Quark and Lepton Compositeness, Searches for

SEARCHES FOR QUARK AND LEPTON COMPOSITENESS

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If quarks and leptons are made of constituents, then at the scale of constituent binding energies, there should appear new interactions among quarks and leptons. At energies much below the compositeness scale (Λ), these interactions are suppressed by inverse powers of Λ. The dominant effect should come from the lowest dimensional interactions with four fermions (contact terms), whose most general chirally invariant form reads [1]

$$L = \frac{g^2}{2\Lambda^2}\Big[\eta_{LL}\,\overline{\psi}_L\,\gamma_\mu\,\psi_L\,\overline{\psi}_L\,\gamma^\mu\,\psi_L + \eta_{RR}\,\overline{\psi}_R\,\gamma_\mu\,\psi_R\,\overline{\psi}_R\,\gamma^\mu\,\psi_R + 2\eta_{LR}\,\overline{\psi}_L\,\gamma_\mu\,\psi_L\,\overline{\psi}_R\,\gamma^\mu\,\psi_R\Big]\ . \qquad (1)$$

Chiral invariance provides a natural explanation why quark and lepton masses are much smaller than their inverse size Λ. We may determine the scale Λ unambiguously by using the above form of the effective interactions; the conventional method [1] is to fix its scale by setting $g^2/4\pi = g^2(\Lambda)/4\pi = 1$ for the new strong interaction coupling and by setting the largest magnitude of the coefficients $\eta_{\alpha\beta}$ to be unity. In the following, we denote

$$\begin{aligned}
\Lambda &= \Lambda^{\pm}_{LL} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm 1, 0, 0)\ ,\\
\Lambda &= \Lambda^{\pm}_{RR} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (0, \pm 1, 0)\ ,\\
\Lambda &= \Lambda^{\pm}_{VV} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm 1, \pm 1, \pm 1)\ ,\\
\Lambda &= \Lambda^{\pm}_{AA} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm 1, \pm 1, \mp 1)\ , \qquad (2)
\end{aligned}$$

as typical examples. Such interactions can arise by constituent interchange (when the fermions have common constituents, e.g., for $ee \to ee$) and/or by exchange of the binding quanta (whenever binding quanta couple to constituents of both particles).

Another typical consequence of compositeness is the appearance of excited leptons and quarks (ℓ^* and q^*). Phenomenologically, an excited lepton is defined to be a heavy lepton which shares leptonic quantum number with one of the existing leptons (an excited quark is defined similarly). For example, an excited electron e^* is characterized by a nonzero transition-magnetic coupling with electrons. Smallness of the lepton mass and the success of QED prediction for g–2 suggest chirality conservation, *i.e.*, an excited lepton should not couple to both left- and right-handed components of the corresponding lepton.

Excited leptons may be classified by SU(2)×U(1) quantum numbers. Typical examples are:

1. Sequential type

$$\begin{pmatrix} \nu^* \\ \ell^* \end{pmatrix}_L , \qquad [\nu^*_R] , \qquad \ell^*_R .$$

   ν^*_R is necessary unless ν^* has a Majorana mass.

2. Mirror type

$$[\nu^*_L] , \qquad \ell^*_L , \qquad \begin{pmatrix} \nu^* \\ \ell^* \end{pmatrix}_R .$$

3. Homodoublet type

$$\begin{pmatrix} \nu^* \\ \ell^* \end{pmatrix}_L , \qquad \begin{pmatrix} \nu^* \\ \ell^* \end{pmatrix}_R .$$

Similar classification can be made for excited quarks.

Excited fermions can be pair produced via their gauge couplings. The couplings of excited leptons with Z are listed

	Sequential type	Mirror type	Homodoublet type
V^{ℓ^*}	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}+2\sin^2\theta_W$	$-1+2\sin^2\theta_W$
A^{ℓ^*}	$-\frac{1}{2}$	$+\frac{1}{2}$	0
$V^{\nu^*_D}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$+1$
$A^{\nu^*_D}$	$+\frac{1}{2}$	$-\frac{1}{2}$	0
$V^{\nu^*_M}$	0	0	—
$A^{\nu^*_M}$	$+1$	-1	—

in the following table (for notation see Eq. (1) in "Standard Model of Electroweak Interactions"):

Here ν^*_D (ν^*_M) stands for Dirac (Majorana) excited neutrino. The corresponding couplings of excited quarks can be easily obtained. Although form factor effects can be present for the gauge couplings at $q^2 \neq 0$, they are usually neglected.

In addition, transition magnetic type couplings with a gauge boson are expected. These couplings can be generally parametrized as follows:

$$\begin{aligned}
\mathcal{L} = {} & \frac{\lambda_\gamma^{(f^*)} e}{2m_{f^*}}\,\overline{f}^*\sigma^{\mu\nu}(\eta_L\tfrac{1-\gamma_5}{2}+\eta_R\tfrac{1+\gamma_5}{2}) f F_{\mu\nu} \\
& + \frac{\lambda_Z^{(f^*)} e}{2m_{f^*}}\,\overline{f}^*\sigma^{\mu\nu}(\eta_L\tfrac{1-\gamma_5}{2}+\eta_R\tfrac{1+\gamma_5}{2}) f Z_{\mu\nu} \\
& + \frac{\lambda_W^{(\ell^*)} g}{2m_{\ell^*}}\,\overline{\ell}^*\sigma^{\mu\nu}\tfrac{1-\gamma_5}{2}\nu W_{\mu\nu} \\
& + \frac{\lambda_W^{(\nu^*)} g}{2m_{\nu^*}}\,\overline{\nu}^*\sigma^{\mu\nu}(\eta_L\tfrac{1-\gamma_5}{2}+\eta_R\tfrac{1+\gamma_5}{2})\ell\, W^\dagger_{\mu\nu} \\
& + \text{h.c.}\,,
\end{aligned} \tag{3}$$

where $g = e/\sin\theta_W$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the photon field strength, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$, *etc.* The normalization of the coupling is chosen such that

$$\max(|\eta_L|, |\eta_R|) = 1 \; .$$

Chirality conservation requires

$$\eta_L \eta_R = 0 \; . \tag{4}$$

These couplings can arise from SU(2)×U(1)-invariant higher-dimensional interactions. A well-studied model is the interaction of homodoublet type ℓ^* with the Lagrangian [2,3]

$$\mathcal{L} = \frac{1}{2\Lambda}\overline{L}^* (g f \tfrac{\tau^a}{2} W^a_{\mu\nu} + g' f' Y B_{\mu\nu}) \tfrac{1-\gamma_5}{2} L + \text{h.c.} \; , \tag{5}$$

where L denotes the lepton doublet (ν, ℓ), Λ is the compositeness scale, g, g' are SU(2) and U(1)$_Y$ gauge couplings, and $W^a_{\mu\nu}$ and $B_{\mu\nu}$ are the field strengths for SU(2) and U(1)$_Y$ gauge fields. The same interaction occurs for mirror-type excited leptons. For sequential-type excited leptons, the ℓ^* and ν^* couplings become unrelated, and the couplings receive the extra suppression of $(250\,\text{GeV})/\Lambda$ or m_{L^*}/Λ. In any case, these couplings satisfy the relation

$$\lambda_W = -\sqrt{2}\sin^2\theta_W (\lambda_Z \cot\theta_W + \lambda_\gamma) \; . \tag{6}$$

Additional coupling with gluons is possible for excited quarks:

$$\mathcal{L} = \frac{1}{2\Lambda}\overline{Q}^* \sigma^{\mu\nu} \left(g_s f_s \tfrac{\lambda^a}{2} G^a_{\mu\nu} + g\, f \tfrac{\tau^a}{2} W^a_{\mu\nu} + g'\, f' Y B_{\mu\nu} \right) \times \tfrac{1-\gamma_5}{2} Q + \text{h.c.} \; , \tag{7}$$

where Q denotes a quark doublet, g_s is the QCD gauge coupling, and $G^a_{\mu\nu}$ the gluon field strength.

Some experimental analyses assume the relation $\eta_L = \eta_R = 1$, which violates chiral symmetry. We encode the results of such analyses if the crucial part of the cross section is proportional to the factor $\eta_L^2 + \eta_R^2$ and the limits can be reinterpreted as those for chirality conserving cases $(\eta_L, \eta_R) = (1,0)$ or $(0,1)$ after rescaling λ.

Several different conventions are used by LEP experiments to express the transition magnetic couplings. To facilitate comparison, we reexpress these in terms of λ_Z and λ_γ using the following relations and taking $\sin^2\theta_W = 0.23$. We assume chiral couplings, *i.e.*, $|c| = |d|$ in the notation of Ref. 2.

1. ALEPH (charged lepton and neutrino)

$$\lambda_Z^{\rm ALEPH} = \frac{1}{2}\lambda_Z \quad \text{(1990 papers)} \tag{8a}$$

$$\frac{2c}{\Lambda} = \frac{\lambda_Z}{m_{\ell^*}[\text{or } m_{\nu^*}]} \quad (\text{for } |c| = |d|) \tag{8b}$$

2. ALEPH (quark)

$$\lambda_u^{\rm ALEPH} = \frac{\sin\theta_W \cos\theta_W}{\sqrt{\frac{1}{4} - \frac{2}{3}\sin^2\theta_W + \frac{8}{9}\sin^4\theta_W}}\,\lambda_Z = 1.11\lambda_Z \tag{9}$$

3. L3 and DELPHI (charged lepton)

$$\lambda^{\rm L3} = \lambda_Z^{\rm DELPHI} = -\frac{\sqrt{2}}{\cot\theta_W - \tan\theta_W}\,\lambda_Z = -1.10\lambda_Z \tag{10}$$

4. L3 (neutrino)

$$f_Z^{\rm L3} = \sqrt{2}\lambda_Z \tag{11}$$

5. OPAL (charged lepton)

$$\frac{f^{\rm OPAL}}{\Lambda} = -\frac{2}{\cot\theta_W - \tan\theta_W}\,\frac{\lambda_Z}{m_{\ell^*}} = -1.56\,\frac{\lambda_Z}{m_{\ell^*}} \tag{12}$$

6. OPAL (quark)

$$\frac{f^{\rm OPAL}c}{\Lambda} = \frac{\lambda_Z}{2m_{q^*}} \quad (\text{for } |c| = |d|) \tag{13}$$

7. DELPHI (charged lepton)

$$\lambda_\gamma^{\rm DELPHI} = -\frac{1}{\sqrt{2}}\,\lambda_\gamma \tag{14}$$

If leptons are made of color triplet and antitriplet constituents, we may expect their color-octet partners. Transitions between the octet leptons (ℓ_8) and the ordinary lepton (ℓ) may take place via the dimension-five interactions

$$\mathcal{L} = \frac{1}{2\Lambda}\sum_\ell \left\{ \overline{\ell}_8^\alpha\, g_S\, F^\alpha_{\mu\nu}\, \sigma^{\mu\nu} \left(\eta_L\, \ell_L + \eta_R\, \ell_R\right) + h.c.\right\} \tag{15}$$

where the summation is over charged leptons and neutrinos. The leptonic chiral invariance implies $\eta_L\,\eta_R = 0$ as before.

