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# Quark and Lepton Compositeness, Searches for

## SEARCHES FOR QUARK AND LEPTON COMPOSITENESS

Revised 2001 by K. Hagiwara (KEK), and K. Hikasa and M. Tanabashi (Tohoku University).

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 ($\Lambda$), these interactions are suppressed by inverse powers of $\Lambda$. 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 $\Lambda$. We may determine the scale $\Lambda$ 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

$$\begin{aligned}
\Lambda &= \Lambda^{\pm}_{LL} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1, 0, 0) \ , \\
\Lambda &= \Lambda^{\pm}_{RR} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (0, \pm1, 0) \ , \\
\Lambda &= \Lambda^{\pm}_{VV} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1, \pm1, \pm1) \ , \\
\Lambda &= \Lambda^{\pm}_{AA} \ \text{ for } \ (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm1, \pm1, \mp1) \ , \qquad (2)
\end{aligned}$$

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 ($\ell^*$ 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

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

$\nu_R^*$ is necessary unless $\nu^*$ 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 |
|---|---|---|---|
| $V^{\ell^*}$ | $-\frac{1}{2}+2\sin^2\theta_W$ | $-\frac{1}{2}+2\sin^2\theta_W$ | $-1+2\sin^2\theta_W$ |
| $A^{\ell^*}$ | $-\frac{1}{2}$ | $+\frac{1}{2}$ | $0$ |
| $V^{\nu_D^*}$ | $+\frac{1}{2}$ | $+\frac{1}{2}$ | $+1$ |
| $A^{\nu_D^*}$ | $+\frac{1}{2}$ | $-\frac{1}{2}$ | $0$ |
| $V^{\nu_M^*}$ | $0$ | $0$ | — |
| $A^{\nu_M^*}$ | $+1$ | $-1$ | — |

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

Here $\nu_D^*$ ($\nu_M^*$) 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 parameterized as follows:

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

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

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

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 $\lambda$.

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

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

where $L$ denotes the lepton doublet $(\nu, \ell)$, $\Lambda$ 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 $\ell^*$ and $\nu^*$ couplings become unrelated, and the couplings receive the extra suppression of $(250\,\text{GeV})/\Lambda$ or $m_{L^*}/\Lambda$. 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.

It should be noted that the electromagnetic radiative decay of $\ell^*(\nu^*)$ is forbidden if $f = -f'$ $(f = f')$. These two possibilities ($f = f'$ and $f = -f'$) are investigated in many analyses of the LEP experiments above the Z pole.

Several different conventions are used by LEP experiments on Z pole to express the transition magnetic couplings. To facilitate comparison, we re-express these in terms of $\lambda_Z$ and $\lambda_\gamma$ 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)

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

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

2. ALEPH (quark)

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

3. L3 and DELPHI (charged lepton)

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

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)

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

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 ($\ell_8$) and the ordinary lepton ($\ell$) 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.

| $\Lambda^{+}_{LL}$(TeV) | $\Lambda^{-}_{LL}$(TeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **>8.3** | **>10.3** | 95 | [1] BOURILKOV | 01 | RVUE | $E_{cm}$= 192–208 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >3.8 | >5.6 | 95 | ABBIENDI | 00R | OPAL | $E_{cm}$= 189 GeV |
| >4.4 | >5.4 | 95 | ABREU | 00S | DLPH | $E_{cm}$= 183–189 GeV |
| >4.3 | >4.9 | 95 | ACCIARRI | 00P | L3 | $E_{cm}$= 130–189 GeV |
| >3.5 | >3.2 | 95 | BARATE | 00I | ALEP | $E_{cm}$= 130–183 GeV |
| >6.0 | >7.7 | 95 | [2] BOURILKOV | 00 | RVUE | $E_{cm}$= 183–189 GeV |
| >3.1 | >3.8 | 95 | ABBIENDI | 99 | OPAL | $E_{cm}$= 130–136, 161–172, 183 GeV |
| >2.2 | >2.8 | 95 | ABREU | 99A | DLPH | $E_{cm}$= 130–172 GeV |
| >2.7 | >2.4 | 95 | ACCIARRI | 98J | L3 | $E_{cm}$= 130–172 GeV |
| >3.0 | >2.5 | 95 | ACKERSTAFF | 98V | OPAL | $E_{cm}$= 130–172 GeV |
| >2.4 | >2.2 | 95 | ACKERSTAFF | 97C | OPAL | $E_{cm}$= 130–136, 161 GeV |
| >1.7 | >2.3 | 95 | 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 | |
| | >3.6 | 95 | [5] KROHA | 92 | RVUE | |
| >1.3 | | 95 | [5] 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 | [6] BRAUNSCH... | 88 | TASS | $E_{cm}$=12–46.8 GeV |
| >1.0 | >0.7 | 95 | [7] FERNANDEZ | 87B | MAC | $E_{cm}$=29 GeV |
| >1.1 | >1.4 | 95 | [8] BARTEL | 86C | JADE | $E_{cm}$=12–46.8 GeV |
| >1.17 | >0.87 | 95 | [9] DERRICK | 86 | HRS | $E_{cm}$=29 GeV |
| >1.1 | >0.76 | 95 | [10] BERGER | 85B | PLUT | $E_{cm}$=34.7 GeV |

