Quark and Lepton Compositeness, Searches for

SEARCHES FOR QUARK AND LEPTON COMPOSITENESS

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]

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

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

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

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

	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	—

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 $\mathrm{U}(1)_Y$ gauge couplings, and $W^a_{\mu\nu}$ and $B_{\mu\nu}$ are the field strengths for SU(2) and $\mathrm{U}(1)_Y$ 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:

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

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)

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

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

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

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

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: Λ(e e e e)

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

Λ_{LL}^{+}(TeV)	Λ_{LL}^{-}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>1.6		95	[1,2] BUSKULIC	93Q	RVUE	
	>3.6	95	[3] KROHA	92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>1.6	>2.0	95	[2] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
	>2.2	95	BUSKULIC	93Q	RVUE	
>1.3		95	[3] 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	[4] BRAUNSCH...	88	TASS	E_{cm}=12–46.8 GeV
>1.0	>0.7	95	[5] FERNANDEZ	87B	MAC	E_{cm}=29 GeV
>1.1	>1.4	95	[6] BARTEL	86C	JADE	E_{cm}=12–46.8 GeV
>1.17	>0.87	95	[7] DERRICK	86	HRS	E_{cm}=29 GeV
>1.1	>0.76	95	[8] BERGER	85B	PLUT	E_{cm}=34.7 GeV

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

[2] 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.

[3] 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 $\eta/\Lambda_{LL}^2 = +0.230 \pm 0.206$ TeV^{-2}.

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

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

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

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

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

SCALE LIMITS for Contact Interactions: Λ(e e μ μ)

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

Λ_{LL}^{+}(TeV)	Λ_{LL}^{-}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2.6	**>1.9**	95	[9,10] BUSKULIC	93Q	RVUE	

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

>1.7	>2.2	95	[10] VELISSARIS	94	AMY	E_{cm}=57.8 GeV
>1.3	>1.5	95	[10] 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	[11] KROHA	92	RVUE	
>2.5	>1.5	95	BEHREND	91C	CELL	E_{cm}=35–43 GeV
>1.6	>2.0	95	[12] 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	[13] BARTEL	86C	JADE	E_{cm}=12–46.8 GeV
>2.9	>0.86	95	[14] BERGER	85	PLUT	E_{cm}=34.7 GeV

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

[10] 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.

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

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

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

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

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

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	**>2.9**	95	[15] KROHA	92	RVUE	

• • • 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
>1.6	>2.3	95	BEHREND	91C	CELL	E_{cm}=35–43 GeV
>1.8	>1.3	95	[18] ABE	90I	VNS	E_{cm}=50–60.8 GeV
>2.2	>3.2	95	[19] BARTEL	86	JADE	E_{cm}=12–46.8 GeV

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

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

[19] 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
>3.5	**>2.8**	95	[20,21] BUSKULIC	93Q	RVUE	

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

>3.0	>2.3	95	[21,22] BUSKULIC	93Q	ALEP	E_{cm}=88.25–94.25 GeV
>2.5	>2.2	95	[23] HOWELL	92	TOPZ	E_{cm}=52–61.4 GeV
>3.4	>2.7	95	[24] KROHA	92	RVUE	

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

[21] 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.

[22] From $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, and $\tau^+\tau^-$.

[23] HOWELL 92 limit is from $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$.

[24] 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: $\Lambda(e\,e\,q\,q)$

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

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 2.3	> 1.0	95	[25] AID	95	H1	$(e\,e\,q\,q)$ (u, d quarks)
> 1.7	**> 2.2**	95	[26] ABE	91D	CDF	$(e\,e\,q\,q)$ (u, d quarks)
>1.2		95	[27] ADACHI	91	TOPZ	$(e\,e\,q\,q)$ (flavor-universal)
	>1.7	95	[28] ABE	89L	VNS	$(e\,e\,q\,q)$ (flavor-universal)
• • • We do not use the following data for averages, fits, limits, etc. • • •						
	>1.6	95	[27] ADACHI	91	TOPZ	$(e\,e\,q\,q)$ (flavor-universal)
>0.6	>1.7	95	[29] BEHREND	91C	CELL	$(e\,e\,c\,c)$
>1.1	>1.0	95	[29] BEHREND	91C	CELL	$(e\,e\,b\,b)$
>0.9		95	[28] ABE	89L	VNS	$(e\,e\,q\,q)$ (flavor-universal)
>1.05	>1.61	95	[30] HAGIWARA	89	RVUE	$(e\,e\,c\,c)$
>1.21	>0.53	95	[31] HAGIWARA	89	RVUE	$(e\,e\,b\,b)$

[25] AID 95 limits are from the Q^2 spectrum measurement of $e\,p \to e\,X$.

