W

$J = 1$

NOTE ON THE MASS OF THE *W* BOSON

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Till 1995 the production and study of the W boson was the exclusive domain of the $\overline{p}p$ colliders at CERN and FNAL. W production in these hadron colliders is tagged by a high p_T lepton from W decay. Owing to unknown parton–parton effective energy and missing energy in the longitudinal direction, the experiments reconstruct only the transverse mass of the W and derive the W mass from comparing the transverse mass distribution with Monte Carlo predictions as a function of M_W.

In 1996 the energy of LEP was increased in two steps to 161 GeV and 172 GeV, allowing the production of pairs of W bosons. A precise knowledge of the e^+e^- centre of mass energy enables one to reconstruct the W mass even if one of them decays leptonically. At LEP two methods have been used to obtain the W mass. In the first method the measured W–pair production cross sections, $\sigma(e^+e^- \rightarrow W^+W^-)$, have been used to determine the W mass using the Standard Model based dependence of this cross section on M_W (see Fig. 1). At 161 GeV, which is just above the W–pair production threshold, this dependence is a much more sensitive function of the W mass than at higher energies.

In the second method, which is used at the higher energies, the W mass has been determined by directly reconstructing the W from its decay products.

Each LEP experiment has combined their own mass values properly taking into account the common systematic errors. We have then combined their values into a LEP average leading to: $m_W = 80.49 \pm 0.14$ GeV. The error includes in the systematics a LEP energy uncertainty of ± 30 MeV and, in the case of the reconstruction method for the $q\overline{q}q\overline{q}$ channel, a possible effect of "color reconnection" and "Bose–Einstein correlations" between quarks from different W's. In our combination, the last two effects have been treated as 100% correlated between the experiments.

OUR AVERAGE is obtained by combining this LEP value with other measurements assuming no common systematics.

Combining published and unpublished preliminary Collider and LEP results (as of end of March 1998) yields an average W-boson mass of 80.375 ± 0.064 GeV (80.40 ± 0.09 GeV for p–p Colliders and 80.35 ± 0.09 GeV for LEP).

The Standard Model prediction from the electroweak fit, excluding the direct W mass measurements from LEP and Tevatron, gives a W–boson mass of 80.364 ± 0.035 GeV.

W MASS

OUR FIT uses the W and Z mass, mass difference, and mass ratio measurements.

VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
80.41 ± 0.10 OUR FIT					
80.41 ± 0.10 OUR AVERAGE					
$80.22 \pm 0.41 \pm 0.07$	72	[1] ABREU	98B	DLPH	E^{ee}_{cm}= 172.14 GeV
$80.32 \pm 0.30 \pm 0.094$	96	[2] ACKERSTAFF	98D	OPAL	E^{ee}_{cm}= 172.12 GeV
$80.5\ ^{+1.4}_{-2.2}\ ^{+0.5}_{-0.6}$	104	[3] ACKERSTAFF	98D	OPAL	E^{ee}_{cm}= 172.12 GeV
$80.80 \pm 0.32 \pm 0.114$	95	[4] BARATE	98B	ALEP	E^{ee}_{cm}= 172.09 GeV
$80.40 \pm 0.44 \pm 0.095$	29	[5] ABREU	97	DLPH	E^{ee}_{cm}= 161.3 GeV
$80.80\ ^{+0.48}_{-0.42} \pm 0.03$	20	[6] ACCIARRI	97	L3	E^{ee}_{cm}= 161.3 GeV
$80.5\ ^{+1.4}_{-2.4} \pm 0.3$	94	[7] ACCIARRI	97M	L3	E^{ee}_{cm}= 172.13 GeV
$80.71\ ^{+0.34}_{-0.35} \pm 0.09$	101	[8] ACCIARRI	97S	L3	E^{ee}_{cm}= 172.13 GeV

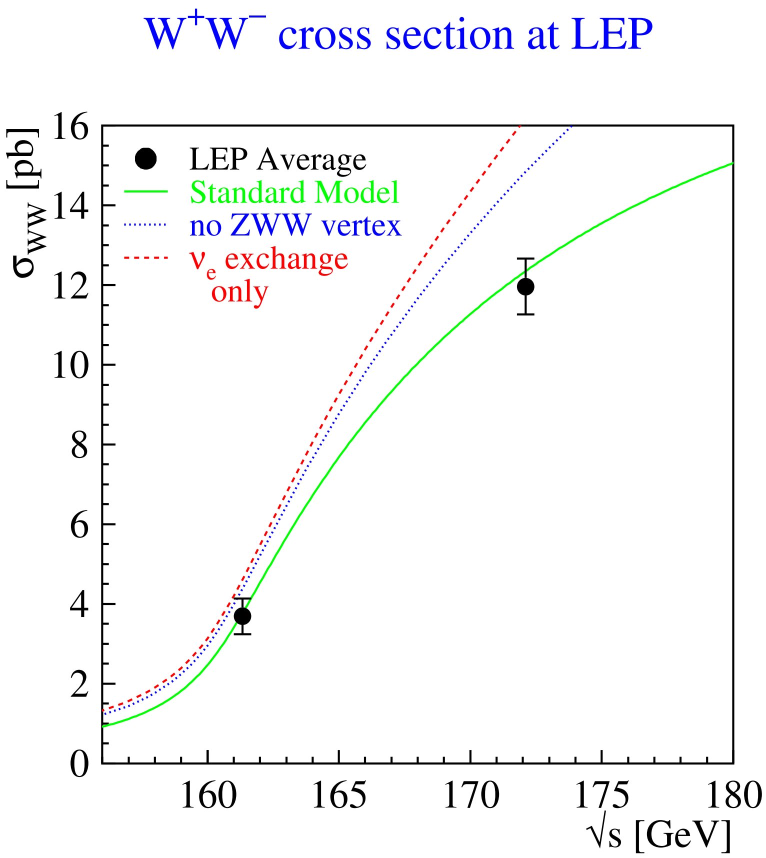

Figure 1: The W–pair cross section as a function of the center–of–mass energy. The data points are the LEP averages. The solid line is the Standard Model prediction. For comparison the figure contains also the cross section if the ZWW coupling did not exist (dotted line), or if only the t–channel ν_e exchange diagram existed (dashed line).