[1] A combined analysis of the data from ALEPH, DELPHI, L3, and OPAL.

[2] A combined analysis of the data from ALEPH, L3, and OPAL.

[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 re-analyzed by KROHA 92.

[5] 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$^{-2}$.

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

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

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

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

[10] 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.

| $\Lambda^{+}_{LL}$(TeV) | $\Lambda^{-}_{LL}$(TeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| >6.6 | **> 6.3** | 95 | ABREU | 00S | DLPH | $E_{cm}$= 183–189 GeV |
| **> 8.5** | >3.8 | 95 | ACCIARRI | 00P | L3 | $E_{cm}$= 130–189 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >7.3 | >4.6 | 95 | ABBIENDI | 00R | OPAL | $E_{cm}$= 189 GeV |
| >4.0 | >4.7 | 95 | BARATE | 00I | ALEP | $E_{cm}$= 130–183 GeV |
| >4.5 | >4.3 | 95 | ABBIENDI | 99 | OPAL | $E_{cm}$= 130–136, 161–172, 183 GeV |
| >3.4 | >2.7 | 95 | ABREU | 99A | DLPH | $E_{cm}$= 130–172 GeV |
| >3.6 | >2.4 | 95 | ACCIARRI | 98J | L3 | $E_{cm}$= 130–172 GeV |
| >2.9 | >3.4 | 95 | ACKERSTAFF | 98V | OPAL | $E_{cm}$= 130–172 GeV |
| >3.1 | >2.0 | 95 | MIURA | 98 | VNS | $E_{cm}$= 57.77 GeV |
| >2.4 | >2.9 | 95 | ACKERSTAFF | 97C | OPAL | $E_{cm}$= 130–136, 161 GeV |
| >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 |
| >2.6 | >1.9 | 95 | [11,12] BUSKULIC | 93Q | RVUE | |
| >2.3 | >2.0 | 95 | HOWELL | 92 | TOPZ | $E_{cm}$=52–61.4 GeV |
| | >1.7 | 95 | [13] KROHA | 92 | RVUE | |
| >2.5 | >1.5 | 95 | BEHREND | 91C | CELL | $E_{cm}$=35–43 GeV |
| >1.6 | >2.0 | 95 | [14] 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 | [15] BARTEL | 86C | JADE | $E_{cm}$=12–46.8 GeV |
| >2.9 | >0.86 | 95 | [16] BERGER | 85 | PLUT | $E_{cm}$=34.7 GeV |

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

[13] 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$^{-2}$.