[26] ABE 91D limits are from e^+e^- mass distribution in $p\overline{p} \to e^+e^-\,X$ at $E_{cm} = 1.8$ TeV.

[27] ADACHI 91 limits are from differential jet cross section. Universality of $\Lambda(e\,e\,q\,q)$ for five flavors is assumed.

[28] ABE 89L limits are from jet charge asymmetry. Universality of $\Lambda(e\,e\,q\,q)$ for five flavors is assumed.

[29] BEHREND 91C is from data at $E_{cm} = 35$–43 GeV.

[30] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurements of D/D^* mesons by ALTHOFF 83C, BARTEL 84E, and BARINGER 88.

[31] 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
>1.4	**>1.6**	95	ABE	92B CDF	$(\mu\,\mu\,q\,q)$ (isosinglet)

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

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3.10	90	[32] 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		[33] DIAZCRUZ	94	RVUE	$\Lambda^{+}_{LL}(\tau\,\nu_\tau\,e\,\nu_e)$
>8.1		[33] DIAZCRUZ	94	RVUE	$\Lambda^{-}_{LL}(\tau\,\nu_\tau\,e\,\nu_e)$
>4.1		[34] DIAZCRUZ	94	RVUE	$\Lambda^{+}_{LL}(\tau\,\nu_\tau\,\mu\,\nu_\mu)$
>6.5		[34] DIAZCRUZ	94	RVUE	$\Lambda^{-}_{LL}(\tau\,\nu_\tau\,\mu\,\nu_\mu)$

[32] JODIDIO 86 limit is from $\mu^+ \to \overline{\nu}_\mu\,e^+\,\nu_e$. Chirality invariant interactions $L = (g^2/\Lambda^2)$ $[\eta_{LL}\,(\overline{\nu}_\mu\,L\gamma^\alpha\mu_L)\,(\overline{e}_L\gamma_\alpha\nu_e\,L) + \eta_{LR}\,(\overline{\nu}_\mu\,L\gamma^\alpha\nu_e\,L\,(\overline{e}_R\gamma_\alpha\mu_R)]$ with $g^2/4\pi = 1$ and $(\eta_{LL},\eta_{LR}) = (0,\pm1)$ are taken. No limits are given for $\Lambda^{\pm}_{LL}$ with $(\eta_{LL},\eta_{LR}) = (\pm1,0)$. For more general constraints with right-handed neutrinos and chirality nonconserving contact interactions, see their text.

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

[34] 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: $\Lambda(q\,q\,q\,q)$

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
		[35] ABE	96	CDF	$p\overline{p} \to$ jets inclusive
>1.4	95	[36] ABE	92D	CDF	$p\overline{p} \to$ jets inclusive

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

>1.3	95	[37] ABE	93G	CDF	$p\overline{p} \to$ dijet mass
>1.0	99	[38] ABE	92M	CDF	$p\overline{p} \to$ dijet angl.
>0.825	95	[39] ALITTI	91B	UA2	$p\overline{p} \to$ jets inclusive
>0.700	95	[36] ABE	89	CDF	$p\overline{p} \to$ jets inclusive
>0.330	95	[40] ABE	89H	CDF	$p\overline{p} \to$ dijet angl.
>0.400	95	[41] ARNISON	86C	UA1	$p\overline{p} \to$ jets inclusive
>0.415	95	[42] ARNISON	86D	UA1	$p\overline{p} \to$ dijet angl.
>0.370	95	[43] APPEL	85	UA2	$p\overline{p} \to$ jets inclusive
>0.275	95	[44] BAGNAIA	84C	UA2	Repl. by APPEL 85

[35] 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.