References

1. E.J. Eichten, K.D. Lane, and M.E. Peskin, Phys. Rev. Lett. **50**, 811 (1983).
2. K. Hagiwara, S. Komamiya, and D. Zeppenfeld, Z. Phys. **C29**, 115 (1985).
3. N. Cabibbo, L. Maiani, and Y. Srivastava, Phys. Lett. **139B**, 459 (1984).

SCALE LIMITS for Contact Interactions: $\Lambda(eeee)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL} (TeV)	Λ^-_{LL} (TeV)	CL%		DOCUMENT ID		TECN	COMMENT
> 2.4	>2.2	95		ACKERSTAFF	97C	OPAL	$E_{\rm cm}$= 130–136, 161 GeV
	>3.6	95	1	KROHA	92	RVUE	

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

>1.7	>2.3	95	[2]	ARIMA	97	VNS	E_{cm}= 57.77 GeV
>1.6	>2.0	95	[3]	BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>1.6		95	[3,4]	BUSKULIC	93Q	RVUE	
	>2.2	95		BUSKULIC	93Q	RVUE	
>1.3		95	[1]	KROHA	92	RVUE	
>0.7	>2.8	95		BEHREND	91C	CELL	E_{cm}=35 GeV
>1.3	>1.3	95		KIM	89	AMY	E_{cm}=50–57 GeV
>1.4	>3.3	95	[5]	BRAUNSCH...	88	TASS	E_{cm}=12–46.8 GeV
>1.0	>0.7	95	[6]	FERNANDEZ	87B	MAC	E_{cm}=29 GeV
>1.1	>1.4	95	[7]	BARTEL	86C	JADE	E_{cm}=12–46.8 GeV
>1.17	>0.87	95	[8]	DERRICK	86	HRS	E_{cm}=29 GeV
>1.1	>0.76	95	[9]	BERGER	85B	PLUT	E_{cm}=34.7 GeV

[1] KROHA 92 limit is from fit to BERGER 85B, BARTEL 86C, DERRICK 86B, FERNANDEZ 87B, BRAUNSCHWEIG 88, BEHREND 91B, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = +0.230 \pm 0.206$ TeV^{-2}.

[2] Z-Z' mixing is assumed to be zero.

[3] BUSKULIC 93Q uses the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[4] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[5] BRAUNSCHWEIG 88 assumed $m_Z = 92$ GeV and $\sin^2\theta_W = 0.23$.

[6] FERNANDEZ 87B assumed $\sin^2\theta_W = 0.22$.

[7] BARTEL 86C assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

[8] DERRICK 86 assumed $m_Z = 93$ GeV and $g_V^2 = (-1/2+2\sin^2\theta_W)^2 = 0.004$.

[9] BERGER 85B assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\mu\mu)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%		DOCUMENT ID		TECN	COMMENT
>2.4	**> 2.9**	95		ACKERSTAFF	97C	OPAL	E_{cm}= 130–136, 161 GeV
> 2.6	>1.9	95	[10,11]	BUSKULIC	93Q	RVUE	

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

>1.7	>2.2	95	[11]	VELISSARIS	94	AMY	E_{cm}=57.8 GeV
>1.3	>1.5	95	[11]	BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>2.3	>2.0	95		HOWELL	92	TOPZ	E_{cm}=52–61.4 GeV
	>1.7	95	[12]	KROHA	92	RVUE	
>2.5	>1.5	95		BEHREND	91C	CELL	E_{cm}=35–43 GeV
>1.6	>2.0	95	[13]	ABE	90I	VNS	E_{cm}=50–60.8 GeV
>1.9	>1.0	95		KIM	89	AMY	E_{cm}=50–57 GeV
>2.3	>1.3	95		BRAUNSCH...	88D	TASS	E_{cm}=30–46.8 GeV
>4.4	>2.1	95	[14]	BARTEL	86C	JADE	E_{cm}=12–46.8 GeV
>2.9	>0.86	95	[15]	BERGER	85	PLUT	E_{cm}=34.7 GeV

[10] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data reanalyzed by KROHA 92.

[11] BUSKULIC 93Q and VELISSARIS 94 use the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[12] KROHA 92 limit is from fit to BARTEL 86C, BEHREND 87C, BRAUNSCHWEIG 88D, BRAUNSCHWEIG 89C, ABE 90I, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = -0.155 \pm 0.095\ \text{TeV}^{-2}$.

[13] ABE 90I assumed m_Z =91.163 GeV and $\sin^2\theta_W = 0.231$.

[14] BARTEL 86C assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

[15] BERGER 85 assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(ee\tau\tau)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.9	**>3.0**	95	ACKERSTAFF	97C	OPAL	E_{cm}= 130–136, 161 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.4	>2.0	95	[16] VELISSARIS	94	AMY	E_{cm}=57.8 GeV
>1.0	>1.5	95	[16] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>1.8	>2.3	95	[16,17] BUSKULIC	93Q	RVUE	
>1.9	>1.7	95	HOWELL	92	TOPZ	E_{cm}=52–61.4 GeV
>1.9	>2.9	95	[18] KROHA	92	RVUE	
>1.6	>2.3	95	BEHREND	91C	CELL	E_{cm}=35–43 GeV
>1.8	>1.3	95	[19] ABE	90I	VNS	E_{cm}=50–60.8 GeV
>2.2	>3.2	95	[20] BARTEL	86	JADE	E_{cm}=12–46.8 GeV

[16] BUSKULIC 93Q and VELISSARIS 94 use the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.

[17] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data re-analyzed by KROHA 92.

[18] KROHA 92 limit is from fit to BARTEL 86C BEHREND 89B, BRAUNSCHWEIG 89C, ABE 90I, and BEHREND 91C. The fit gives $\eta/\Lambda^2_{LL} = +0.095 \pm 0.120\ \text{TeV}^{-2}$.

[19] ABE 90I assumed m_Z =91.163 GeV and $\sin^2\theta_W = 0.231$.

[20] BARTEL 86 assumed $m_Z = 93$ GeV and $\sin^2\theta_W = 0.217$.

SCALE LIMITS for Contact Interactions: $\Lambda(\ell\ell\ell\ell)$

Lepton universality assumed. Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2.7	**> 3.8**	95	ACKERSTAFF	97C	OPAL	E_{cm}= 130–136, 161 GeV
> 3.5	>2.8	95	[21,22] BUSKULIC	93Q	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>3.0	>2.3	95	[22,23] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>2.5	>2.2	95	[24] HOWELL	92	TOPZ	E_{cm}=52–61.4 GeV
>3.4	>2.7	95	[25] KROHA	92	RVUE	

[21] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data re-analyzed by KROHA 92.

[22] BUSKULIC 93Q uses the following prescription to obtain the limit: when the naive 95%CL limit is better than the statistically expected sensitivity for the limit, the latter is adopted for the limit.
[23] From $e^+ e^- \rightarrow e^+ e^-$, $\mu^+ \mu^-$, and $\tau^+ \tau^-$.
[24] HOWELL 92 limit is from $e^+ e^- \rightarrow \mu^+ \mu^-$ and $\tau^+ \tau^-$.
[25] KROHA 92 limit is from fit to most PEP/PETRA/TRISTAN data. The fit gives $\eta/\Lambda^2_{LL} = -0.0200 \pm 0.0666$ TeV^{-2}.

SCALE LIMITS for Contact Interactions: $\Lambda(eeqq)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2.5	**>3.7**	95	[26] ABE	97T	CDF	$(eeqq)$ (isosinglet)
>3.1	**>2.9**	95	[27] ACKERSTAFF	97C	OPAL	$(eebb)$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>2.5	>2.1	95	[28] ACKERSTAFF	97C	OPAL	$(eeqq)$
>7.4	>11.7	95	[29] DEANDREA	97	RVUE	$eeuu$, atomic parity violation
>2.3	>1.0	95	[30] AID	95	H1	$(eeqq)$ (u, d quarks)
1.7	>2.2	95	[31] ABE	91D	CDF	$(eeqq)$ (u, d quarks)
>1.2		95	[32] ADACHI	91	TOPZ	$(eeqq)$ (flavor-universal)
	>1.6	95	[32] ADACHI	91	TOPZ	$(eeqq)$ (flavor-universal)
>0.6	>1.7	95	[33] BEHREND	91C	CELL	$(eecc)$
>1.1	>1.0	95	[33] BEHREND	91C	CELL	$(eebb)$
>0.9		95	[34] ABE	89L	VNS	$(eeqq)$ (flavor-universal)
	>1.7	95	[34] ABE	89L	VNS	$(eeqq)$ (flavor-universal)
>1.05	>1.61	95	[35] HAGIWARA	89	RVUE	$(eecc)$
>1.21	>0.53	95	[36] HAGIWARA	89	RVUE	$(eebb)$

[26] ABE 97T limits are from $e^+ e^-$ mass distribution in $\overline{p}p \rightarrow e^+ e^- X$ at E_{cm}=1.8 TeV.
[27] ACKERSTAFF 97C limits are R_b measurements at E_{cm} = 133 GeV and 161 GeV.
[28] ACKERSTAFF 97C limits are from $e^+ e^- \rightarrow q\overline{q}$ cross section at E_{cm} = 130–136 GeV and 161 GeV.
[29] DEANDREA 97 limit is from atomic parity violation of cesium. The limit is eluded if the contact interactions are parity conserving.
[30] AID 95 limits are from the Q^2 spectrum measurement of $ep \rightarrow eX$.
[31] ABE 91D limits are from $e^+ e^-$ mass distribution in $p\overline{p} \rightarrow e^+ e^- X$ at E_{cm} = 1.8 TeV.
[32] ADACHI 91 limits are from differential jet cross section. Universality of $\Lambda(eeqq)$ for five flavors is assumed.
[33] BEHREND 91C is from data at E_{cm} = 35–43 GeV.
[34] ABE 89L limits are from jet charge asymmetry. Universality of $\Lambda(eeqq)$ for five flavors is assumed.
[35] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurements of D/D^* mesons by ALTHOFF 83C, BARTEL 84E, and BARINGER 88.
[36] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurement of b hadrons by BARTEL 84D.

SCALE LIMITS for Contact Interactions: $\Lambda(\mu\mu q q)$

Λ^+_{LL}(TeV)	Λ^-_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2.9	>4.2	95	[37] ABE	97T	CDF	$(\mu\mu q q)$ (isosinglet)
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.4	>1.6	95	ABE	92B	CDF	$(\mu\mu q q)$ (isosinglet)

[37] ABE 97T limits are from $\mu^+\mu^-$ mass distribution in $\overline{p}p \to \mu^+\mu^- X$ at E_{cm}=1.8 TeV.