$80.14 \pm 0.34 \pm 0.095$	32	[9] BARATE	97	ALEP	$E^{ee}_{\rm cm}$= 161.3 GeV
$81.17 {+1.15 \atop -1.62}$	106	[10] BARATE	97S	ALEP	$E^{ee}_{\rm cm}$= 172.09 GeV
$80.350 \pm 0.140 \pm 0.230$	5982	[11] ABACHI	96E	D0	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
$80.40 {+0.44 \atop -0.41} {+0.09 \atop -0.10}$	23	[12] ACKERSTAFF	96B	OPAL	$E^{ee}_{\rm cm}$= 161.3 GeV
80.410 ± 0.180	8986	[13] ABE	95P	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
79.91 ± 0.39	1722	[14] ABE	90G	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$84 {+10 \atop -7}$	13	[15] AID	96D	H1	$e^{\pm} p \rightarrow \nu_e(\overline{\nu}_e) + X$ $\sqrt{s} \approx 300$ GeV
$80.84 \pm 0.22 \pm 0.83$	2065	[16] ALITTI	92B	UA2	See W/Z ratio below
$80.79 \pm 0.31 \pm 0.84$		[17] ALITTI	90B	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
$80.0 \pm 3.3 \pm 2.4$	22	[18] ABE	89I	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
$82.7 \pm 1.0 \pm 2.7$	149	[19] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
$81.8 {+6.0 \atop -5.3} \pm 2.6$	46	[20] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
$89 \pm 3 \pm 6$	32	[21] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
$81. \pm 5.$	6	ARNISON	83	UA1	$E^{ee}_{\rm cm}$= 546 GeV
$80. {+10. \atop -6.}$	4	BANNER	83B	UA2	Repl. by ALITTI 90B

[1] ABREU 98B obtain this value from a fit to the reconstructed W mass distribution. The W width was taken as its Standard Model value at the fitted W mass. The systematic error includes ± 0.03 GeV due to the beam energy uncertainty and ± 0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with ABREU 97 authors find: $M(W) = 80.33 \pm 0.30 \pm 0.06 \pm 0.03$ (LEP) GeV.

[2] ACKERSTAFF 98D obtain this value from a fit to the reconstructed W mass distribution. The W width was taken as its Standard Model value at the fitted W mass. When both W mass and width are varied they obtain $M(W) = 80.30 \pm 0.27 \pm 0.095$ GeV. The systematic error includes ± 0.03 GeV due to the beam energy uncertainty and ± 0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining both values of ACKERSTAFF 98D with ACKERSTAFF 96B authors find: $M(W) = 80.35 \pm 0.24 \pm 0.07 \pm 0.03$ (LEP) GeV.

[3] ACKERSTAFF 98D derive this value from their measured $W W$ production cross section $\sigma_{W W}$ =12.3 $\pm$ 1.3 $\pm$ 0.4 pb using the Standard Model dependence of $\sigma_{W W}$ on M_W at the given c.m. energy.

[4] BARATE 98B obtain this value from a fit to the reconstructed W mass distribution. The W width was taken as its Standard Model value at the fitted W mass. The systematic error includes ± 0.03 GeV due to the beam energy uncertainty and ± 0.032 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with the M_W values from cross section measurements at 161 and 172 GeV (BARATE 97 and BARATE 97S) authors find: $M(W) = 80.51 \pm 0.23 \pm 0.08$ GeV.

[5] ABREU 97 derive this value from their measured W-W production cross section σ_{WW} $= 3.67^{+0.97}_{-0.85} \pm 0.19$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. The systematics include an error of ± 0.03 GeV arising from the beam energy uncertainty.

[6] ACCIARRI 97 derive this value from their measured W-W production cross section $\sigma_{WW} = 2.89^{+0.81}_{-0.70} \pm 0.14$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. Statistical and systematic errors are added in quadrature

and the last error of ± 0.03 GeV arises from the beam energy uncertainty. The same result is given by a fit of the production cross sections to the data.

[7] ACCIARRI 97M derive this value from their measured WW production cross section $\sigma_{WW} = 12.27^{+1.41}_{-1.32} \pm 0.23$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. Combining with ACCIARRI 97 authors find $M(W) = 80.78^{+0.45}_{-0.41} \pm 0.03$ GeV where the last error is due to beam energy uncertainty.

[8] ACCIARRI 97S obtain this value from a fit to the reconstructed W mass distribution. The W width was taken as its Standard Model value at the fitted W mass. When both W mass and width are varied they obtain $M(W) = 80.72^{+0.31}_{-0.33} \pm 0.09$ GeV. The systematic error includes ± 0.03 GeV due to the beam energy uncertainty and ± 0.05 GeV due to the possible color reconnection and Bose-Einstein effects in the purely hadronic final state. Combining with ACCIARRI 97 and ACCIARRI 97M authors find: $M(W) = 80.75^{+0.26}_{-0.27} \pm 0.03$ (LEP) GeV.