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

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

[16] 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.

| $\Lambda^{+}_{LL}$(TeV) | $\Lambda^{-}_{LL}$(TeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| >3.9 | **> 6.5** | 95 | ABBIENDI | 00R | OPAL | $E_{cm}$= 189 GeV |
| **> 5.4** | >4.7 | 95 | ACCIARRI | 00P | L3 | $E_{cm}$= 130–189 GeV |

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

| | | | | | |
|---|---|---|---|---|---|
| >5.2 | >5.4 | 95 | ABREU 00S | DLPH | $E_{cm}$= 183–189 GeV |
| >3.9 | >3.7 | 95 | BARATE 00I | ALEP | $E_{cm}$= 130–183 GeV |
| >3.8 | >4.0 | 95 | ABBIENDI 99 | OPAL | $E_{cm}$= 130–136, 161–172, 183 GeV |
| >2.8 | >2.6 | 95 | ABREU 99A | DLPH | $E_{cm}$= 130–172 GeV |
| >2.4 | >2.8 | 95 | ACCIARRI 98J | L3 | $E_{cm}$= 130–172 GeV |
| >2.3 | >3.7 | 95 | ACKERSTAFF 98V | OPAL | $E_{cm}$= 130–172 GeV |
| >1.9 | >3.0 | 95 | ACKERSTAFF 97C | OPAL | $E_{cm}$= 130–136, 161 GeV |
| >1.4 | >2.0 | 95 | [17] VELISSARIS 94 | AMY | $E_{cm}$=57.8 GeV |
| >1.0 | >1.5 | 95 | [17] BUSKULIC 93Q | ALEP | $E_{cm}$=88.25–94.25 GeV |
| >1.8 | >2.3 | 95 | [17,18] BUSKULIC 93Q | RVUE | |
| >1.9 | >1.7 | 95 | HOWELL 92 | TOPZ | $E_{cm}$=52–61.4 GeV |
| >1.9 | >2.9 | 95 | [19] KROHA 92 | RVUE | |
| >1.6 | >2.3 | 95 | BEHREND 91C | CELL | $E_{cm}$=35–43 GeV |
| >1.8 | >1.3 | 95 | [20] ABE 90I | VNS | $E_{cm}$=50–60.8 GeV |
| >2.2 | >3.2 | 95 | [21] BARTEL 86 | JADE | $E_{cm}$=12–46.8 GeV |

[17] 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.

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

[19] 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$^{-2}$.

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

[21] 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.

| $\Lambda^{+}_{LL}$(TeV) | $\Lambda^{-}_{LL}$(TeV) | *CL%* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| >7.3 | **> 7.8** | 95 | ABREU 00S | DLPH | $E_{cm}$= 183–189 GeV |
| **> 9.0** | >5.2 | 95 | ACCIARRI 00P | L3 | $E_{cm}$= 130–189 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >6.4 | >7.2 | 95 | ABBIENDI 00R | OPAL | $E_{cm}$= 189 GeV |
| >5.3 | >5.5 | 95 | BARATE 00I | ALEP | $E_{cm}$= 130–183 GeV |
| >5.2 | >5.3 | 95 | ABBIENDI 99 | OPAL | $E_{cm}$= 130–136, 161–172, 183 GeV |
| >4.4 | >4.2 | 95 | ABREU 99A | DLPH | $E_{cm}$= 130–172 GeV |
| >4.0 | >3.1 | 95 | [22] ACCIARRI 98J | L3 | $E_{cm}$= 130–172 GeV |
| >3.4 | >4.4 | 95 | ACKERSTAFF 98V | OPAL | $E_{cm}$= 130–172 GeV |
| >2.7 | >3.8 | 95 | ACKERSTAFF 97C | OPAL | $E_{cm}$= 130–136, 161 GeV |
| >3.0 | >2.3 | 95 | [22,23] BUSKULIC 93Q | ALEP | $E_{cm}$=88.25–94.25 GeV |
| >3.5 | >2.8 | 95 | [23,24] BUSKULIC 93Q | RVUE | |
| >2.5 | >2.2 | 95 | [25] HOWELL 92 | TOPZ | $E_{cm}$=52–61.4 GeV |
| >3.4 | >2.7 | 95 | [26] KROHA 92 | RVUE | |

[22] From $e^+ e^- \rightarrow e^+ e^-$, $\mu^+ \mu^-$, and $\tau^+ \tau^-$.
[23] 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.
[24] This BUSKULIC 93Q value is from ALEPH data plus PEP/PETRA/TRISTAN data re-analyzed by KROHA 92.
[25] HOWELL 92 limit is from $e^+ e^- \rightarrow \mu^+ \mu^-$ and $\tau^+ \tau^-$.
[26] 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.