SCALE LIMITS for Contact Interactions: $\Lambda(\ell\nu\ell\nu)$

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3.10	90	[38] JODIDIO	86	SPEC	$\Lambda^{\pm}_{LR}(\nu_\mu \nu_e \mu e)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>3.8		[39] DIAZCRUZ	94	RVUE	$\Lambda^+_{LL}(\tau\nu_\tau e\nu_e)$
>8.1		[39] DIAZCRUZ	94	RVUE	$\Lambda^-_{LL}(\tau\nu_\tau e\nu_e)$
>4.1		[40] DIAZCRUZ	94	RVUE	$\Lambda^+_{LL}(\tau\nu_\tau \mu\nu_\mu)$
>6.5		[40] DIAZCRUZ	94	RVUE	$\Lambda^-_{LL}(\tau\nu_\tau \mu\nu_\mu)$

[38] JODIDIO 86 limit is from $\mu^+ \to \overline{\nu}_\mu e^+ \nu_e$. Chirality invariant interactions $L = (g^2/\Lambda^2)$ $[\eta_{LL}\ (\overline{\nu}_{\mu L}\gamma^\alpha \mu_L)\ (\overline{e}_L \gamma_\alpha \nu_{eL}) + \eta_{LR}\ (\overline{\nu}_{\mu L}\gamma^\alpha \nu_{eL})\ (\overline{e}_R \gamma_\alpha \mu_R)]$ with $g^2/4\pi = 1$ and (η_{LL},η_{LR}) = (0,±1) are taken. No limits are given for $\Lambda^{\pm}_{LL}$ with (η_{LL},η_{LR}) = (±1,0). For more general constraints with right-handed neutrinos and chirality nonconserving contact interactions, see their text.

[39] DIAZCRUZ 94 limits are from $\Gamma(\tau \to e\nu\nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau\nu_\tau e\nu_e) \ll \Lambda(\mu\nu_\mu e\nu_e)$.

[40] DIAZCRUZ 94 limits are from $\Gamma(\tau \to \mu\nu\nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau\nu_\tau \mu\nu_\mu) \ll \Lambda(\mu\nu_\mu e\nu_e)$.

SCALE LIMITS for Contact Interactions: $\Lambda(qqqq)$

Limits are for $\Lambda^{\pm}_{LL}$ with color-singlet isoscalar exchanges among u_L's and d_L's only. See EICHTEN 84 for details.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
		[41] ABE	96	CDF	$p\overline{p} \to$ jets inclusive
>1.6	95	[42] ABE	96S	CDF	$p\overline{p} \to$ dijet angl.; Λ^+_{LL}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>1.3	95	[43] ABE	93G	CDF	$p\overline{p} \to$ dijet mass
>1.4	95	[44] ABE	92D	CDF	$p\overline{p} \to$ jets inclusive
>1.0	99	[45] ABE	92M	CDF	$p\overline{p} \to$ dijet angl.
>0.825	95	[46] ALITTI	91B	UA2	$p\overline{p} \to$ jets inclusive
>0.700	95	[44] ABE	89	CDF	$p\overline{p} \to$ jets inclusive
>0.330	95	[47] ABE	89H	CDF	$p\overline{p} \to$ dijet angl.
>0.400	95	[48] ARNISON	86C	UA1	$p\overline{p} \to$ jets inclusive
>0.415	95	[49] ARNISON	86D	UA1	$p\overline{p} \to$ dijet angl.
>0.370	95	[50] APPEL	85	UA2	$p\overline{p} \to$ jets inclusive
>0.275	95	[51] BAGNAIA	84C	UA2	Repl. by APPEL 85

[41] ABE 96 finds that the inclusive jet cross section for E_T >200 GeV is significantly higher than the $\mathcal{O}(\alpha_s^3)$ perturbative QCD prediction. This could be interpreted as the effect of a contact interaction with $\Lambda_{LL} \sim 1.6$ TeV. However, ABE 96 state that uncertainty in the parton distribution functions, higher-order QCD corrections, and the detector calibration may possibly account for the effect.

[42] ABE 96S limit is from dijet angular distribution in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV. The limit for Λ^-_{LL} is > 1.4 TeV. ABE 96S also obtain limits for flavor symmetric contact interactions among all quark flavors: $\Lambda^+_{LL} > 1.8$ TeV and $\Lambda^-_{LL} > 1.6$ TeV.

[43] ABE 93G limit is from dijet mass distribution in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV. The limit is the weakest from several choices of structure functions and renormalization scale.

[44] Limit is from inclusive jet cross-section data in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[45] ABE 92M limit is from dijet angular distribution for m_{dijet} >550 GeV in $p\overline{p}$ collisions at E_{cm}=1.8 TeV.

[46] ALITTI 91B limit is from inclusive jet cross section in $p\overline{p}$ collisions at $E_{cm} = 630$ GeV. The limit takes into account uncertainties in choice of structure functions and in choice of process scale.

[47] ABE 89H limit is from dijet angular distribution for $m_{dijet} > 200$ GeV at the Fermilab Tevatron Collider with $E_{cm} = 1.8$ TeV. The QCD prediction is quite insensitive to choice of structure functions and choice of process scale.

[48] ARNISON 86C limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider ($E_{cm} = 546$ and 630 GeV). The QCD prediction renormalized to the low-p_T region gives a good fit to the data.

[49] ARNISON 86D limit is from the study of dijet angular distribution in the range $240 < m(\text{dijet}) < 300$ GeV at the CERN $\overline{p}p$ collider ($E_{cm} = 630$ GeV). QCD prediction using EHLQ structure function (EICHTEN 84) with $\Lambda_{QCD} = 0.2$ GeV for the choice of $Q^2 = {p_T}^2$ gives the best fit to the data.

[50] APPEL 85 limit is from the study of inclusive high-p_T jet distributions at the CERN $\overline{p}p$ collider ($E_{cm} = 630$ GeV). The QCD prediction renormalized to the low-p_T region gives a good description of the data.

[51] BAGNAIA 84C limit is from the study of jet p_T and dijet mass distributions at the CERN $\overline{p}p$ collider ($E_{cm} = 540$ GeV). The limit suffers from the uncertainties in comparing the data with the QCD prediction.

MASS LIMITS for Excited *e* (e^*)

Most e^+e^- experiments assume one-photon or Z exchange. The limits from some e^+e^- experiments which depend on λ have assumed transition couplings which are chirality violating ($\eta_L = \eta_R$). However they can be interpreted as limits for chirality-conserving interactions after multiplying the coupling value λ by $\sqrt{2}$; see Note.

Excited leptons have the same quantum numbers as other ortholeptons. See also the searches for ortholeptons in the "Searches for Heavy Leptons" section.

Limits for Excited *e* (e^*) from Pair Production

These limits are obtained from $e^+e^- \rightarrow e^{*+}e^{*-}$ and thus rely only on the (electroweak) charge of e^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the e^* coupling is assumed to be of sequential type. Possible t channel contribution from transition magnetic coupling is neglected. All limits assume $e^* \rightarrow e\gamma$ decay except the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	*CL%*		*DOCUMENT ID*		*TECN*	*COMMENT*
>85.0	95	[52]	ACKERSTAFF	98C	OPAL	$e^+e^- \rightarrow e^*e^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>79.6	95	[53,54]	ABREU	97B	DLPH	$e^+e^- \rightarrow e^*e^*$ Homodoublet type
>77.9	95	[53,55]	ABREU	97B	DLPH	$e^+e^- \rightarrow e^*e^*$ Sequential type
>79.7	95	[53]	ACCIARRI	97G	L3	$e^+e^- \rightarrow e^*e^*$ Sequential type
>79.9	95	[53,56]	ACKERSTAFF	97	OPAL	$e^+e^- \rightarrow e^*e^*$ Homodoublet type
>62.5	95	[57]	ABREU	96K	DLPH	$e^+e^- \rightarrow e^*e^*$ Homodoublet type
>64.7	95	[58]	ACCIARRI	96D	L3	$e^+e^- \rightarrow e^*e^*$ Sequential type
>66.5	95	[58]	ALEXANDER	96Q	OPAL	$e^+e^- \rightarrow e^*e^*$ Homodoublet type
>65.2	95	[58]	BUSKULIC	96W	ALEP	$e^+e^- \rightarrow e^*e^*$ Sequential type
>45.6	95		ADRIANI	93M	L3	$Z \rightarrow e^*e^*$
>45.6	95		ABREU	92C	DLPH	$Z \rightarrow e^*e^*$
>29.8	95	[59]	BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[60]	DECAMP	92	ALEP	$Z \rightarrow e^*e^*$; $\Gamma(Z)$
>46.1	95		DECAMP	92	ALEP	$Z \rightarrow e^*e^*$
>33	95	[60]	ABREU	91F	DLPH	$Z \rightarrow e^*e^*$; $\Gamma(Z)$
>45.0	95	[61]	ADEVA	90F	L3	$Z \rightarrow e^*e^*$
>44.9	95		AKRAWY	90I	OPAL	$Z \rightarrow e^*e^*$
>44.6	95	[62]	DECAMP	90G	ALEP	$e^+e^- \rightarrow e^*e^*$
>30.2	95		ADACHI	89B	TOPZ	$e^+e^- \rightarrow e^*e^*$
>28.3	95		KIM	89	AMY	$e^+e^- \rightarrow e^*e^*$
>27.9	95	[63]	ABE	88B	VNS	$e^+e^- \rightarrow e^*e^*$

[52] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from $e^* \rightarrow \nu W$ decay mode: $m_{e^*} > 81.3$ GeV.

[53] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[54] ABREU 97B also obtain limit from charged current decay mode $e^* \rightarrow \nu W$, $m_{e^*} > 70.9$ GeV.

[55] ABREU 97B also obtain limit from charged current decay mode $e^* \rightarrow \nu W$, $m_{e^*} > 44.6$ GeV.

[56] ACKERSTAFF 97 also obtain limit from charged current decay mode $e^* \rightarrow \nu W$, $m_{\nu_e^*} >$ 77.1 GeV.

[57] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.

[58] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.

[59] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.

[60] Limit is independent of e^* decay mode.

[61] ADEVA 90F is superseded by ADRIANI 93M.

[62] Superseded by DECAMP 92.

[63] ABE 88B limits assume $e^+e^- \rightarrow e^{*+}e^{*-}$ with one photon exchange only and $e^* \rightarrow e\gamma$ giving $ee\gamma\gamma$.