[9] BARATE 97 derive this value from their measured W-W production cross section $\sigma_{WW} = 4.23 \pm 0.73 \pm 0.19$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. The systematics include an error of ± 0.03 GeV arising from the beam energy uncertainty.

[10] BARATE 97S derive this value from their measured WW production cross section $\sigma_{WW} = 11.71 \pm 1.23 \pm 0.28$ pb using the Standard Model dependence of σ_{WW} on M_W at the given c.m. energy. The errors quoted on the mass are statistical only. Combining with BARATE 97 authors find: $M(W) = 80.20 \pm 0.33 \pm 0.09 \pm 0.03$ (LEP) GeV.

[11] ABACHI 96E fit the transverse mass distribution of 5982 $W \to e\nu_e$ decays. An error of ± 160 MeV due to the uncertainty in the absolute energy scale of the EM calorimeter is included in the total systematics.

[12] ACKERSTAFF 96B derive this value from an analysis of the predicted M_W dependence of their accepted four-fermion cross section, explicitly taking into account interference effects. The systematics include an error of ± 0.03 GeV arising from the beam energy uncertainty.

[13] ABE 95P use 3268 $W \to \mu\nu_\mu$ events to find $M = 80.310 \pm 0.205 \pm 0.130$ GeV and 5718 $W \to e\nu_e$ events to find $M = 80.490 \pm 0.145 \pm 0.175$ GeV. The result given here combines these while accounting for correlated uncertainties.

[14] ABE 90G result from $W \to e\nu$ is $79.91 \pm 0.35 \pm 0.24 \pm 0.19$(scale) GeV and from $W \to \mu\nu$ is $79.90 \pm 0.53 \pm 0.32 \pm 0.08$(scale) GeV.

[15] AID 96D derive this value as a propagator mass using the Q^2 shape and magnitude of the $e^\pm$ charged-current cross sections. $Q^2 > 5000\,\mathrm{GeV}^2$ events with p_T of the outgoing lepton > 25 GeV/c are used.

[16] ALITTI 92B result has two contributions to the systematic error (± 0.83); one (± 0.81) cancels in m_W/m_Z and one (± 0.17) is noncancelling. These were added in quadrature. We choose the ALITTI 92B value without using the LEP m_Z value, because we perform our own combined fit.

[17] There are two contributions to the systematic error (± 0.84): one (± 0.81) which cancels in m_W/m_Z and one (± 0.21) which is non-cancelling. These were added in quadrature.

[18] ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.

[19] ALBAJAR 89 result is from a total sample of 299 $W \to e\nu$ events.

[20] ALBAJAR 89 result is from a total sample of 67 $W \to \mu\nu$ events.

[21] ALBAJAR 89 result is from $W \to \tau\nu$ events.

W/*Z* MASS RATIO

The fit uses the *W* and *Z* mass, mass difference, and mass ratio measurements.

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.8818±0.0011 OUR FIT					
0.8813±0.0036±0.0019	156	[22] ALITTI	92B	UA2	$E_{\rm cm}^{p\overline{p}}$= 630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.8831±0.0048±0.0026		[22] ALITTI	90B	UA2	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV

[22] Scale error cancels in this ratio.

$m_Z - m_W$

The fit uses the *W* and *Z* mass, mass difference, and mass ratio measurements.

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
10.78±0.10 OUR FIT				
10.4 ±1.4 ±0.8	ALBAJAR	89	UA1	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
11.3 ±1.3 ±0.9	ANSARI	87	UA2	$E_{\rm cm}^{p\overline{p}}$= 546,630 GeV

$m_{W^+} - m_{W^-}$

Test of *CPT* invariance.

VALUE (GeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.19±0.58	1722	ABE	90G	CDF	$E_{\rm cm}^{p\overline{p}}$= 1.8 TeV

W WIDTH

The CDF and DØ widths labelled "extracted value" are obtained by measuring $R = [\sigma(W)/\sigma(Z)]\,[\Gamma(W \rightarrow e\nu_e)]/(\mathrm{B}(Z \rightarrow ee)\Gamma(W))$ where the bracketed quantities can be calculated with plausible reliability. $\Gamma(W)$ is then extracted by using a value of $\mathrm{B}(Z \rightarrow ee)$ measured at LEP. The UA1 and UA2 widths used $R = [\sigma(W)/\sigma(Z)]\,[\Gamma(W \rightarrow e\nu_e)/\Gamma(Z \rightarrow ee)]\,\Gamma(Z)/\Gamma(W)$ and the measured value of $\Gamma(Z)$. The Standard Model prediction is 2.067 ± 0.021 (ROSNER 94).

