CERN)
CONFORTO	62	NC 26 261	+Conversi, Dilella+	(INFN, ROMA, CERN)
ALI-ZADE	61	JETP 13 313	+Gurevich, Nikolski	
		Translated from ZETF 40 452.		
CRITTENDEN	61	PR 121 1823	+Walker, Ballam	(WISC, MSU)
KRUGER	61	UCRL 9322 unpub.		(LRL)
GUREVICH	60	JETP 10 225	+Nikolski, Surkova	(ITEP)
		Translated from ZETF 37 318.		
PLANO	60	PR 119 1400		(COLU)
ASHKIN	59	NC 14 1266	+Fazzini, Fidecaro, Lipman, Merrison+	(CERN)
BARDON	59	PRL 2 56	+Berley, Lederman	(COLU)
LEE	59	PRL 3 55	+Samios	(COLU)