Limits for Excited *e* (e^*) from Single Production

These limits are from $e^+e^- \rightarrow e^* e$, $W \rightarrow e^* \nu$, or $ep \rightarrow e^* X$ and depend on transition magnetic coupling between e and e^*. All limits assume $e^* \rightarrow e\gamma$ decay except as noted. Limits from LEP, UA2, and H1 are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{e^*}$ plane. See the original papers.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
none 30–200	95	[64] BREITWEG	97C	ZEUS	$ep \rightarrow e^* X$
>89	95	ADRIANI	93M	L3	$Z \rightarrow ee^*$, $\lambda_Z > 0.5$
>88	95	ABREU	92C	DLPH	$Z \rightarrow ee^*$, $\lambda_Z > 0.5$
>91	95	DECAMP	92	ALEP	$Z \rightarrow ee^*$, $\lambda_Z > 1$
>87	95	AKRAWY	90I	OPAL	$Z \rightarrow ee^*$, $\lambda_Z > 0.5$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	95	[65] ACKERSTAFF	98C	OPAL	$e^+e^- \rightarrow ee^*$
		[66,67] ABREU	97B	DLPH	$e^+e^- \rightarrow ee^*$
		[66,68] ACCIARRI	97G	L3	$e^+e^- \rightarrow ee^*$
		[69] ACKERSTAFF	97	OPAL	$e^+e^- \rightarrow ee^*$
		[70] ADLOFF	97	H1	Lepton-flavor violation
		[71] ABREU	96K	DLPH	$e^+e^- \rightarrow ee^*$
		[72] ACCIARRI	96D	L3	$e^+e^- \rightarrow ee^*$
		[73] ALEXANDER	96Q	OPAL	$e^+e^- \rightarrow ee^*$
		[74] BUSKULIC	96W	ALEP	$e^+e^- \rightarrow ee^*$
		[75] DERRICK	95B	ZEUS	$ep \rightarrow e^* X$
		[76] ABT	93	H1	$ep \rightarrow e^* X$
>86	95	ADRIANI	93M	L3	$\lambda_\gamma > 0.04$
		[77] DERRICK	93B	ZEUS	Superseded by DERRICK 95B
>86	95	ABREU	92C	DLPH	$e^+e^- \rightarrow ee^*$, $\lambda_\gamma > 0.1$
>88	95	[78] ADEVA	90F	L3	$Z \rightarrow ee^*$, $\lambda_Z > 0.5$
>86	95	[78] ADEVA	90F	L3	$Z \rightarrow ee^*$, $\lambda_Z > 0.04$
>81	95	[79] DECAMP	90G	ALEP	$Z \rightarrow ee^*$, $\lambda_Z > 1$
>50	95	ADACHI	89B	TOPZ	$e^+e^- \rightarrow ee^*$, $\lambda_\gamma > 0.04$
>56	95	KIM	89	AMY	$e^+e^- \rightarrow ee^*$, $\lambda_\gamma > 0.03$
none 23–54	95	[80] ABE	88B	VNS	$e^+e^- \rightarrow ee^*$ $\lambda_\gamma > 0.04$
>75	95	[81] ANSARI	87D	UA2	$W \rightarrow e^* \nu$; $\lambda_W > 0.7$
>63	95	[81] ANSARI	87D	UA2	$W \rightarrow e^* \nu$; $\lambda_W > 0.2$
>40	95	[81] ANSARI	87D	UA2	$W \rightarrow e^* \nu$; $\lambda_W > 0.09$

[64] BREITWEG 97C search for single e^* production in ep collisions with the decays $e^* \rightarrow e\gamma$, eZ, νW. $f = -f' = 2\Lambda / m_{e^*}$ is assumed for the e^* coupling. See their Fig. 9 for the exclusion plot in the mass-coupling plane.

[65] ACKERSTAFF 98C from e^+e^- collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.

[66] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[67] See Fig. 4a and Fig. 5a of ABREU 97B for the exclusion limit in the mass-coupling plane.

[68] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.

[69] ACKERSTAFF 97 result is from $e^+ e^-$ collisions at $\sqrt{s}$= 161 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[70] ADLOFF 97 search for single e^* production in ep collisions with the decays $e^* \rightarrow e\gamma$, eZ, νW. See their Fig. 4 for the rejection limits on the product of the production cross section and the branching ratio into a specific decay channel.

[71] ABREU 96K result is from $e^+ e^-$ collisions at $\sqrt{s}$= 130–136 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.

[72] ACCIARRI 96D result is from $e^+ e^-$ collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.

[73] ALEXANDER 96Q result is from $e^+ e^-$ collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3a for the exclusion limit in the mass-coupling plane.

[74] BUSKULIC 96W result is from $e^+ e^-$ collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[75] DERRICK 95B search for single e^* production via $e^* e\gamma$ coupling in ep collisions with the decays $e^* \rightarrow e\gamma$, eZ, νW. See their Fig. 13 for the exclusion plot in the m_{e^*}–$\lambda\gamma$ plane.

[76] ABT 93 search for single e^* production via $e^* e\gamma$ coupling in ep collisions with the decays $e^* \rightarrow e\gamma$, eZ, νW. See their Fig. 4 for exclusion plot in the m_{e^*}–λ_γ plane.

[77] DERRICK 93B search for single e^* production via $e^* e\gamma$ coupling in ep collisions with the decays $e^* \rightarrow e\gamma$, eZ, νW. See their Fig. 3 for exclusion plot in the m_{e^*}–λ_γ plane.

[78] Superseded by ADRIANI 93M.

[79] Superseded by DECAMP 92.

[80] ABE 88B limits use $e^+ e^- \rightarrow e e^*$ where t-channel photon exchange dominates giving $e\gamma(e)$ (quasi-real compton scattering).

[81] ANSARI 87D is at E_{cm} = 546–630 GeV.

Limits for Excited e (e^*) from $e^+ e^- \rightarrow \gamma\gamma$

These limits are derived from indirect effects due to e^* exchange in the t channel and depend on transition magnetic coupling between e and e^*. All limits are for $\lambda_\gamma = 1$. All limits except ABE 89J are for nonchiral coupling with $\eta_L = \eta_R = 1$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>194	95	ACKERSTAFF	98	OPAL	$\sqrt{s}$=130–172 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>129	95	ACCIARRI	96L	L3	$\sqrt{s}$=133 GeV
>147	95	ALEXANDER	96K	OPAL	
>136	95	BUSKULIC	96Z	ALEP	$\sqrt{s}$=130, 136 GeV
>146	95	ACCIARRI	95G	L3	
		[82] BUSKULIC	93Q	ALEP	
>127	95	[83] ADRIANI	92B	L3	
>114	95	[84] BARDADIN-...	92	RVUE	
> 99	95	DECAMP	92	ALEP	
		[85] SHIMOZAWA	92	TOPZ	
>100	95	ABREU	91E	DLPH	
>116	95	AKRAWY	91F	OPAL	
> 83	95	ADEVA	90K	L3	
> 82	95	AKRAWY	90F	OPAL	
> 68	95	[86] ABE	89J	VNS	η_L=1, η_R=0
> 90.2	95	ADACHI	89B	TOPZ	
> 65	95	KIM	89	AMY	

[82] BUSKULIC 93Q obtain $\Lambda^+ > 121$ GeV (95%CL) from ALEPH experiment and $\Lambda^+ > 135$ GeV from combined TRISTAN and ALEPH data. These limits roughly correspond to limits on m_{e^*}.

[83] ADRIANI 92B superseded by ACCIARRI 95G.

[84] BARDADIN-OTWINOWSKA 92 limit from fit to the combined data of DECAMP 92, ABREU 91E, ADEVA 90K, AKRAWY 91F.

[85] SHIMOZAWA 92 fit the data to the limiting form of the cross section with $m_{e^*} \gg E_{cm}$ and obtain $m_{e^*} > 168$ GeV at 95%CL. Use of the full form would reduce this limit by a few GeV. The statistically unexpected large value is due to fluctuation in the data.

[86] The ABE 89J limit assumes chiral coupling. This corresponds to $\lambda_\gamma = 0.7$ for nonchiral coupling.

Indirect Limits for Excited e (e*)

These limits make use of loop effects involving e^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[87] DORENBOS...	89	CHRM	$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$
	[88] GRIFOLS	86	THEO	$\nu_\mu e \to \nu_\mu e$
	[89] RENARD	82	THEO	$g-2$ of electron

[87] DORENBOSCH 89 obtain the limit $\lambda_\gamma^2 \Lambda_{cut}^2 / m_{e^*}^2 < 2.6$ (95% CL), where Λ_{cut} is the cutoff scale, based on the one-loop calculation by GRIFOLS 86. If one assumes that Λ_{cut} = 1 TeV and $\lambda_\gamma = 1$, one obtains $m_{e^*} > 620$ GeV. However, one generally expects $\lambda_\gamma \approx m_{e^*}/\Lambda_{cut}$ in composite models.

[88] GRIFOLS 86 uses $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ data from CHARM Collaboration to derive mass limits which depend on the scale of compositeness.

[89] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited μ (μ*)

Limits for Excited μ (μ*) from Pair Production

These limits are obtained from $e^+ e^- \to \mu^{*+} \mu^{*-}$ and thus rely only on the (electroweak) charge of μ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the μ^* coupling is assumed to be of sequential type. All limits assume $\mu^* \to \mu\gamma$ decay except for the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>85.3	95	[90] ACKERSTAFF	98C	OPAL	$e^+ e^- \to \mu^* \mu^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>79.6	95	[91,92] ABREU	97B	DLPH	$e^+ e^- \to \mu^* \mu^*$ Homodoublet type
>78.4	95	[91,93] ABREU	97B	DLPH	$e^+ e^- \to \mu^* \mu^*$ Sequential type
>79.9	95	[91] ACCIARRI	97G	L3	$e^+ e^- \to \mu^* \mu^*$ Sequential type
>80.0	95	[91,94] ACKERSTAFF	97	OPAL	$e^+ e^- \to \mu^* \mu^*$ Homodoublet type
>62.6	95	[95] ABREU	96K	DLPH	$e^+ e^- \to \mu^* \mu^*$ Homodoublet type
>64.9	95	[96] ACCIARRI	96D	L3	$e^+ e^- \to \mu^* \mu^*$ Sequential type

>66.8	95	[96] ALEXANDER	96Q	OPAL	$e^+e^- \to \mu^*\mu^*$ Homodoublet type
>65.4	95	[96] BUSKULIC	96W	ALEP	$e^+e^- \to \mu^*\mu^*$ Sequential type
>45.6	95	ADRIANI	93M	L3	$Z \to \mu^*\mu^*$
>45.6	95	ABREU	92C	DLPH	$Z \to \mu^*\mu^*$
>29.8	95	[97] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[98] DECAMP	92	ALEP	$Z \to \mu^*\mu^*$; $\Gamma(Z)$
>46.1	95	DECAMP	92	ALEP	$Z \to \mu^*\mu^*$
>33	95	[98] ABREU	91F	DLPH	$Z \to \mu^*\mu^*$; $\Gamma(Z)$
>45.3	95	[99] ADEVA	90F	L3	$Z \to \mu^*\mu^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \to \mu^*\mu^*$
>44.6	95	[100] DECAMP	90G	ALEP	$e^+e^- \to \mu^*\mu^*$
>29.9	95	ADACHI	89B	TOPZ	$e^+e^- \to \mu^*\mu^*$
>28.3	95	KIM	89	AMY	$e^+e^- \to \mu^*\mu^*$

[90] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from $\mu^* \to \nu W$ decay mode: $m_{\mu^*} > 81.3$ GeV.
[91] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.
[92] ABREU 97B also obtain limit from charged current decay mode $\mu^* \to \nu W$, $m_{\mu^*} > 70.9$ GeV.
[93] ABREU 97B also obtain limit from charged current decay mode $\mu^* \to \nu W$, $m_{\mu^*} > 44.6$ GeV.
[94] ACKERSTAFF 97 also obtain limit from charged current decay mode $\mu^* \to \nu W$, $m_{\nu^*_\mu} > 77.1$ GeV.
[95] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.
[96] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.
[97] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.
[98] Limit is independent of μ^* decay mode.
[99] Superseded by ADRIANI 93M.
[100] Superseded by DECAMP 92.