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

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

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

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

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

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

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

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

[44] BAGNAIA 84C limit is from the study of jet p_T and dijet mass distributions at the CERN $\overline{p}p$ collider ($E_{\rm cm} = 540$ 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 $e^+e^- \to e^{*+}e^{*-}$ 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 $e^* \to e\gamma$ 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*
>45.6	95	ADRIANI	93M	L3	$Z \to e^*e^*$
>45.6	95	ABREU	92C	DLPH	$Z \to e^*e^*$
>46.1	95	DECAMP	92	ALEP	$Z \to e^*e^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \to e^*e^*$

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

>29.8	95	[45] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[46] DECAMP	92	ALEP	$Z \to e^* e^*$; $\Gamma(Z)$
>33	95	[46] ABREU	91F	DLPH	$Z \to e^* e^*$; $\Gamma(Z)$
>45.0	95	[47] ADEVA	90F	L3	$Z \to e^* e^*$
>44.6	95	[48] DECAMP	90G	ALEP	$e^+ e^- \to e^* e^*$
>30.2	95	ADACHI	89B	TOPZ	$e^+ e^- \to e^* e^*$
>28.3	95	KIM	89	AMY	$e^+ e^- \to e^* e^*$
>27.9	95	[49] ABE	88B	VNS	$e^+ e^- \to e^* e^*$

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

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

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

[48] Superseded by DECAMP 92.

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

Limits for Excited e (e*) from Single Production

These limits are from $e^+ e^- \to e^* e$, $W \to e^* \nu$, or $ep \to e^* X$ and depend on transition magnetic coupling between e and e^*. All limits assume $e^* \to e\gamma$ 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
>89	95	ADRIANI	93M	L3	$Z \to ee^*$, $\lambda_Z > 0.5$
>88	95	ABREU	92C	DLPH	$Z \to ee^*$, $\lambda_Z > 0.5$
>91	95	DECAMP	92	ALEP	$Z \to ee^*$, $\lambda_Z > 1$
>87	95	AKRAWY	90I	OPAL	$Z \to ee^*$, $\lambda_Z > 0.5$

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

		[50] DERRICK	95B	ZEUS	$ep \to e^* X$
		[51] ABT	93	H1	$ep \to e^* X$
>86	95	ADRIANI	93M	L3	$\lambda_\gamma > 0.04$
		[52] DERRICK	93B	ZEUS	Superseded by DERRICK 95B
>86	95	ABREU	92C	DLPH	$e^+ e^- \to ee^*$, $\lambda_\gamma > 0.1$
>88	95	[53] ADEVA	90F	L3	$Z \to ee^*$, $\lambda_Z > 0.5$
>86	95	[53] ADEVA	90F	L3	$Z \to ee^*$, $\lambda_Z > 0.04$
>81	95	[54] DECAMP	90G	ALEP	$Z \to ee^*$, $\lambda_Z > 1$
>50	95	ADACHI	89B	TOPZ	$e^+ e^- \to ee^*$, $\lambda_\gamma > 0.04$
>56	95	KIM	89	AMY	$e^+ e^- \to ee^*$, $\lambda_\gamma > 0.03$
none 23–54	95	[55] ABE	88B	VNS	$e^+ e^- \to ee^*$ $\lambda_\gamma > 0.04$
>75	95	[56] ANSARI	87D	UA2	$W \to e^* \nu$; $\lambda_W > 0.7$
>63	95	[56] ANSARI	87D	UA2	$W \to e^* \nu$; $\lambda_W > 0.2$
>40	95	[56] ANSARI	87D	UA2	$W \to e^* \nu$; $\lambda_W > 0.09$

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

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

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

[53] Superseded by ADRIANI 93M.

[54] Superseded by DECAMP 92.

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

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

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

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
>146	95	ACCIARRI	95G	L3	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[57] BUSKULIC	93Q	ALEP	
>127	95	[58] ADRIANI	92B	L3	
>114	95	[59] BARDADIN-...	92	RVUE	
> 99	95	DECAMP	92	ALEP	
		[60] 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	[61] ABE	89J	VNS	η_L=1, η_R=0
> 90.2	95	ADACHI	89B	TOPZ	
> 65	95	KIM	89	AMY	

[57] 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^*}.

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

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

[60] 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.

[61] 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. • • •				
	[62] DORENBOS...	89	CHRM	$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$
	[63] GRIFOLS	86	THEO	$\nu_\mu e \to \nu_\mu e$
	[64] RENARD	82	THEO	$g-2$ of electron

[62] 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 $\Lambda_{cut} = 1$ 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.

[63] 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.