VALUE (GeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.06 ±0.06 OUR AVERAGE						
$1.30\,^{+0.70}_{-0.55}\,\pm0.18$		92	[23] ACKERSTAFF	98D	OPAL	$E_{\rm cm}^{ee}$= 172.12 GeV
$1.74\,^{+0.88}_{-0.78}\,\pm0.25$		101	[24] ACCIARRI	97S	L3	$E_{\rm cm}^{ee}$= 172.13 GeV
2.044±0.093		13k	[25] ABACHI	95D	D0	Extracted value
2.11 ±0.28 ±0.16		58	[26] ABE	95C	CDF	Direct meas.
2.064±0.060±0.059			[27] ABE	95W	CDF	Extracted value
$2.10\,^{+0.14}_{-0.13}\,\pm0.09$		3559	[28] ALITTI	92	UA2	Extracted value
$2.18\,^{+0.26}_{-0.24}\,\pm0.04$			[29] ALBAJAR	91	UA1	Extracted value

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

2.16 ± 0.17			[30] ABE	92I	CDF	Repl. by ABE 95W
2.12 ± 0.20			[31] ABE	90	CDF	Repl. by ABE 92I
2.30 ± 0.19 ± 0.06			[32] ALITTI	90C	UA2	Extracted value
2.8 $^{+1.4}_{-1.5}$ ± 1.3		149	[33] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
<7	90	251	ANSARI	87	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
<7	90	119	APPEL	86	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
<6.5	90	86	[34] ARNISON	86	UA1	Repl. by ALBAJAR 89

[23] ACKERSTAFF 98D obtain this value from a fit to the reconstructed W mass distribution.

[24] ACCIARRI 97S obtain this value from a fit to the reconstructed W mass distribution.

[25] ABACHI 95D measured $R = 10.90 \pm 0.49$ and used the measured value B($Z \rightarrow \ell\ell$) = (3.367 $\pm$ 0.006)% from LEP.

[26] ABE 95C use the tail of the transverse mass distribution of $W \rightarrow e\nu_e$ decays.

[27] ABE 95W measured $R = 10.90 \pm 0.32 \pm 0.29$. They use m_W=80.23 $\pm$ 0.18 GeV, $\sigma(W)/\sigma(Z) = 3.35 \pm 0.03$, $\Gamma(W \rightarrow e\nu) = 225.9 \pm 0.9$ MeV, $\Gamma(Z \rightarrow e^+e^-)$ = 83.98 $\pm$ 0.18 MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$ GeV.

[28] ALITTI 92 measured $R = 10.4^{+0.7}_{-0.6} \pm 0.3$. The values of $\sigma(Z)$ and $\sigma(W)$ come from $O(\alpha_s^2)$ calculations using m_W = 80.14 $\pm$ 0.27 GeV, and m_Z = 91.175 $\pm$ 0.021 GeV along with the corresponding value of $\sin^2\theta_W = 0.2274$. They use $\sigma(W)/\sigma(Z)$ = 3.26 $\pm$ 0.07 $\pm$ 0.05 and $\Gamma(Z) = 2.487 \pm 0.010$ GeV.

[29] ALBAJAR 91 measured $R = 9.5^{+1.1}_{-1.0}$ (stat. + syst.). $\sigma(W)/\sigma(Z)$ is calculated in QCD at the parton level using m_W = 80.18 $\pm$ 0.28 GeV and m_Z = 91.172 $\pm$ 0.031 GeV along with $\sin^2\theta_W = 0.2322 \pm 0.0014$. They use $\sigma(W)/\sigma(Z) = 3.23 \pm 0.05$ and $\Gamma(Z)$ = 2.498 $\pm$ 0.020 GeV.

[30] ABE 92I report $1216 \pm 38^{+27}_{-31}$ $W \rightarrow \mu\nu$ and $106 \pm 10^{+0.2}_{-1}$ $Z \rightarrow \mu^+\mu^-$ events which are combined with 2426 $W \rightarrow e\nu$ events of ABE 91C to derive the ratio σ_W B($W \rightarrow \ell\nu)/\sigma_Z$ B($Z \rightarrow \ell^+\ell^-$)= 10.0 $\pm$ 0.6 $\pm$ 0.4. Finally the value of $\Gamma(Z)$ measured by LEP 92 is used to extract $\Gamma(W)$.

[31] ABE 90 extract $\Gamma(W) = 2.19 \pm 0.20$ by using the value $\Gamma(Z) = 2.57 \pm 0.07$ GeV. However, in ABE 91C they update their analysis with a new LEP value $\Gamma(Z) = 2.496 \pm 0.016$; the value $\Gamma(W) = 2.12 \pm 0.20$ above reflects this update. They measured $R = 10.2 \pm 0.8 \pm 0.4$, assumed $\sin^2\theta_W = 0.229 \pm 0.007$, and took predicted values $\sigma(W)/\sigma(Z)$ = 3.23 $\pm$ 0.03 and $\Gamma(W \rightarrow e\nu)/\Gamma(Z \rightarrow ee) = 2.70 \pm 0.02$. This yields $\Gamma(W)/\Gamma(Z)$ = 0.85 $\pm$ 0.08. The quoted error for $\Gamma(W)$ includes systematic uncertainties. $E^{p\overline{p}}_{\rm cm}$ = 1.8 TeV.

[32] ALITTI 90C used the same technique as described for ABE 90. They measured $R = 9.38^{+0.82}_{-0.72} \pm 0.25$, obtained $\Gamma(W)/\Gamma(Z) = 0.902 \pm 0.074 \pm 0.024$. Using $\Gamma(Z)$ = 2.546 $\pm$ 0.032 GeV, they obtained the $\Gamma(W)$ value quoted above and the limits $\Gamma(W)$ < 2.56 (2.64) GeV at the 90% (95%) CL. $E^{p\overline{p}}_{\rm cm}$ = 546,630 GeV.

[33] ALBAJAR 89 result is from a total sample of 299 $W \rightarrow e\nu$ events.

[34] If systematic error is neglected, result is $2.7^{+1.4}_{-1.5}$ GeV. This is enhanced subsample of 172 total events.