Limits for Excited μ (μ^*) from Single Production

These limits are from $e^+e^- \to \mu^*\mu$ and depend on transition magnetic coupling between μ and μ^*. All limits assume $\mu^* \to \mu\gamma$ decay. Limits from LEP are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{\mu^*}$ plane. See the original papers.

For limits prior to 1987, see our 1992 edition (Physical Review **D45,** 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>89	95	ADRIANI	93M	L3	$Z \to \mu\mu^*$, $\lambda_Z > 0.5$
>88	95	ABREU	92C	DLPH	$Z \to \mu\mu^*$, $\lambda_Z > 0.5$
>91	95	DECAMP	92	ALEP	$Z \to \mu\mu^*$, $\lambda_Z > 1$
>87	95	AKRAWY	90I	OPAL	$Z \to \mu\mu^*$, $\lambda_Z > 1$

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

	95	[101]	ACKERSTAFF	98C	OPAL	$e^+e^- \rightarrow \mu\mu^*$
		[102,103]	ABREU	97B	DLPH	$e^+e^- \rightarrow \mu\mu^*$
		[102,104]	ACCIARRI	97G	L3	$e^+e^- \rightarrow \mu\mu^*$
		[105]	ACKERSTAFF	97	OPAL	$e^+e^- \rightarrow \mu\mu^*$
		[106]	ABREU	96K	DLPH	$e^+e^- \rightarrow \mu\mu^*$
		[107]	ACCIARRI	96D	L3	$e^+e^- \rightarrow \mu\mu^*$
		[108]	ALEXANDER	96Q	OPAL	$e^+e^- \rightarrow \mu\mu^*$
		[109]	BUSKULIC	96W	ALEP	$e^+e^- \rightarrow \mu\mu^*$
>85	95	[110]	ADEVA	90F	L3	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 1$
>75	95	[110]	ADEVA	90F	L3	$Z \rightarrow \mu\mu^*$, $\lambda_Z > 0.1$
>80	95	[111]	DECAMP	90G	ALEP	$e^+e^- \rightarrow \mu\mu^*$, λ_Z=1
>50	95		ADACHI	89B	TOPZ	$e^+e^- \rightarrow \mu\mu^*$, λ_γ=0.7
>46	95		KIM	89	AMY	$e^+e^- \rightarrow \mu\mu^*$, λ_γ=0.2

[101] ACKERSTAFF 98C from e^+e^- collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.

[102] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[103] See Fig. 4a and Fig. 5a of ABREU 97B for the exclusion limit in the mass-coupling plane.

[104] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.

[105] ACKERSTAFF 97 result is from e^+e^- collisions at $\sqrt{s}$= 161 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[106] ABREU 96K result is from e^+e^- collisions at $\sqrt{s}$= 130–136 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.

[107] ACCIARRI 96D result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.

[108] ALEXANDER 96Q result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3a for the exclusion limit in the mass-coupling plane.

[109] BUSKULIC 96W result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[110] Superseded by ADRIANI 93M.

[111] Superseded by DECAMP 92.

Indirect Limits for Excited μ (μ^*)

These limits make use of loop effects involving μ^* and are therefore subject to theoretical uncertainty.

VALUE (GeV)		*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	[112]	RENARD	82	THEO	$g-2$ of muon

[112] RENARD 82 derived from $g-2$ data limits on mass and couplings of e^* and μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited τ (τ^*)

Limits for Excited τ (τ^*) from Pair Production

These limits are obtained from $e^+e^- \rightarrow \tau^{*+}\tau^{*-}$ and thus rely only on the (electroweak) charge of τ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the τ^* coupling is assumed to be of sequential type. All limits assume $\tau^* \rightarrow \tau\gamma$ decay except for the limits from $\Gamma(Z)$.

For limits prior to 1987, see our 1992 edition (Physical Review **D45**, 1 June, Part II (1992)).

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>84.6	95	[113] ACKERSTAFF	98C	OPAL	$e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>79.4	95	[114,115] ABREU	97B	DLPH	$e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type
>77.4	95	[114,116] ABREU	97B	DLPH	$e^+e^- \rightarrow \tau^*\tau^*$ Sequential type
>79.3	95	[114] ACCIARRI	97G	L3	$e^+e^- \rightarrow \tau^*\tau^*$ Sequential type
>79.1	95	[114,117] ACKERSTAFF	97	OPAL	$e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type
>62.2	95	[118] ABREU	96K	DLPH	$e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type
>64.2	95	[119] ACCIARRI	96D	L3	$e^+e^- \rightarrow \tau^*\tau^*$ Sequential type
>65.3	95	[119] ALEXANDER	96Q	OPAL	$e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type
>64.8	95	[119] BUSKULIC	96W	ALEP	$e^+e^- \rightarrow \tau^*\tau^*$ Sequential type
>45.6	95	ADRIANI	93M	L3	$Z \rightarrow \tau^*\tau^*$
>45.3	95	ABREU	92C	DLPH	$Z \rightarrow \tau^*\tau^*$
>29.8	95	[120] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[121] DECAMP	92	ALEP	$Z \rightarrow \tau^*\tau^*$; $\Gamma(Z)$
>46.0	95	DECAMP	92	ALEP	$Z \rightarrow \tau^*\tau^*$
>33	95	[121] ABREU	91F	DLPH	$Z \rightarrow \tau^*\tau^*$; $\Gamma(Z)$
>45.5	95	[122] ADEVA	90L	L3	$Z \rightarrow \tau^*\tau^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \rightarrow \tau^*\tau^*$
>41.2	95	[123] DECAMP	90G	ALEP	$e^+e^- \rightarrow \tau^*\tau^*$
>29.0	95	ADACHI	89B	TOPZ	$e^+e^- \rightarrow \tau^*\tau^*$

[113] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from $\tau^* \rightarrow \nu W$ decay mode: $m_{\tau^*} > 81.3$ GeV.

[114] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[115] ABREU 97B also obtain limit from charged current decay mode $\tau^* \rightarrow \nu W$, $m_{\tau^*} > 70.9$ GeV.

[116] ABREU 97B also obtain limit from charged current decay mode $\tau^* \rightarrow \nu W$, $m_{\tau^*} > 44.6$ GeV.

[117] ACKERSTAFF 97 also obtain limit from charged current decay mode $\tau^* \rightarrow \nu W$, $m_{\nu_\tau^*} > 77.1$ GeV.

[118] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.

[119] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.

[120] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)$<36 MeV.

[121] Limit is independent of τ^* decay mode.

[122] Superseded by ADRIANI 93M.

[123] Superseded by DECAMP 92.

Limits for Excited τ (τ^*) from Single Production

These limits are from $e^+e^- \rightarrow \tau^*\tau$ and depend on transition magnetic coupling between τ and τ^*. All limits assume $\tau^* \rightarrow \tau\gamma$ decay. Limits from LEP are for chiral coupling, whereas all other limits are for nonchiral coupling, $\eta_L = \eta_R = 1$. In most papers, the limit is expressed in the form of an excluded region in the $\lambda - m_{\tau^*}$ plane. See the original papers.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>88	95	ADRIANI	93M	L3	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 0.5$
>87	95	ABREU	92C	DLPH	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 0.5$
>90	95	DECAMP	92	ALEP	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 0.18$
>86.5	95	AKRAWY	90I	OPAL	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	95	[124] ACKERSTAFF	98C	OPAL	$e^+e^- \rightarrow \tau\tau^*$
		[125,126] ABREU	97B	DLPH	$e^+e^- \rightarrow \tau\tau^*$
		[125,127] ACCIARRI	97G	L3	$e^+e^- \rightarrow \tau\tau^*$
		[128] ACKERSTAFF	97	OPAL	$e^+e^- \rightarrow \tau\tau^*$
		[129] ABREU	96K	DLPH	$e^+e^- \rightarrow \tau\tau^*$
		[130] ACCIARRI	96D	L3	$e^+e^- \rightarrow \tau\tau^*$
		[131] ALEXANDER	96Q	OPAL	$e^+e^- \rightarrow \tau\tau^*$
		[132] BUSKULIC	96W	ALEP	$e^+e^- \rightarrow \tau\tau^*$
>88	95	[133] ADEVA	90L	L3	$Z \rightarrow \tau\tau^*$, $\lambda_Z > 1$
>59	95	[134] DECAMP	90G	ALEP	$Z \rightarrow \tau\tau^*$, $\lambda_Z = 1$
>40	95	[135] BARTEL	86	JADE	$e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 1$
>41.4	95	[136] BEHREND	86	CELL	$e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 1$
>40.8	95	[136] BEHREND	86	CELL	$e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 0.7$

[124] ACKERSTAFF 98C from e^+e^- collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.

[125] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[126] See Fig. 4a and Fig. 5a of ABREU 97B for the exclusion limit in the mass-coupling plane.

[127] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.

[128] ACKERSTAFF 97 result is from e^+e^- collisions at $\sqrt{s}$= 161 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[129] ABREU 96K result is from e^+e^- collisions at $\sqrt{s}$= 130–136 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.

[130] ACCIARRI 96D result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.

[131] ALEXANDER 96Q result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3a for the exclusion limit in the mass-coupling plane.

[132] BUSKULIC 96W result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[133] Superseded by ADRIANI 93M.

[134] Superseded by DECAMP 92.

[135] BARTEL 86 is at E_{cm} = 30–46.78 GeV.

[136] BEHREND 86 limit is at E_{cm} = 33–46.8 GeV.

MASS LIMITS for Excited Neutrino (ν^*)

Limits for Excited ν (ν^*) from Pair Production

These limits are obtained from $e^+e^- \to \nu^*\nu^*$ and thus rely only on the (electroweak) charge of ν^*. Form factor effects are ignored unless noted. The ν^* coupling is assumed to be of sequential type unless otherwise noted. Limits assume $\nu^* \to \nu\gamma$ decay except for the $\Gamma(Z)$ measurement which makes no assumption about decay mode.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>84.9	95	[137] ACKERSTAFF 98C	OPAL	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>77.6	95	[138,139] ABREU 97B	DLPH	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
>64.4	95	[138,140] ABREU 97B	DLPH	$e^+e^- \to \nu^*\nu^*$ Sequential type
>71.2	95	[138,141] ACCIARRI 97G	L3	$e^+e^- \to \nu^*\nu^*$ Sequential type
>77.8	95	[138,142] ACKERSTAFF 97	OPAL	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
>61.4	95	[143,144] ACCIARRI 96D	L3	$e^+e^- \to \nu^*\nu^*$ Sequential type
>65.0	95	[145,146] ALEXANDER 96Q	OPAL	$e^+e^- \to \nu^*\nu^*$ Homodoublet type
>63.6	95	[143] BUSKULIC 96W	ALEP	$e^+e^- \to \nu^*\nu^*$ Sequential type
>43.7	95	[147] BARDADIN-... 92	RVUE	$\Gamma(Z)$
>47	95	[148] DECAMP 92	ALEP	
>42.6	95	[149] DECAMP 92	ALEP	$\Gamma(Z)$
>35.4	95	[150,151] DECAMP 90O	ALEP	$\Gamma(Z)$
>46	95	[151,152] DECAMP 90O	ALEP	

[137] From e^+e^- collisions at $\sqrt{s}$=170–172 GeV. ACKERSTAFF 98C also obtain limit from charged decay modes: $m_{\nu_e^*} > 84.1$ GeV, $m_{\nu_\mu^*} > 83.9$ GeV, and $m_{\nu_\tau^*} > 79.4$ GeV.