[64] 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
>45.6	95	ADRIANI	93M	L3	$Z \to \mu^*\mu^*$
>45.6	95	ABREU	92C	DLPH	$Z \to \mu^*\mu^*$
>46.1	95	DECAMP	92	ALEP	$Z \to \mu^*\mu^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \to \mu^*\mu^*$

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

>29.8	95	[65] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[66] DECAMP	92	ALEP	$Z \to \mu^* \mu^*$; $\Gamma(Z)$
>33	95	[66] ABREU	91F	DLPH	$Z \to \mu^* \mu^*$; $\Gamma(Z)$
>45.3	95	[67] ADEVA	90F	L3	$Z \to \mu^* \mu^*$
>44.6	95	[68] 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	$e^+ e^- \to \mu^* \mu^*$

[65] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)<36$ MeV.
[66] Limit is independent of μ^* decay mode.
[67] Superseded by ADRIANI 93M.
[68] 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. • • •

>85	95	[69] ADEVA	90F	L3	$Z \to \mu\mu^*$, $\lambda_Z > 1$
>75	95	[69] ADEVA	90F	L3	$Z \to \mu\mu^*$, $\lambda_Z > 0.1$
>80	95	[70] DECAMP	90G	ALEP	$e^+ e^- \to \mu\mu^*$, λ_Z=1
>50	95	ADACHI	89B	TOPZ	$e^+ e^- \to \mu\mu^*$, λ_γ=0.7
>46	95	KIM	89	AMY	$e^+ e^- \to \mu\mu^*$, λ_γ=0.2

[69] Superseded by ADRIANI 93M.
[70] 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. • • •				
	[71] RENARD	82	THEO	$g-2$ of muon

[71] 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 $e^+ e^- \to \tau^{*+} \tau^{*-}$ 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 $\tau^* \to \tau\gamma$ 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
>45.6	95	ADRIANI	93M	L3	$Z \to \tau^* \tau^*$
>45.3	95	ABREU	92C	DLPH	$Z \to \tau^* \tau^*$
>46.0	95	DECAMP	92	ALEP	$Z \to \tau^* \tau^*$
>44.9	95	AKRAWY	90I	OPAL	$Z \to \tau^* \tau^*$

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

>29.8	95	[72] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>26.1	95	[73] DECAMP	92	ALEP	$Z \to \tau^*\tau^*$; $\Gamma(Z)$
>33	95	[73] ABREU	91F	DLPH	$Z \to \tau^*\tau^*$; $\Gamma(Z)$
>45.5	95	[74] ADEVA	90L	L3	$Z \to \tau^*\tau^*$
>41.2	95	[75] DECAMP	90G	ALEP	$e^+e^- \to \tau^*\tau^*$
>29.0	95	ADACHI	89B	TOPZ	$e^+e^- \to \tau^*\tau^*$

[72] BARDADIN-OTWINOWSKA 92 limit is independent of decay modes. Based on $\Delta\Gamma(Z)<36$ MeV.
[73] Limit is independent of τ^* decay mode.
[74] Superseded by ADRIANI 93M.
[75] Superseded by DECAMP 92.

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

These limits are from $e^+e^- \to \tau^*\tau$ and depend on transition magnetic coupling between τ and τ^*. All limits assume $\tau^* \to \tau\gamma$ 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	$Z \to \tau\tau^*$, $\lambda_Z > 0.5$
>87	95	ABREU	92C	DLPH	$Z \to \tau\tau^*$, $\lambda_Z > 0.5$
>90	95	DECAMP	92	ALEP	$Z \to \tau\tau^*$, $\lambda_Z > 0.18$
>86.5	95	AKRAWY	90I	OPAL	$Z \to \tau\tau^*$, $\lambda_Z > 1$

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

>88	95	[76] ADEVA	90L	L3	$Z \to \tau\tau^*$, $\lambda_Z > 1$
>59	95	[77] DECAMP	90G	ALEP	$Z \to \tau\tau^*$, $\lambda_Z = 1$
>40	95	[78] BARTEL	86	JADE	$e^+e^- \to \tau\tau^*$, $\lambda_\gamma = 1$
>41.4	95	[79] BEHREND	86	CELL	$e^+e^- \to \tau\tau^*$, $\lambda_\gamma = 1$
>40.8	95	[79] BEHREND	86	CELL	$e^+e^- \to \tau\tau^*$, $\lambda_\gamma = 0.7$

[76] Superseded by ADRIANI 93M.
[77] Superseded by DECAMP 92.
[78] BARTEL 86 is at $E_{cm} = 30$–46.78 GeV.
[79] 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 $Z \to \nu^*\nu^*$ decay 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. 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
>47	95	[80] DECAMP	92	ALEP	