W ANOMALOUS MAGNETIC MOMENT ($\Delta\kappa$)

The full magnetic moment is given by $\mu_W = e(1+\kappa+\lambda)/2m_W$. In the Standard Model, at tree level, $\kappa = 1$ and $\lambda = 0$. Some papers have defined $\Delta\kappa = 1-\kappa$ and assume that $\lambda = 0$. Note that the electric quadrupole moment is given by $-e(\kappa-\lambda)/m^2_W$. A description of the parameterization of these moments and additional references can be found in HAGIWARA 87 and BAUR 88. The parameter Λ appearing in the theoretical limits below is a regularization cutoff which roughly corresponds to the energy scale where the structure of the W boson becomes manifest.

VALUE ($e/2m_W$)	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[35] ABACHI	97B	D0
	[36] ABE	95G	CDF
	[37] ALITTI	92C	UA2
	[38] SAMUEL	92	THEO
	[39] SAMUEL	91	THEO
	[40] GRIFOLS	88	THEO
	[41] GROTCH	87	THEO
	[42] VANDERBIJ	87	THEO
	[43] GRAU	85	THEO
	[44] SUZUKI	85	THEO
	[45] HERZOG	84	THEO

[35] ABACHI 97B obtain the 95% CL limits (for $\Lambda = 1.5$ TeV) $-0.93 < \Delta\kappa < 0.94$ for $\lambda = 0$ and $-0.31 < \lambda < 0.29$ for $\Delta\kappa = 0$ in $\overline{p}p \to W\gamma + X$ ($W \to \ell\nu_\ell$, with $\ell = e,\mu$) at $\sqrt{s} = 1.8$ TeV.

[36] ABE 95G report $-1.3 < \kappa < 3.2$ for λ=0 and $-0.7 < \lambda < 0.7$ for κ=1 in $p\overline{p} \to e\nu_e\gamma X$ and $\mu\nu_\mu\gamma X$ at $\sqrt{s} = 1.8$ TeV.

[37] ALITTI 92C measure $\kappa = 1^{+2.6}_{-2.2}$ and $\lambda = 0^{+1.7}_{-1.8}$ in $p\overline{p} \to e\nu\gamma + X$ at $\sqrt{s} = 630$ GeV. At 95%CL they report $-3.5 < \kappa < 5.9$ and $-3.6 < \lambda < 3.5$.

[38] SAMUEL 92 use preliminary CDF and UA2 data and find $-2.4 < \kappa < 3.7$ at 96%CL and $-3.1 < \kappa < 4.2$ at 95%CL respectively. They use data for $W\gamma$ production and radiative W decay.

[39] SAMUEL 91 use preliminary CDF data for $p\overline{p} \to W\gamma X$ to obtain $-11.3 \leq \Delta\kappa \leq 10.9$. Note that their $\kappa = 1-\Delta\kappa$.

[40] GRIFOLS 88 uses deviation from ρ parameter to set limit $\Delta\kappa \lesssim 65$ (M^2_W/Λ^2).

[41] GROTCH 87 finds the limit $-37 < \Delta\kappa < 73.5$ (90% CL) from the experimental limits on $e^+e^- \to \nu\overline{\nu}\gamma$ assuming three neutrino generations and $-19.5 < \Delta\kappa < 56$ for four generations. Note their $\Delta\kappa$ has the opposite sign as our definition.

[42] VANDERBIJ 87 uses existing limits to the photon structure to obtain $|\Delta\kappa| < 33$ (m_W/Λ). In addition VANDERBIJ 87 discusses problems with using the ρ parameter of the Standard Model to determine $\Delta\kappa$.

[43] GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole (λ) moments $1.05 > \Delta\kappa\ \ln(\Lambda/m_W) + \lambda/2 > -2.77$. In the Standard Model $\lambda = 0$.

[44] SUZUKI 85 uses partial-wave unitarity at high energies to obtain $|\Delta\kappa| \lesssim 190$ $(m_W/\Lambda)^2$. From the anomalous magnetic moment of the muon, SUZUKI 85 obtains $|\Delta\kappa| \lesssim 2.2/\ln(\Lambda/m_W)$. Finally SUZUKI 85 uses deviations from the ρ parameter and obtains a very qualitative, order-of-magnitude limit $|\Delta\kappa| \lesssim 150$ $(m_W/\Lambda)^4$ if $|\Delta\kappa| \ll 1$.

[45] HERZOG 84 consider the contribution of W-boson to muon magnetic moment including anomalous coupling of $WW\gamma$. Obtain a limit $-1 < \Delta\kappa < 3$ for $\Lambda \gtrsim 1$ TeV.

W^+ DECAY MODES

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

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$\ell^+\nu$	[a]	(10.74 ± 0.33) %	
Γ_2	$e^+\nu$		$(10.9\ \pm0.4\ )$ %	
Γ_3	$\mu^+\nu$		$(10.2\ \pm0.5\ )$ %	
Γ_4	$\tau^+\nu$		$(11.3\ \pm0.8\ )$ %	
Γ_5	hadrons		$(67.8\ \pm1.0\ )$ %	
Γ_6	$\pi^+\gamma$		$< 2.2 \times 10^{-4}$	95%

[a] ℓ indicates each type of lepton (e, μ, and τ), not sum over them.