| $\Lambda^+_{LL}$(TeV) | $\Lambda^-_{LL}$(TeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|---|
| **>23.3** | **>12.5** | 95 | [27] CHEUNG | 01B | RVUE | ($eeuu$) |
| **>11.1** | **>26.4** | 95 | [27] CHEUNG | 01B | RVUE | ($eedd$) |
| **> 5.6** | **>4.9** | 95 | [28] BARATE | 00I | ALEP | ($eebb$) |
| **> 1.0** | **>2.1** | 95 | [29] ABREU | 99A | DLPH | ($eecc$) |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| > 5.5 | >3.1 | 95 | [30] ABBIENDI | 00R | OPAL | ($eeqq$) |
| > 4.9 | >6.1 | 95 | [30] ABBIENDI | 00R | OPAL | ($eeuu$) |
| > 5.7 | >4.5 | 95 | [30] ABBIENDI | 00R | OPAL | ($eedd$) |
| > 4.2 | >2.8 | 95 | [31] ACCIARRI | 00P | L3 | ($eeqq$) |
| > 2.4 | >1.3 | 95 | [32] ADLOFF | 00 | H1 | ($eeqq$) |
| > 5.4 | >6.2 | 95 | [33] BARATE | 00I | ALEP | ($eeqq$) |
| | | | [34] BREITWEG | 00B | ZEUS | |
| > 4.4 | >2.8 | 95 | [35] ABBIENDI | 99 | OPAL | ($eeqq$) |
| > 4.0 | >4.8 | 95 | [36] ABBIENDI | 99 | OPAL | ($eebb$) |
| > 3.3 | >4.2 | 95 | [37] ABBOTT | 99D | D0 | ($eeqq$) |
| > 2.4 | >2.8 | 95 | [29] ABREU | 99A | DLPH | ($eeqq$) ($d$ or $s$ quark) |
| > 4.4 | >3.9 | 95 | [29] ABREU | 99A | DLPH | ($eebb$) |
| > 1.0 | >2.4 | 95 | [29] ABREU | 99A | DLPH | ($eeuu$) |
| > 4.0 | >3.4 | 95 | [38] ZARNECKI | 99 | RVUE | ($eedd$) |
| > 4.3 | >5.6 | 95 | [38] ZARNECKI | 99 | RVUE | ($eeuu$) |
| > 3.0 | >2.1 | 95 | [39] ACCIARRI | 98J | L3 | ($eeqq$) |
| > 3.4 | >2.2 | 95 | [40] ACKERSTAFF | 98V | OPAL | ($eeqq$) |
| > 4.0 | >2.8 | 95 | [41] ACKERSTAFF | 98V | OPAL | ($eebb$) |
| > 9.3 | >12.0 | 95 | [42] BARGER | 98E | RVUE | ($eeuu$) |
| > 8.8 | >11.9 | 95 | [42] BARGER | 98E | RVUE | ($eedd$) |
| > 2.5 | >3.7 | 95 | [43] ABE | 97T | CDF | ($eeqq$) (isosinglet) |
| > 2.5 | >2.1 | 95 | [44] ACKERSTAFF | 97C | OPAL | ($eeqq$) |
| > 3.1 | >2.9 | 95 | [45] ACKERSTAFF | 97C | OPAL | ($eebb$) |
| > 7.4 | >11.7 | 95 | [46] DEANDREA | 97 | RVUE | $eeuu$, atomic parity violation |
| > 2.3 | >1.0 | 95 | [47] AID | 95 | H1 | ($eeqq$) ($u$, $d$ quarks) |
| 1.7 | >2.2 | 95 | [48] ABE | 91D | CDF | ($eeqq$) ($u$, $d$ quarks) |
| > 1.2 | | 95 | [49] ADACHI | 91 | TOPZ | ($eeqq$) (flavor-universal) |
| | >1.6 | 95 | [49] ADACHI | 91 | TOPZ | ($eeqq$) (flavor-universal) |