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

>43.7	95	[81] BARDADIN-...	92	RVUE	$\Gamma(Z)$
>42.6	95	[82] DECAMP	92	ALEP	$\Gamma(Z)$
>35.4	95	[83,84] DECAMP	90O	ALEP	$\Gamma(Z)$
>46	95	[84,85] DECAMP	90O	ALEP	

[80] 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^*, $B(\nu^* \to \nu\gamma) = 1$.
[81] 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^*.
[82] Limit is for Dirac ν^*. The limit is 34.6 GeV for Majorana ν^*, 45.4 GeV for homodoublet ν^*.
[83] 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^*.
[84] Superseded by DECAMP 92.
[85] 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 $Z \to \nu\nu^*$ or $ep \to \nu^* X$ 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
>91	95	ADRIANI	93M	L3	$\lambda_Z > 1$, $\nu^* \to \nu\gamma$
>89	95	ADRIANI	93M	L3	$\lambda_Z > 1$, $\nu^*_e \to eW$
>91	95	[86] DECAMP	92	ALEP	$\lambda_Z > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[87] DERRICK	95B	ZEUS	$ep \to \nu^* X$
		[88] ABT	93	H1	$ep \to \nu^* X$
>87	95	ADRIANI	93M	L3	$\lambda_Z > 0.1$, $\nu^* \to \nu\gamma$
>74	95	ADRIANI	93M	L3	$\lambda_Z > 0.1$, $\nu^*_e \to eW$
		[89] BARDADIN-...	92	RVUE	
>74	95	[86] DECAMP	92	ALEP	$\lambda_Z > 0.034$
>91	95	[90,91] ADEVA	900	L3	$\lambda_Z > 1$
>83	95	[91] ADEVA	900	L3	$\lambda_Z > 0.1$, $\nu^* \to \nu\gamma$
>74	95	[91] ADEVA	900	L3	$\lambda_Z > 0.1$, $\nu^*_e \to eW$
>90	95	[92,93] DECAMP	900	ALEP	$\lambda_Z > 1$
>74.7	95	[92,93] DECAMP	900	ALEP	$\lambda_Z > 0.06$

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

[87] DERRICK 95B search for single ν^* production via $\nu^* eW$ coupling in ep collisions with the decays $\nu^* \to \nu\gamma$, νZ, eW. See their Fig. 14 for the exclusion plot in the m_{ν^*}–λ_γ plane.

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

[89] See Fig. 5 of BARDADIN-OTWINOWSKA 92 for combined limit of ADEVA 900, DECAMP 900, and DECAMP 92.

[90] Limit is either for $\nu^* \to \nu\gamma$ or $\nu^* \to eW$.

[91] Superseded by ADRIANI 93M.

[92] DECAMP 900 limit based on $B(Z \to \nu\nu^*) \cdot B(\nu^* \to \nu\gamma) < 6 \times 10^{-5}$ (95%CL), assuming $B(\nu^* \to \nu\gamma) = 1$.

[93] Superseded by DECAMP 92.

MASS LIMITS for Excited q (q^*)

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

These limits are obtained from $e^+e^- \to q^*\overline{q}^*$ 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	[94] ADRIANI	93M	L3	u or d type, $Z \to q^*q^*$
>45	95	[95] DECAMP	92	ALEP	u or d type, $Z \to q^*q^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[96] ADRIANI	92F	L3	$Z \to q^*q^*$
>41.7	95	[97] BARDADIN-...	92	RVUE	u-type, $\Gamma(Z)$
>44.7	95	[97] BARDADIN-...	92	RVUE	d-type, $\Gamma(Z)$
>40.6	95	[98] DECAMP	92	ALEP	u-type, $\Gamma(Z)$
>44.2	95	[98] DECAMP	92	ALEP	d-type, $\Gamma(Z)$
>45	95	[98] ABREU	91F	DLPH	u-type, $\Gamma(Z)$
>45	95	[98] ABREU	91F	DLPH	d-type, $\Gamma(Z)$
>21.1	95	[99] BEHREND	86C	CELL	$e(q^*) = -1/3$, $q^* \to qg$
>22.3	95	[99] BEHREND	86C	CELL	$e(q^*) = 2/3$, $q^* \to qg$
>22.5	95	[99] BEHREND	86C	CELL	$e(q^*) = -1/3$, $q^* \to q\gamma$
>23.2	95	[99] BEHREND	86C	CELL	$e(q^*) = 2/3$, $q^* \to q\gamma$

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

[95] Limit is for $B(q^* \to qg) + B(q^* \to q\gamma) = 1$.