CONSTRAINED FIT INFORMATION

Overall fits are performed to determine the branching ratios of the W. For each LEP experiment the correlation matrix of the leptonic branching ratios is used. A first fit determines three individual leptonic branching ratios, B($W \to e\nu_e$), B($W \to \mu\nu_\mu$), and B($W \to \tau\nu_\tau$). This fit has a χ^2 = 9.0 for 17 degrees of freedom. The second fit assumes lepton universality and determines the leptonic branching ratio B($W \to \ell\nu_\ell$), from which one also derives the hadronic branching ratio, assuming B($W \to$ hadrons) = 1–3·B($W \to \ell\nu_\ell$). This fit has a χ^2 = 10.9 for 19 degrees of freedom.

W BRANCHING RATIOS

The LEP collaborations obtain the W branching ratios by a fit to their measured cross sections of the final states $e^+e^- \to W^+W^- \to q\overline{q}e\nu_e$, $q\overline{q}\mu\nu_\mu$, $q\overline{q}\tau\nu_\tau$, $q\overline{q}q\overline{q}$, $\ell\nu_\ell\ell\nu_\ell$. The leptonic branching ratios and $\sigma(e^+e^- \to W^+W^-)$ at the respective center-of-mass energies are the fitted parameters. Two fits are performed, one without and one assuming lepton universality. The hadronic branching ratio is derived from the second fit assuming B($W \to$ hadrons) = 1–3 · B($W \to \ell\nu_\ell$).

$\Gamma(\ell^+\nu)/\Gamma_{\text{total}}$ — Γ_1/Γ

ℓ indicates average over e, μ, and τ modes, not sum over modes.

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.1074±0.0033 OUR FIT						
0.108 ±0.005 OUR AVERAGE						
0.113 ±0.012 ±0.003	avg	52	ABREU	98B	DLPH	E^{ee}_{cm}= 161.3 + 172.14 GeV

0.101	$^{+0.011}_{-0.010}$	± 0.002	avg	61	ACKERSTAFF	98D	OPAL	$E^{ee}_{\rm cm}$= 161.3 + 172.12 GeV
0.119	$^{+0.013}_{-0.012}$	± 0.002	avg	51	ACCIARRI	97M	L3	$E^{ee}_{\rm cm}$= 161.3 + 172.13 GeV
0.104	± 0.008		avg	3642	[46] ABE	92I	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV

[46] $1216 \pm 38^{+27}_{-31}$ $W \rightarrow \mu\nu$ events from ABE 92I and 2426 $W \rightarrow e\nu$ events of ABE 91C. ABE 92I give the inverse quantity as 9.6 ± 0.7 and we have inverted.

$\Gamma(e^+\nu)/\Gamma_{\rm total}$ — Γ_2/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE				*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.109	**±0.004**	**OUR FIT**						
0.109	**±0.004**	**OUR AVERAGE**						
0.102	$^{+0.038}_{-0.032}$	± 0.003	f&a	16	ABREU	98B	DLPH	$E^{ee}_{\rm cm}$= 161.3 + 172.14 GeV
0.098	$^{+0.022}_{-0.020}$	± 0.003	f&a	21	ACKERSTAFF	98D	OPAL	$E^{ee}_{\rm cm}$= 161.3 + 172.12 GeV
0.165	$^{+0.037}_{-0.033}$	± 0.005	f&a	23	ACCIARRI	97M	L3	$E^{ee}_{\rm cm}$= 161.3 + 172.13 GeV
0.097	± 0.02	± 0.005	f&a	21	BARATE	97S	ALEP	$E^{ee}_{\rm cm}$= 161.3 + 172.09 GeV
0.1094	± 0.0033	± 0.0031	f&a		[47] ABE	95W	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
0.10	± 0.014	$^{+0.02}_{-0.03}$	f&a	248	[48] ANSARI	87C	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •								
0.106	± 0.0096			2426	[49] ABE	91C	CDF	Repl. by ABE 94B
seen				299	[50] ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
seen				119	APPEL	86	UA2	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
seen				172	ARNISON	86	UA1	Repl. by ALBAJAR 89

[47] ABE 95W result is from a measurement of $\sigma B(W \rightarrow e\nu)/\sigma B(Z \rightarrow e^+e^-) = 10.90 \pm 0.32 \pm 0.29$, the theoretical prediction for the cross section ratio, the experimental knowledge of $\Gamma(Z \rightarrow e^+e^-) = 83.98 \pm 0.18$ MeV, and $\Gamma(Z) = 2.4969 \pm 0.0038$.

[48] The first error was obtained by adding the statistical and systematic experimental uncertainties in quadrature. The second error reflects the dependence on theoretical prediction of total W cross section: $\sigma(546\ \text{GeV}) = 4.7^{+1.4}_{-0.7}$ nb and $\sigma(630\ \text{GeV}) = 5.8^{+1.8}_{-1.0}$ nb. See ALTARELLI 85B.

[49] ABE 91C result is from a measurement of $\sigma B(W \rightarrow e\nu)/\sigma B(Z \rightarrow e^+e^-)$, the theoretical prediction for the cross section ratio, and the experimental knowledge of $\Gamma(Z \rightarrow e^+e^-)/\Gamma(Z \rightarrow \text{all})$.

[50] ALBAJAR 89 experiment determines values of branching ratio times production cross section.