[138] From e^+e^- collisions at $\sqrt{s}$= 161 GeV.

[139] ABREU 97B also obtain limits from charged current decay modes, $m_{\nu^*} > 56.4$ GeV.

[140] ABREU 97B also obtain limits from charged current decay modes, $m_{\nu^*} > 44.9$ GeV.

[141] ACCIARRI 97G also obtain limits from charged current decay mode $\nu_e^* \to eW$, $m_{\nu^*} >$ 64.5 GeV.

[142] ACKERSTAFF 97 also obtain limits from charged current decay modes $m_{\nu_e^*} > 78.3$ GeV, $m_{\nu_\mu^*} > 78.9$ GeV, $m_{\nu_\tau^*} > 76.2$ GeV.

[143] From e^+e^- collisions at $\sqrt{s}$= 130–140 GeV.

[144] ACCIARRI 96D also obtain limit from $\nu^* \to eW$ decay mode: $m_{\nu^*} > 57.3$ GeV.

[145] From e^+e^- collisions at $\sqrt{s}$= 130–136 GeV.

[146] ALEXANDER 96Q also obtain limits from charged current decay modes: $m_{\nu_e^*} > 66.2$ GeV, $m_{\nu_\mu^*} > 66.5$ GeV, $m_{\nu_\tau^*} > 64.7$ GeV.

[147] BARDADIN-OTWINOWSKA 92 limit is for Dirac ν^*. Based on $\Delta\Gamma(Z)$<36 MeV. The limit is 36.4 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.

[148] Limit is based on $B(Z \to \nu^*\overline{\nu}^*)\times B(\nu^* \to \nu\gamma)^2 < 5 \times 10^{-5}$ (95%CL) assuming Dirac ν^*, $B(\nu^* \to \nu\gamma) = 1$.

[149] Limit is for Dirac ν^*. The limit is 34.6 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.

[150] DECAMP 90O limit is from excess $\Delta\Gamma(Z) < 89$ MeV. The above value is for Dirac ν^*; 26.6 GeV for Majorana ν^*; 44.8 GeV for homodoublet ν^*.

[151] Superseded by DECAMP 92.

[152] DECAMP 90O limit based on $B(Z \to \nu^*\nu^*)\cdot B(\nu^* \to \nu\gamma)^2 < 7 \times 10^{-5}$ (95%CL), assuming Dirac ν^*, $B(\nu^* \to \nu\gamma) = 1$.

Limits for Excited ν (ν^*) from Single Production

These limits are from $Z \rightarrow \nu\nu^*$ or $ep \rightarrow \nu^* X$ and depend on transition magnetic coupling between ν/e and ν^*. Assumptions about ν^* decay mode are given in footnotes.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
none 40–96	95	[153] BREITWEG	97C	ZEUS	$ep \rightarrow \nu^* X$
>91	95	ADRIANI	93M	L3	$\lambda_Z > 1$, $\nu^* \rightarrow \nu\gamma$
>89	95	ADRIANI	93M	L3	$\lambda_Z > 1$, $\nu^*_e \rightarrow eW$
>91	95	[154] DECAMP	92	ALEP	$\lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	95	[155] ACKERSTAFF	98C	OPAL	$ep \rightarrow \nu^* \nu^*$
		[156,157] ABREU	97B	DLPH	$e^+ e^- \rightarrow \nu\nu^*$
		[158] ABREU	97I	DLPH	$\nu^* \rightarrow \ell W$, νZ
		[159] ABREU	97J	DLPH	$\nu^* \rightarrow \nu\gamma$
		[156,160] ACCIARRI	97G	L3	$e^+ e^- \rightarrow \nu\nu^*$
		[161] ACKERSTAFF	97	OPAL	$e^+ e^- \rightarrow \nu\nu^*$
		[162] ADLOFF	97	H1	Lepton-flavor violation
		[163] ACCIARRI	96D	L3	$e^+ e^- \rightarrow \nu\nu^*$
		[164] ALEXANDER	96Q	OPAL	$e^+ e^- \rightarrow \nu\nu^*$
		[165] BUSKULIC	96W	ALEP	$e^+ e^- \rightarrow \nu\nu^*$
		[166] DERRICK	95B	ZEUS	$ep \rightarrow \nu^* X$
		[167] ABT	93	H1	$ep \rightarrow \nu^* X$
>87	95	ADRIANI	93M	L3	$\lambda_Z > 0.1$, $\nu^* \rightarrow \nu\gamma$
>74	95	ADRIANI	93M	L3	$\lambda_Z > 0.1$, $\nu^*_e \rightarrow eW$
		[168] BARDADIN-...	92	RVUE	
>74	95	[154] DECAMP	92	ALEP	$\lambda_Z > 0.034$
>91	95	[169,170] ADEVA	90O	L3	$\lambda_Z > 1$
>83	95	[170] ADEVA	90O	L3	$\lambda_Z > 0.1$, $\nu^* \rightarrow \nu\gamma$
>74	95	[170] ADEVA	90O	L3	$\lambda_Z > 0.1$, $\nu^*_e \rightarrow eW$
>90	95	[171,172] DECAMP	90O	ALEP	$\lambda_Z > 1$
>74.7	95	[171,172] DECAMP	90O	ALEP	$\lambda_Z > 0.06$

[153] BREITWEG 97C search for single ν^* production in ep collisions with the decay $\nu^* \rightarrow \nu\gamma$. $f = -f' = 2\Lambda/m_{\nu^*}$ is assumed for the ν^* coupling. See their Fig. 10 for the exclusion plot in the mass-coupling plane.

[154] DECAMP 92 limit is based on $B(Z \rightarrow \nu^* \overline{\nu}) \times B(\nu^* \rightarrow \nu\gamma) < 2.7 \times 10^{-5}$ (95%CL) assuming Dirac ν^*, $B(\nu^* \rightarrow \nu\gamma) = 1$.

[155] ACKERSTAFF 98C from $e^+ e^-$ collisions at $\sqrt{s}$=170–172 GeV. See their Fig. 11 for the exclusion limit in the mass-coupling plane.

[156] From $e^+ e^-$ collisions at $\sqrt{s}$= 161 GeV.

[157] See Fig. 4b and Fig. 5b of ABREU 97B for the exclusion limit in the mass-coupling plane.

[158] ABREU 97I limit is from $Z \rightarrow \nu\nu^*$. See their Fig. 12 for the exclusion limit in the mass-coupling plane.

[159] ABREU 97J limit is from $Z \rightarrow \nu\nu^*$. See their Fig. 5 for the exclusion limit in the mass-coupling plane.

[160] See Fig. 2 and Fig. 3 of ACCIARRI 97G for the exclusion limit in the mass-coupling plane.

[161] ACKERSTAFF 97 result is from $e^+ e^-$ collisions at $\sqrt{s}$= 161 GeV, for homodoublet ν^*. See their Fig. 3 for the exclusion limit in the mass-coupling plane.

[162] ADLOFF 97 search for single e^* production in ep collisions with the decays $e^* \rightarrow e\gamma$, eZ, νW. See their Fig. 4 for the rejection limits on the product of the production cross section and the branching ratio.

[163] ACCIARRI 96D result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 2 for the exclusion limit in the mass-coupling plane.

[164] ALEXANDER 96Q result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV for homedoublet ν^*. See their Fig. 3b and Fig. 3c for the exclusion limit in the mass-coupling plane.

[165] BUSKULIC 96W result is from e^+e^- collisions at $\sqrt{s}$= 130–140 GeV. See their Fig. 4 for the exclusion limit in the mass-coupling plane.

[166] DERRICK 95B search for single ν^* production via $\nu^* e W$ coupling in $e p$ collisions with the decays $\nu^* \rightarrow \nu\gamma$, νZ, $e W$. See their Fig. 14 for the exclusion plot in the m_{ν^*}–$\lambda\gamma$ plane.

[167] ABT 93 search for single ν^* production via $\nu^* e W$ coupling in $e p$ collisions with the decays $\nu^* \rightarrow \nu\gamma$, νZ, $e W$. See their Fig. 4 for exclusion plot in the m_{ν^*}–λ_W plane.

[168] See Fig. 5 of BARDADIN-OTWINOWSKA 92 for combined limit of ADEVA 90O, DECAMP 90O, and DECAMP 92.

[169] Limit is either for $\nu^* \rightarrow \nu\gamma$ or $\nu^* \rightarrow e W$.

[170] Superseded by ADRIANI 93M.

[171] DECAMP 90O limit based on B($Z \rightarrow \nu\nu^*$)·B($\nu^* \rightarrow \nu\gamma$) $< 6 \times 10^{-5}$ (95%CL), assuming B($\nu^* \rightarrow \nu\gamma$) = 1.

[172] Superseded by DECAMP 92.

MASS LIMITS for Excited *q* (*q**)

Limits for Excited *q* (*q**) from Pair Production

These limits are obtained from $e^+e^- \rightarrow q^*\overline{q}^*$ and thus rely only on the (electroweak) charge of the q^*. Form factor effects are ignored unless noted. Assumptions about the q^* decay are given in the comments and footnotes.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45.6	95	[173] ADRIANI	93M	L3	u or d type, $Z \rightarrow q^* q^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[174] ADRIANI	92F	L3	$Z \rightarrow q^* q^*$
>41.7	95	[175] BARDADIN-...	92	RVUE	u-type, $\Gamma(Z)$
>44.7	95	[175] BARDADIN-...	92	RVUE	d-type, $\Gamma(Z)$
>40.6	95	[176] DECAMP	92	ALEP	u-type, $\Gamma(Z)$
>44.2	95	[176] DECAMP	92	ALEP	d-type, $\Gamma(Z)$
>45	95	[177] DECAMP	92	ALEP	u or d type, $Z \rightarrow q^* q^*$
>45	95	[176] ABREU	91F	DLPH	u-type, $\Gamma(Z)$
>45	95	[176] ABREU	91F	DLPH	d-type, $\Gamma(Z)$
>21.1	95	[178] BEHREND	86C	CELL	$e(q^*) = -1/3$, $q^* \rightarrow q g$
>22.3	95	[178] BEHREND	86C	CELL	$e(q^*) = 2/3$, $q^* \rightarrow q g$
>22.5	95	[178] BEHREND	86C	CELL	$e(q^*) = -1/3$, $q^* \rightarrow q\gamma$
>23.2	95	[178] BEHREND	86C	CELL	$e(q^*) = 2/3$, $q^* \rightarrow q\gamma$

[173] ADRIANI 93M limit is valid for B($q^* \rightarrow q g$)> 0.25 (0.17) for up (down) type.