| | | | | | | |
|---|---|---|---|---|---|---|
| > 0.6 | >1.7 | 95 | [50] BEHREND | 91C | CELL | ($eecc$) |
| > 1.1 | >1.0 | 95 | [50] BEHREND | 91C | CELL | ($eebb$) |
| > 0.9 | | 95 | [51] ABE | 89L | VNS | ($eeqq$) (flavor-universal) |
| | >1.7 | 95 | [51] ABE | 89L | VNS | ($eeqq$) (flavor-universal) |
| > 1.05 | >1.61 | 95 | [52] HAGIWARA | 89 | RVUE | ($eecc$) |
| > 1.21 | >0.53 | 95 | [53] HAGIWARA | 89 | RVUE | ($eebb$) |

[27] CHEUNG 01B is an update of BARGER 98E.

[28] BARATE 00I limits are from $R_b$ and jet-charge asymmetry at 130–183 GeV.

[29] ABREU 99A limits are from flavor-tagged $e^+e^- \rightarrow q\overline{q}$ cross section at 130–172 GeV.

[30] ABBIENDI 00R limits are from $e^+e^- \rightarrow q\overline{q}$ cross section at $\sqrt{s}$= 130–189 GeV.

[31] ACCIARRI 00P limit is from $e^+e^- \rightarrow qq$ cross section at $\sqrt{s}$=130–189 GeV.

[32] ADLOFF 00 limits are from the $Q^2$ spectrum measurement of $e^+p \rightarrow e^+X$.

[33] BARATE 00I limits are from $e^+e^- \rightarrow q\overline{q}$ cross section and jet-charge asymmetry at 130–183 GeV.

[34] BREITWEG 00B limits are from $Q^2$ spectrum measurement of $e^+p$ collisions. See their Table 3 for the limits of various models.

[35] ABBIENDI 99 limits are from $e^+e^- \rightarrow q\overline{q}$ cross section at 130–136, 161–172, 183 GeV.

[36] ABBIENDI 99 limits are from $R_b$ at 130–136, 161–172, 183 GeV.

[37] ABBOTT 99D limits are from $e^+e^-$ mass distribution in $p\overline{p} \rightarrow e^+e^-X$ at $E_{cm}$= 1.8 TeV.

[38] ZARNECKI 99 use data from HERA, LEP, Tevatron, and various low-energy experiments.

[39] ACCIARRI 98J limits are from $e^+e^- \rightarrow q\overline{q}$ cross section at $E_{cm}$= 130–172 GeV.

[40] ACKERSTAFF 98V limits are from $e^+e^- \rightarrow q\overline{q}$ at $E_{cm}$= 130–172 GeV.

[41] ACKERSTAFF 98V limits are from $R_b$ measurements at $E_{cm}$= 130–172 GeV.

[42] BARGER 98E use data from HERA, LEP, Tevatron, and various low-energy experiments.

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

[44] ACKERSTAFF 97C limits are from $e^+e^- \rightarrow q\overline{q}$ cross section at $E_{cm}$ = 130–136 GeV and 161 GeV.

[45] ACKERSTAFF 97C limits are $R_b$ measurements at $E_{cm}$ = 133 GeV and 161 GeV.

[46] DEANDREA 97 limit is from atomic parity violation of cesium. The limit is eluded if the contact interactions are parity conserving.

[47] AID 95 limits are from the $Q^2$ spectrum measurement of $ep \rightarrow eX$.

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

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

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

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

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

[53] The HAGIWARA 89 limit is derived from forward-backward asymmetry measurement of $b$ hadrons by BARTEL 84D.