$\Gamma(\mu^+\nu)/\Gamma_{total}$ — Γ_3/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		EVTS	DOCUMENT ID		TECN	COMMENT
0.102±0.005 OUR FIT						
0.097±0.007 OUR AVERAGE						
$0.107^{+0.032}_{-0.027}\pm0.003$	f&a	20	ABREU	98B	DLPH	E^{ee}_{cm}= 161.3 + 172.14 GeV
$0.073^{+0.019}_{-0.017}\pm0.002$	f&a	16	ACKERSTAFF	98D	OPAL	E^{ee}_{cm}= 161.3 + 172.12 GeV
$0.084^{+0.028}_{-0.024}\pm0.003$	f&a	13	ACCIARRI	97M	L3	E^{ee}_{cm}= 161.3 + 172.13 GeV
$0.112\pm0.02\pm0.006$	f&a	25	BARATE	97S	ALEP	E^{ee}_{cm}= 161.3 + 172.09 GeV
0.10 ± 0.01	f&a	1216	[51] ABE	92I	CDF	$E^{p\overline{p}}_{cm}$= 1.8 TeV

[51] ABE 92I quote the inverse quantity as 9.9 ± 1.2 which we have inverted.

$\Gamma(\tau^+\nu)/\Gamma_{total}$ — Γ_4/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		EVTS	DOCUMENT ID		TECN	COMMENT
0.113±0.008 OUR FIT						
0.124±0.017 OUR AVERAGE						
$0.134^{+0.050}_{-0.048}\pm0.007$	f&a	16	ABREU	98B	DLPH	E^{ee}_{cm}= 161.3 + 172.14 GeV
$0.140^{+0.030}_{-0.028}\pm0.005$	f&a	23	ACKERSTAFF	98D	OPAL	E^{ee}_{cm}= 161.3 + 172.12 GeV
$0.109^{+0.042}_{-0.039}\pm0.005$	f&a	15	ACCIARRI	97M	L3	E^{ee}_{cm}= 161.3 + 172.13 GeV
$0.113\pm0.027\pm0.006$	f&a	37	BARATE	97S	ALEP	E^{ee}_{cm}= 161.3 + 172.09 GeV

$\Gamma(\text{hadrons})/\Gamma_{total}$ — Γ_5/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		EVTS	DOCUMENT ID		TECN	COMMENT
0.678±0.010 OUR FIT						
0.672±0.017 OUR AVERAGE						
$0.660^{+0.036}_{-0.037}\pm0.009$	avg	57	ABREU	98B	DLPH	E^{ee}_{cm}= 161.3 + 172.14 GeV
$0.698^{+0.030}_{-0.032}\pm0.007$	avg	52	ACKERSTAFF	98D	OPAL	E^{ee}_{cm}= 161.3 + 172.12 GeV
$0.642^{+0.037}_{-0.038}\pm0.005$	avg	70	ACCIARRI	97M	L3	E^{ee}_{cm}= 161.3 + 172.13 GeV
$0.677\pm0.031\pm0.007$	avg	65	BARATE	97S	ALEP	E^{ee}_{cm}= 161.3 + 172.09 GeV

$\Gamma(\mu^+\nu)/\Gamma(e^+\nu)$ Γ_3/Γ_2

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.94±0.05 OUR FIT						
0.97±0.06 OUR AVERAGE						
0.89±0.10	f&a	13k	[52] ABACHI	95D	D0	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
1.02±0.08	f&a	1216	[53] ABE	92I	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.00±0.14±0.08		67	ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
$1.24^{+0.6}_{-0.4}$		14	ARNISON	84D	UA1	Repl. by ALBAJAR 89

[52] ABACHI 95D obtain this result from the measured σ_WB($W \rightarrow \mu\nu$)= 2.09 ± 0.23 ± 0.11 nb and σ_WB($W \rightarrow e\nu$)= 2.36 ± 0.07 ± 0.13 nb in which the first error is the combined statistical and systematic uncertainty, the second reflects the uncertainty in the luminosity.
[53] ABE 92I obtain σ_WB($W \rightarrow \mu\nu$)= 2.21 ± 0.07 ± 0.21 and combine with ABE 91C σ_W B(($W \rightarrow e\nu$)) to give a ratio of the couplings from which we derive this measurement.

$\Gamma(\tau^+\nu)/\Gamma(e^+\nu)$ Γ_4/Γ_2

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.03 ±0.07 OUR FIT						
1.00 ±0.08 OUR AVERAGE						
0.94 ±0.14	f&a	179	[54] ABE	92E	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
1.04 ±0.08 ±0.08	f&a	754	[55] ALITTI	92F	UA2	$E^{p\overline{p}}_{\rm cm}$= 630 GeV
1.02 ±0.20 ±0.12	f&a	32	ALBAJAR	89	UA1	$E^{p\overline{p}}_{\rm cm}$= 546,630 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.995±0.112±0.083		198	ALITTI	91C	UA2	Repl. by ALITTI 92F
1.02 ±0.20 ±0.10		32	ALBAJAR	87	UA1	Repl. by ALBAJAR 89

[54] ABE 92E use two procedures for selecting $W \rightarrow \tau\nu_\tau$ events. The missing E$_T$ trigger leads to 132 ± 14 ± 8 events and the τ trigger to 47 ± 9 ± 4 events. Proper statistical and systematic correlations are taken into account to arrive at σB($W \rightarrow \tau\nu$) = 2.05 ± 0.27 nb. Combined with ABE 91C result on σB($W \rightarrow e\nu$), ABE 92E quote a ratio of the couplings from which we derive this measurement.
[55] This measurement is derived by us from the ratio of the couplings of ALITTI 92F.