[174] ADRIANI 92F search for $Z \rightarrow q^*\overline{q}^*$ followed with $q^* \rightarrow q\gamma$ decays and give the limit $\sigma_Z \cdot$ B($Z \rightarrow q^*\overline{q}^*$) $\cdot$ B^2($q^* \rightarrow q\gamma$) <2 pb at 95%CL. Assuming five flavors of degenerate q^* of homodoublet type, B($q^* \rightarrow q\gamma$) <4% is obtained for m_{q^*} <45 GeV.

[175] BARDADIN-OTWINOWSKA 92 limit based on $\Delta\Gamma(Z)$<36 MeV.

[176] These limits are independent of decay modes.

177 Limit is for B($q^* \rightarrow qg$)+B($q^* \rightarrow q\gamma$)=1.

178 BEHREND 86C search for $e^+e^- \rightarrow q^*\overline{q}^*$ for m_{q^*} >5 GeV. But $m <$ 5 GeV excluded by total hadronic cross section. The limits are for point-like photon couplings of excited quarks.

Limits for Excited q (q^*) from Single Production

These limits are from $e^+e^- \rightarrow q^*\overline{q}$ or $p\overline{p} \rightarrow q^*$X and depend on transition magnetic couplings between q and q^*. Assumptions about q^* decay mode are given in the footnotes and comments.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>570 (CL = 95%) OUR EVALUATION					
none 200–520 and 580–760	95	179 ABE	97G	CDF	$p\overline{p} \rightarrow q^*$X, $q^* \rightarrow$ 2 jets
none 40–169	95	180 BREITWEG	97C	ZEUS	$ep \rightarrow q^*$X
none 80–570	95	181 ABE	95N	CDF	$p\overline{p} \rightarrow q^*$X, $q^* \rightarrow qg$ $q\gamma$, qW
>288	90	182 ALITTI	93	UA2	$p\overline{p} \rightarrow q^*$X, $q^* \rightarrow qg$
> 88	95	183 DECAMP	92	ALEP	$Z \rightarrow qq^*$, λ_Z >1
> 86	95	183 AKRAWY	90J	OPAL	$Z \rightarrow qq^*$, λ_Z > 1.2
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		184 ADLOFF	97	H1	Lepton-flavor violation
		185 DERRICK	95B	ZEUS	$ep \rightarrow q^*$X
none 80–540	95	186 ABE	94	CDF	$p\overline{p} \rightarrow q^*$X, $q^* \rightarrow q\gamma$, qW
> 79	95	187 ADRIANI	93M	L3	λ_Z(L3)> 0.06
		188 ABREU	92D	DLPH	$Z \rightarrow qq^*$
		189 ADRIANI	92F	L3	$Z \rightarrow qq^*$
> 75	95	187 DECAMP	92	ALEP	$Z \rightarrow qq^*$, λ_Z >1
		190 ALBAJAR	89	UA1	$p\overline{p} \rightarrow q^*$X, $q^* \rightarrow qW$
> 39	95	191 BEHREND	86C	CELL	$e^+e^- \rightarrow q^*\overline{q}$ ($q^* \rightarrow qg$,$q\gamma$), λ_γ=1

179 ABE 97G search for new particle decaying to dijets.

180 BREITWEG 97C search for single q^* production in ep collisions with the decays $q^* \rightarrow q\gamma$, qW. f_s=0, and f=$-f'$=2Λ/m_{q^*} is assumed for the q^* coupling. See their Fig. 11 for the exclusion plot in the mass-coupling plane.

181 ABE 95N assume a degenerate u^* and d^* with f_s=f=f'=Λ/m_{q^*}. See their Fig. 4 for the excluded region in $m_{q^*} - f$ plane.

182 ALITTI 93 search for resonances in the two-jet invariant mass. The limit is for $f_s = f = f' = \Lambda/m_{q^*}$. u^* and d^* are assumed to be degenerate. If not, the limit for u^* (d^*) is 277 (247) GeV if $m_{d^*} \gg m_{u^*}$ ($m_{u^*} \gg m_{d^*}$).

183 Assumes B($q^* \rightarrow q\gamma$) = 0.1.

184 ADLOFF 97 search for single q^* production in ep collisions with the decay $q^* \rightarrow q\gamma$. See their Fig. 6 for the rejection limits on the product of the production cross section and the branching ratio.

185 DERRICK 95B search for single q^* production via $q^*q\gamma$ coupling in ep collisions with the decays $q^* \rightarrow qW$, qZ, qg, $q\gamma$. See their Fig. 15 for the exclusion plot in the $m_{q^*}-\lambda\gamma$ plane.

[186] ABE 94 search for resonances in jet-γ and jet-W invariant mass in $p\overline{p}$ collisions at $E_{\rm cm}$ = 1.8 TeV. The limit is for $f_s = f = f' = \Lambda/m_{q^*}$ and u^* and d^* are assumed to be degenerate. See their Fig. 4 for the excluded region in m_{q^*}-f plane.

[187] Assumes B($q^* \rightarrow qg$) = 1.

[188] ABREU 92D give $\sigma(e^+e^- \rightarrow Z \rightarrow q^*\overline{q}$ or $q\overline{q}^*)\times$B($q^* \rightarrow q\gamma$) <15 pb (95% CL) for m_{q^*} <80 GeV.

[189] ADRIANI 92F search for $Z \rightarrow qq^*$ with $q^* \rightarrow q\gamma$ and give the limit $\sigma_Z \cdot$ B($Z \rightarrow qq^*$) $\cdot$ B($q^* \rightarrow q\gamma$) <(2–10) pb (95%CL) for m_{q^*} = (46–82) GeV.

[190] ALBAJAR 89 give $\sigma(q^* \rightarrow W+$ jet$)/\sigma(W) < 0.019$ (90% CL) for $m_{q^*} > 220$ GeV.

[191] BEHREND 86C has $E_{\rm cm}$ = 42.5–46.8 GeV. See their Fig. 3 for excluded region in the $m_{q^*}-(\lambda_\gamma/m_{q^*})^2$ plane. The limit is for $\lambda_\gamma = 1$ with $\eta_L = \eta_R = 1$.

MASS LIMITS for Color Sextet Quarks (q_6)

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>84	95	[192] ABE	89D	CDF	$p\overline{p} \rightarrow q_6\overline{q}_6$

[192] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color sextet quark is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. A limit of 121 GeV is obtained for a color decuplet.

MASS LIMITS for Color Octet Charged Leptons (ℓ_8)

$\lambda \equiv m_{\ell_8}/\Lambda$

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>86	95	[193] ABE	89D	CDF	Stable ℓ_8: $p\overline{p} \rightarrow \ell_8\overline{\ell}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[194] ABT	93	H1	e_8: $ep \rightarrow e_8$X
none 3.0–30.3	95	[195] KIM	90	AMY	e_8: $e^+e^- \rightarrow ee+$ jets
none 3.5–30.3	95	[195] KIM	90	AMY	μ_8: $e^+e^- \rightarrow \mu\mu+$ jets
		[196] KIM	90	AMY	e_8: $e^+e^- \rightarrow gg$; R
>19.8	95	[197] BARTEL	87B	JADE	e_8, μ_8, τ_8: e^+e^-; R
none 5–23.2	95	[197] BARTEL	87B	JADE	μ_8: $e^+e^- \rightarrow \mu\mu+$ jets
		[198] BARTEL	85K	JADE	e_8: $e^+e^- \rightarrow gg$; R

[193] ABE 89D look for pair production of unit-charged particles which leave the detector before decaying. In the above limit the color octet lepton is assumed to fragment into a unit-charged or neutral hadron with equal probability and to have long enough lifetime not to decay within the detector. The limit improves to 99 GeV if it always fragments into a unit-charged hadron.

[194] ABT 93 search for e_8 production via e-gluon fusion in ep collisions with $e_8 \rightarrow eg$. See their Fig. 3 for exclusion plot in the m_{e_8}–Λ plane for m_{e_8} = 35–220 GeV.

[195] KIM 90 is at $E_{\rm cm}$ = 50–60.8 GeV. The same assumptions as in BARTEL 87B are used.

[196] KIM 90 result $(m_{e_8}\Lambda_M)^{1/2} >$ 178.4 GeV (95%CL, $\alpha_s = 0.16$ used) is subject to the same restriction as for BARTEL 85K.

[197] BARTEL 87B is at E_{cm} = 46.3–46.78 GeV. The limits assume ℓ_8 pair production cross sections to be eight times larger than those of the corresponding heavy lepton pair production.

[198] In BARTEL 85K, R can be affected by $e^+e^- \rightarrow gg$ via e_q exchange. Their limit m_{e_8} >173 GeV (CL=95%) at $\lambda = m_{e_8}/\Lambda_M = 1$ ($\eta_L = \eta_R = 1$) is not listed above because the cross section is sensitive to the product $\eta_L \eta_R$, which should be absent in ordinary theory with electronic chiral invariance.

MASS LIMITS for Color Octet Neutrinos (ν_8)

$\lambda \equiv m_{\ell_8}/\Lambda$

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>110	90	[199] BARGER	89	RVUE	ν_8: $p\overline{p} \rightarrow \nu_8 \overline{\nu}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 3.8–29.8	95	[200] KIM	90	AMY	ν_8: $e^+e^- \rightarrow$ acoplanar jets
none 9–21.9	95	[201] BARTEL	87B	JADE	ν_8: $e^+e^- \rightarrow$ acoplanar jets

[199] BARGER 89 used ABE 89B limit for events with large missing transverse momentum. Two-body decay $\nu_8 \rightarrow \nu g$ is assumed.

[200] KIM 90 is at E_{cm} = 50–60.8 GeV. The same assumptions as in BARTEL 87B are used.

[201] BARTEL 87B is at E_{cm} = 46.3–46.78 GeV. The limit assumes the ν_8 pair production cross section to be eight times larger than that of the corresponding heavy neutrino pair production. This assumption is not valid in general for the weak couplings, and the limit can be sensitive to its $SU(2)_L \times U(1)_Y$ quantum numbers.

MASS LIMITS for W_8 (Color Octet W Boson)

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[202] ALBAJAR	89	UA1	$p\overline{p} \rightarrow W_8 X$, $W_8 \rightarrow W g$

[202] ALBAJAR 89 give $\sigma(W_8 \rightarrow W + \text{jet})/\sigma(W) < 0.019$ (90% CL) for $m_{W_8} > 220$ GeV.