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

| $\Lambda^+_{LL}$(TeV) | $\Lambda^-_{LL}$(TeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **> 2.9** | **> 4.2** | 95 | [54] ABE | 97T | CDF | ($\mu\mu qq$) (isosinglet) |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >1.4 | >1.6 | 95 | ABE | 92B | CDF | ($\mu\mu qq$) (isosinglet) |

[54] ABE 97T limits are from $\mu^+\mu^-$ mass distribution in $\overline{p}p \rightarrow \mu^+\mu^- X$ 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 | [55] 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 | | [56] DIAZCRUZ | 94 | RVUE | $\Lambda^{+}_{LL}(\tau \nu_\tau e \nu_e)$ |
| >8.1 | | [56] DIAZCRUZ | 94 | RVUE | $\Lambda^{-}_{LL}(\tau \nu_\tau e \nu_e)$ |
| >4.1 | | [57] DIAZCRUZ | 94 | RVUE | $\Lambda^{+}_{LL}(\tau \nu_\tau \mu \nu_\mu)$ |
| >6.5 | | [57] DIAZCRUZ | 94 | RVUE | $\Lambda^{-}_{LL}(\tau \nu_\tau \mu \nu_\mu)$ |

[55] JODIDIO 86 limit is from $\mu^+ \rightarrow \overline{\nu}_\mu e^+ \nu_e$. 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 $(\eta_{LL},\eta_{LR}) = (0,\pm1)$ 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.

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

[57] DIAZCRUZ 94 limits are from $\Gamma(\tau \rightarrow \mu\nu\nu)$ 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: $\Lambda(e\nu qq)$

| VALUE (TeV) | CL% | DOCUMENT ID | | TECN |
|---|---|---|---|---|
| **>2.81** | 95 | [58] AFFOLDER | 01I | CDF |

[58] AFFOLDER 00I bound is for a scalar interaction $\overline{q}_R q_L \overline{\nu} e_L$.

## 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, unless otherwise noted. See EICHTEN 84 for details.

| VALUE (TeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **>2.7** | 95 | [59] ABBOTT | 99C | D0 | $p\overline{p} \rightarrow$ dijet mass. $\Lambda^{+}_{LL}$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >2.0 | 95 | [60] ABBOTT | 00E | D0 | $H_T$ distribution; $\Lambda^{+}_{LL}$ |
| >2.1 | 95 | [61] ABBOTT | 98G | D0 | $p\overline{p} \rightarrow$ dijet angl. $\Lambda^{+}_{LL}$ |
| | | [62] BERTRAM | 98 | RVUE | $p\overline{p} \rightarrow$ dijet mass |
| | | [63] ABE | 96 | CDF | $p\overline{p} \rightarrow$ jets inclusive |
| >1.6 | 95 | [64] ABE | 96S | CDF | $p\overline{p} \rightarrow$ dijet angl.; $\Lambda^{+}_{LL}$ |
| >1.3 | 95 | [65] ABE | 93G | CDF | $p\overline{p} \rightarrow$ dijet mass |
| >1.4 | 95 | [66] ABE | 92D | CDF | $p\overline{p} \rightarrow$ jets inclusive |
| >1.0 | 99 | [67] ABE | 92M | CDF | $p\overline{p} \rightarrow$ dijet angl. |

| | | | | | |
|---|---|---|---|---|---|
| >0.825 | 95 | [68] ALITTI | 91B | UA2 | $p\overline{p} \to$ jets inclusive |
| >0.700 | 95 | [66] ABE | 89 | CDF | $p\overline{p} \to$ jets inclusive |
| >0.330 | 95 | [69] ABE | 89H | CDF | $p\overline{p} \to$ dijet angl. |
| >0.400 | 95 | [70] ARNISON | 86C | UA1 | $p\overline{p} \to$ jets inclusive |
| >0.415 | 95 | [71] ARNISON | 86D | UA1 | $p\overline{p} \to$ dijet angl. |
| >0.370 | 95 | [72] APPEL | 85 | UA2 | $p\overline{p} \to$ jets inclusive |
| >0.275 | 95 | [73] BAGNAIA | 84C | UA2 | Repl. by APPEL 85 |

[59] The quoted limit is from inclusive dijet mass spectrum in $p\overline{p}$ collisions at $E_{\text{cm}}$=1.8 TeV. ABBOTT 99C also obtain $\Lambda^-_{LL} > 2.4$ TeV. All quarks are assumed composite.