$\Gamma(\pi^+\gamma)/\Gamma(e^+\nu)$ Γ_6/Γ_2

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 2.0 × 10^{-3}	95	ABE	96I	CDF	$E^{p\overline{p}}_{\rm cm}$= 1.8 TeV
< 4.9 × 10^{-3}	95	[56] ALITTI	92D	UA2	$E^{p\overline{p}}_{\rm cm}$= 630 GeV
<58 × 10^{-3}	95	[57] ALBAJAR	90	UA1	$E^{p\overline{p}}_{\rm cm}$= 546, 630 GeV

[56] ALITTI 92D limit is 3.8 × 10^{-3} at 90%CL.
[57] ALBAJAR 90 obtain < 0.048 at 90%CL.

W REFERENCES

ABREU	98B	EPJ C1 (accepted)	P. Abreu+	(DELPHI Collab.)
CERN-PPE/97-160				
ACKERSTAFF	98D	EPJ C1 395	K. Ackerstaff+	(OPAL Collab.)
BARATE	98B	PL B422 384	R. Barate+	(ALEPH Collab.)
ABACHI	97B	PRL 78 3634	S. Abachi+	(D0 Collab.)
ABREU	97	PL B397 158	+Adam, Adye, Adzic+	(DELPHI Collab.)
ACCIARRI	97	PL B398 223	+Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACCIARRI	97M	PL B407 419	M. Acciarri+	(L3 Collab.)
ACCIARRI	97S	PL B413 176	M. Acciarri+	(L3 Collab.)
BARATE	97	PL B401 347	+Buskulic, Decamp, Ghez+	(ALEPH Collab.)
BARATE	97S	PL B415 435	R. Barate+	(ALEPH Collab.)
ABACHI	96E	PRL 77 3309	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABE	96I	PRL 76 2852	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ACKERSTAFF	96B	PL B389 416	+Alexander, Allison, Altekamp+	(OPAL Collab.)
AID	96D	PL B379 319	+Andreev, Andrieu, Appuhn+	(H1 Collab.)
ABACHI	95D	PRL 75 1456	+Abbott, Abolins, Acharya+	(D0 Collab.)
ABE	95C	PRL 74 341	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95G	PRL 74 1936	+Albrow, Amidei, Antos+	(CDF Collab.)
ABE	95P	PRL 75 11	+Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
Also	95Q	PR D52 4784	Abe, Albrow, Amidei, Antos, Anway-Wiese+	(CDF Collab.)
ABE	95W	PR D52 2624	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
Also	94B	PRL 73 220	Abe, Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ABE	94B	PRL 73 220	+Albrow, Amidei, Anway-Wiese+	(CDF Collab.)
ROSNER	94	PR D49 1363	+Worah, Takeuchi	(EFI, FNAL)
ABE	92E	PRL 68 3398	+Amidei, Apollinari, Atac+	(CDF Collab.)
ABE	92I	PRL 69 28	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALITTI	92	PL B276 365	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92B	PL B276 354	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92C	PL B277 194	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92D	PL B277 203	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
ALITTI	92F	PL B280 137	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
SAMUEL	92	PL B280 124	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
ABE	91C	PR D44 29	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	91	PL B253 503	+Albrow, Allkofer, Ankoviak, Apsimon+	(UA1 Collab.)
ALITTI	91C	ZPHY C52 209	+Ambrosini, Ansari, Autiero+	(UA2 Collab.)
SAMUEL	91	PRL 67 9	+Li, Sinha, Sinha, Sundaresan	(OKSU, CARL)
Also	91C	PRL 67 2920 erratum		
ABE	90	PRL 64 152	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
Also	91C	PR D44 29	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	90G	PRL 65 2243	+Amidei, Apollinari, Atac+	(CDF Collab.)
Also	91B	PR D43 2070	Abe, Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ALBAJAR	90	PL B241 283	+Albrow, Allkofer+	(UA1 Collab.)
ALITTI	90B	PL B241 150	+Ansari, Ansorge, Autiero+	(UA2 Collab.)
ALITTI	90C	ZPHY C47 11	+Ansari, Ansorge, Bagnaia+	(UA2 Collab.)
ABE	89I	PRL 62 1005	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BAUR	88	NP B308 127	+Zeppenfeld	(FSU, WISC)
GRIFOLS	88	IJMP A3 225	+Peris, Sola	(BARC, DESY)
Also	87	PL B197 437	Grifols, Peris, Sola	(BARC, DESY)
ALBAJAR	87	PL B185 233	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
ANSARI	87	PL B186 440	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ANSARI	87C	PL B194 158	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
GROTCH	87	PR D36 2153	+Robinett	(PSU)
HAGIWARA	87	NP B282 253	+Peccei, Zeppenfeld, Hikasa	(KEK, UCLA, FSU)
VANDERBIJ	87	PR D35 1088	van der Bij	(FNAL)
APPEL	86	ZPHY C30 1	+Bagnaia, Banner, Battiston+	(UA2 Collab.)
ARNISON	86	PL 166B 484	+Albrow, Allkofer, Astbury+	(UA1 Collab.) J
ALTARELLI	85B	ZPHY C27 617	+Ellis, Martinelli	(CERN, FNAL, FRAS)
GRAU	85	PL 154B 283	+Grifols	(BARC)
SUZUKI	85	PL 153B 289		(LBL)
ARNISON	84D	PL 134B 469	+Astbury, Aubert, Bacci+	(UA1 Collab.)
HERZOG	84	PL 148B 355		(WISC)
Also	84B	PL 155B 468 erratum	Herzog	(WISC)
ARNISON	83	PL 122B 103	+Astbury, Aubert, Bacci+	(UA1 Collab.)
BANNER	83B	PL 122B 476	+Battiston, Bloch, Bonaudi+	(UA2 Collab.)