Limits on $ZZ\gamma$ Coupling

Limits are for the electric dipole transition form factor for $Z \rightarrow \gamma Z^*$ parametrized as $f(s') = \beta(s'/m_Z^2 - 1)$, where s' is the virtual Z mass. In the Standard Model $\beta \sim 10^{-5}$.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.80	95	ADRIANI	92J	L3	$Z \rightarrow \gamma \nu \overline{\nu}$

REFERENCES FOR Searches for Quark and Lepton Compositeness

ACKERSTAFF	98	EPJ C1 21	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	98C	EPJ C1 45	K. Ackerstaff+	(OPAL Collab.)
ABE	97G	PR D55 R5263	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABE	97T	PRL 79 2198	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABREU	97B	PL B393 245	+Adam, Adye, Ajinenko, Alekseev+	(DELPHI Collab.)
ABREU	97I	ZPHY C74 57	+Adam, Adye, Ajinenko, Alekseev+	(DELPHI Collab.)
Also	97L	ZPHY C75 580 erratum	Abreu, Adam, Adye, Ajinenko+	(DELPHI Collab.)
ABREU	97J	ZPHY C74 577	P. Abreu+	(DELPHI Collab.)
ACCIARRI	97G	PL B401 139	+Adriani, Aguilar-Benitez, Ahlen, Alpat+	(L3 Collab.)
ACKERSTAFF	97	PL B391 197	+Alexander, Allison, Altekamp, Ametewee+	(OPAL Collab.)
ACKERSTAFF	97C	PL B391 221	+Alexander, Allison, Altekamp, Ametewee+	(OPAL Collab.)
ADLOFF	97	NP B483 44	+Aid, Anderson, Andreev, Andrieu, Arndt+	(H1 Collab.)
ARIMA	97	PR D55 19	+Odaka, Ogawa, Shirai, Tsuboyama+	(VENUS Collab.)
BREITWEG	97C	ZPHY C76 631	+Derrick, Krakauer, Magill+	(ZEUS Collab.)
DEANDREA	97	PL B409 277		(MARS)
ABE	96	PRL 77 438	+Akimoto, Akopian, Albrow+	(CDF Collab.)
ABE	96S	PRL 77 5336	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABREU	96K	PL B380 480	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ACCIARRI	96D	PL B370 211	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
ACCIARRI	96L	PL B384 323	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
ALEXANDER	96K	PL B377 222	+	(OPAL Collab.)
ALEXANDER	96Q	PL B386 463	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BUSKULIC	96W	PL B385 445	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
BUSKULIC	96Z	PL B384 333	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
ABE	95N	PRL 74 3538	+Albrow, Amendolia, Amidei, Antos+	(CDF Collab.)
ACCIARRI	95G	PL B353 136	+Adam, Adriani, Aguilar-Benitez, Ahlen+	(L3 Collab.)
AID	95	PL B353 578	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
DERRICK	95B	ZPHY C65 627	+Krakauer, Magill, Musgrave, Repond+	(ZEUS Collab.)
ABE	94	PRL 72 3004	+Albrow, Amidei, Anway-Wiese, Apollinari+	(CDF Collab.)
DIAZCRUZ	94	PR D49 R2149	Diaz Cruz, Sampayo	(CINV)
VELISSARIS	94	PL B331 227	+Lusin, Chung, Park, Cho, Bodek, Kim+	(AMY Collab.)
ABE	93G	PRL 71 2542	+Albrow, Akimoto, Amidei, Anway-Wiese+	(CDF Collab.)
ABT	93	NP B396 3	+Andreev, Andrieu, Appuhn, Arpagaus+	(H1 Collab.)
ADRIANI	93M	PRPL 236 1	+Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+	(L3 Collab.)
ALITTI	93	NP B400 3	+Ambrosini, Ansari, Autiero, Bareyre+	(UA2 Collab.)
BUSKULIC	93Q	ZPHY C59 215	+Decamp, Goy, Lees, Minard, Mours+	(ALEPH Collab.)
DERRICK	93B	PL B316 207	+Krakauer, Magill, Musgrave, Repond+	(ZEUS Collab.)
ABE	92B	PRL 68 1463	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92D	PRL 68 1104	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABE	92M	PRL 69 2896	+Amidei, Anway-Wiese, Apollinari, Atac+	(CDF Collab.)
ABREU	92C	ZPHY C53 41	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ABREU	92D	ZPHY C53 555	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ADRIANI	92B	PL B288 404	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
ADRIANI	92F	PL B292 472	+Aguilar-Benitez, Ahlen, Akbari, Alcarez+	(L3 Collab.)
ADRIANI	92J	PL B297 469	+Aguilar-Benitez, Ahlen, Alcarez, Aloisio+	(L3 Collab.)
BARDADIN-...	92	ZPHY C55 163	Bardadin-Otwinowska	(CLER)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
HOWELL	92	PL B291 206	+Koltick, Tauchi, Miyamoto, Kichimi+	(TOPAZ Collab.)
KROHA	92	PR D46 58		(ROCH)
PDG	92	PR D45, 1 June, Part II	Hikasa, Barnett, Stone+	(KEK, LBL, BOST+)
SHIMOZAWA	92	PL B284 144	+Fujimoto, Abe, Adachi, Doser+	(TOPAZ Collab.)
ABE	91D	PRL 67 2418	+Amidei, Apollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	91E	PL B268 296	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ADACHI	91	PL B255 613	+Anazawa, Doser, Enomoto+	(TOPAZ Collab.)
AKRAWY	91F	PL B257 531	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALITTI	91B	PL B257 232	+Ansari, Autiero, Bareyre, Blaylock+	(UA2 Collab.)
BEHREND	91B	ZPHY C51 143	+Criegee, Field, Franke, Jung+	(CELLO Collab.)
BEHREND	91C	ZPHY C51 149	+Criegee, Field, Franke, Jung, Meyer+	(CELLO Collab.)
Also	91B	ZPHY C51 143	Behrend, Criegee, Field, Franke, Jung+	(CELLO Collab.)
ABE	90I	ZPHY C48 13	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ADEVA	90F	PL B247 177	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90K	PL B250 199	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
ADEVA	90L	PL B250 205	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)

ADEVA	90O	PL B252 525	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	90F	PL B241 133	+Alexander, Allison, Allport+	(OPAL Collab.)
AKRAWY	90I	PL B244 135	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90J	PL B246 285	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	90G	PL B236 501	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90O	PL B250 172	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
KIM	90	PL B240 243	+Breedon, Ko, Lander, Maeshima, Malchow+	(AMY Collab.)
ABE	89	PRL 62 613	+Amidei, Apollinari, Ascori, Atac+	(CDF Collab.)
ABE	89B	PRL 62 1825	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89D	PRL 63 1447	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89H	PRL 62 3020	+Amidei, Apollinari, Ascoli, Atac+	(CDF Collab.)
ABE	89J	ZPHY C45 175	+Amako, Arai, Fukawa+	(VENUS Collab.)
ABE	89L	PL B232 425	+Amako, Arai, Asano, Chiba+	(VENUS Collab.)
ADACHI	89B	PL B228 553	+Aihara, Doser, Enomoto, Fujii+	(TOPAZ Collab.)
ALBAJAR	89	ZPHY C44 15	+Albrow, Allkofer, Arnison, Astbury+	(UA1 Collab.)
BARGER	89	PL B220 464	+Hagiwara, Han, Zeppenfeld	(WISC, KEK)
BEHREND	89B	PL B222 163	+Criegee, Dainton, Field, Franke+	(CELLO Collab.)
BRAUNSCH...	89C	ZPHY C43 549	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
DORENBOS...	89	ZPHY C41 567	Dorenbosch, Udo, Allaby, Amaldi+	(CHARM Collab.)
HAGIWARA	89	PL B219 369	+Sakuda, Terunuma	(KEK, DURH, HIRO)
KIM	89	PL B223 476	+Kim, Kang, Lee, Myung, Bacala	(AMY Collab.)
ABE	88B	PL B213 400	+Amako, Arai, Asano, Chiba, Chiba+	(VENUS Collab.)
BARINGER	88	PL B206 551	+Bylsma, De Bonte, Koltick, Low+	(HRS Collab.)
BRAUNSCH...	88	ZPHY C37 171	Braunschweig, Gerhards+	(TASSO Collab.)
BRAUNSCH...	88D	ZPHY C40 163	Braunschweig, Gerhards, Kirschfink+	(TASSO Collab.)
ANSARI	87D	PL B195 613	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	+Becker, Felst+	(JADE Collab.)
BEHREND	87C	PL B191 209	+Buerger, Criegee, Dainton+	(CELLO Collab.)
FERNANDEZ	87B	PR D35 10	+Ford, Qi, Read, Smith, Camporesi+	(MAC Collab.)
ARNISON	86C	PL B172 461	+Albrow, Allkofer+	(UA1 Collab.)
ARNISON	86D	PL B177 244	+Albajar, Albrow+	(UA1 Collab.)
BARTEL	86	ZPHY C31 359	+Becker, Felst, Haidt+	(JADE Collab.)
BARTEL	86C	ZPHY C30 371	+Becker, Cords, Felst, Haidt+	(JADE Collab.)
BEHREND	86	PL 168B 420	+Buerger, Criegee, Fenner+	(CELLO Collab.)
BEHREND	86C	PL B181 178	+Buerger, Criegee, Dainton+	(CELLO Collab.)
DERRICK	86	PL 166B 463	+Gan, Kooijman, Loos+	(HRS Collab.)
Also	86B	PR D34 3286	Derrick, Gan, Kooijman, Loos, Musgrave+	(HRS Collab.)
DERRICK	86B	PR D34 3286	+Gan, Kooijman, Loos, Musgrave+	(HRS Collab.)
GRIFOLS	86	PL 168B 264	+Peris	(BARC)
JODIDIO	86	PR D34 1967	+Balke, Carr, Gidal, Shinsky+	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	Jodidio, Balke, Carr+	(LBL, NWES, TRIU)
APPEL	85	PL 160B 349	+Bagnaia, Banner+	(UA2 Collab.)
BARTEL	85K	PL 160B 337	+Becker, Cords, Eichler+	(JADE Collab.)
BERGER	85	ZPHY C28 1	+Genzel, Lackas, Pielorz+	(PLUTO Collab.)
BERGER	85B	ZPHY C27 341	+Deuter, Genzel, Lackas, Pielorz+	(PLUTO Collab.)
BAGNAIA	84C	PL 138B 430	+Banner, Battiston+	(UA2 Collab.)
BARTEL	84D	PL 146B 437	+Becker, Bowdery, Cords+	(JADE Collab.)
BARTEL	84E	PL 146B 121	+Becker, Bowdery, Cords, Felst+	(JADE Collab.)
EICHTEN	84	RMP 56 579	+Hinchliffe, Lane, Quigg	(FNAL, LBL, OSU)
ALTHOFF	83C	PL 126B 493	+Fischer, Burkhardt+	(TASSO Collab.)
RENARD	82	PL 116B 264		(CERN)