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

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

[98] These limits are independent of decay modes.

[99] BEHREND 86C search for $e^+e^- \to q^*\overline{q}^*$ 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 $e^+e^- \to q^*\overline{q}$ or $p\overline{p} \to q^*X$ 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 80–570	95	[100] ABE	95N	CDF	$p\overline{p} \to q^*X$, $q^* \to qg$ $q\gamma$, qW
>288	90	[101] ALITTI	93	UA2	$p\overline{p} \to q^*X$, $q^* \to qg$
> 88	95	[102] DECAMP	92	ALEP	$Z \to qq^*$, λ_Z >1
> 86	95	[102] AKRAWY	90J	OPAL	$Z \to qq^*$, $\lambda_Z > 1.2$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[103] DERRICK	95B	ZEUS	$ep \to q^*X$
none 80–540	95	[104] ABE	94	CDF	$p\overline{p} \to q^*X$, $q^* \to q\gamma$, qW
> 79	95	[105] ADRIANI	93M	L3	λ_Z(L3)> 0.06
		[106] ABREU	92D	DLPH	$Z \to qq^*$
		[107] ADRIANI	92F	L3	$Z \to qq^*$
> 75	95	[105] DECAMP	92	ALEP	$Z \to qq^*$, λ_Z >1
		[108] ALBAJAR	89	UA1	$p\overline{p} \to q^*X$, $q^* \to qW$
> 39	95	[109] BEHREND	86C	CELL	$e^+e^- \to q^*\overline{q}$ ($q^* \to qg, q\gamma$), λ_γ=1

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

[101] 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 $m_{d^*} \gg m_{u^*}$ ($m_{u^*} \gg m_{d^*}$).

[102] Assumes B($q^* \to q\gamma$) = 0.1.

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

[104] ABE 94 search for resonances in jet-γ and jet-W invariant mass in $p\overline{p}$ collisions at E_{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.

[105] Assumes B($q^* \to qg$) = 1.

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

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

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

[109] BEHREND 86C has E_{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	[110] ABE	89D	CDF	$p\overline{p} \to q_6\overline{q}_6$

[110] 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	[111] ABE	89D	CDF	Stable ℓ_8: $p\overline{p} \to \ell_8\overline{\ell}_8$

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

		[112] ABT	93	H1	e_8: $ep \to e_8 X$
none 3.0–30.3	95	[113] KIM	90	AMY	e_8: $e^+e^- \to ee +$ jets
none 3.5–30.3	95	[113] KIM	90	AMY	μ_8: $e^+e^- \to \mu\mu +$ jets
		[114] KIM	90	AMY	e_8: $e^+e^- \to gg$; R
>19.8	95	[115] BARTEL	87B	JADE	e_8, μ_8, τ_8: e^+e^-; R
none 5–23.2	95	[115] BARTEL	87B	JADE	μ_8: $e^+e^- \to \mu\mu +$ jets
		[116] BARTEL	85K	JADE	e_8: $e^+e^- \to gg$; R

[111] 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.

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

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

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

[115] 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.

[116] In BARTEL 85K, R can be affected by $e^+e^- \to gg$ 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	[117] BARGER	89	RVUE	ν_8: $p\overline{p} \to \nu_8\overline{\nu}_8$

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

none 3.8–29.8	95	[118] KIM	90	AMY	ν_8: $e^+e^- \to$ acoplanar jets
none 9–21.9	95	[119] BARTEL	87B	JADE	ν_8: $e^+e^- \to$ acoplanar jets

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

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

[119] 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. • • •				
	[120] ALBAJAR	89	UA1	$p\overline{p} \to W_8 X$, $W_8 \to Wg$

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

Limits on $ZZ\gamma$ Coupling

Limits are for the electric dipole transition form factor for $Z \to \gamma Z^*$ 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	$Z \to \gamma\nu\overline{\nu}$

REFERENCES FOR Searches for Quark and Lepton Compositeness

ABE 96 PRL (submitted) +Akimoto, Akopian, Albrow+ (CDF Collab.)
CDF/ANAL/JET/CDFR/2995
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)