[60] The quoted limit for ABBOTT 00E is from $H_T$ distribution in $p\overline{p}$ collisions at $E_{\text{cm}}$=1.8 TeV. CTEQ4M PDF and $\mu=E_T^{\text{max}}$ are assumed. For limits with different assumptions, see their Tables 2 and 3. All quarks are assumed composite.

[61] ABBOTT 98G limit is from dijet angular distribution in $p\overline{p}$ collisions at $E_{\text{cm}}$= 1.8 TeV. All quarks are assumed composite.

[62] BERTRAM 98 obtain limit on the scale of color-octet axial-vector flavor-universal contact interactions: $\Lambda_{A8} > 2.1$ TeV. They also obtain a limit $\Lambda_{V8} > 2.4$ TeV on a color-octet flavor-universal vectorial contact interaction.

[63] 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.

[64] ABE 96S limit is from dijet angular distribution in $p\overline{p}$ collisions at $E_{\text{cm}}$ = 1.8 TeV. The limit for $\Lambda^-_{LL}$ 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.

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

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

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

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

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

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

[71] 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 ($E_{\text{cm}}$ = 630 GeV). QCD prediction using EHLQ structure function (EICHTEN 84) with $\Lambda_{\text{QCD}}$ = 0.2 GeV for the choice of $Q^2 = {p_T}^2$ gives the best fit to the data.

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

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

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

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

| $\Lambda^{+}_{LL}$(TeV) | $\Lambda^{-}_{LL}$(TeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **>5.0** | **>5.4** | 95 | [74] MCFARLAND | 98 | CCFR | $\nu N$ scattering |

[74] MCFARLAND 98 assumed a flavor universal interaction. Neutrinos were mostly of muon type.

## 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 $\lambda$ 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 $\lambda$ 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 a dominant $e^* \rightarrow e\gamma$ 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 |
|---|---|---|---|---|---|
| **>100.0** | 95 | [75] ACCIARRI | 01D | L3 | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $>$ 91.3 | 95 | [76] ABBIENDI | 00I | OPAL | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| $>$ 94.2 | 95 | [77] ACCIARRI | 00E | L3 | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| $>$ 90.7 | 95 | [78] ABREU | 99O | DLPH | Homodoublet type |
| $>$ 85.0 | 95 | [79] ACKERSTAFF | 98C | OPAL | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| | | [80] BARATE | 98U | ALEP | $Z \rightarrow e^*e^*$ |
| $>$ 79.6 | 95 | [81,82] ABREU | 97B | DLPH | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| $>$ 77.9 | 95 | [81,83] ABREU | 97B | DLPH | $e^+e^- \rightarrow e^*e^*$ Sequential type |
| $>$ 79.7 | 95 | [81] ACCIARRI | 97G | L3 | $e^+e^- \rightarrow e^*e^*$ Sequential type |
| $>$ 79.9 | 95 | [81,84] ACKERSTAFF | 97 | OPAL | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| $>$ 62.5 | 95 | [85] ABREU | 96K | DLPH | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| $>$ 64.7 | 95 | [86] ACCIARRI | 96D | L3 | $e^+e^- \rightarrow e^*e^*$ Sequential type |
| $>$ 66.5 | 95 | [86] ALEXANDER | 96Q | OPAL | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| $>$ 65.2 | 95 | [86] 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 | [87] BARDADIN-... | 92 | RVUE | $\Gamma(Z)$ |
| $>26.1$ | 95 | [88] DECAMP | 92 | ALEP | $Z \rightarrow e^* e^*$; $\Gamma(Z)$ |
| $>46.1$ | 95 | DECAMP | 92 | ALEP | $Z \rightarrow e^* e^*$ |
| $>33$ | 95 | [88] ABREU | 91F | DLPH | $Z \rightarrow e^* e^*$; $\Gamma(Z)$ |
| $>45.0$ | 95 | [89] ADEVA | 90F | L3 | $Z \rightarrow e^* e^*$ |
| $>44.9$ | 95 | AKRAWY | 90I | OPAL | $Z \rightarrow e^* e^*$ |
| $>44.6$ | 95 | [90] 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 | [91] ABE | 88B | VNS | $e^+ e^- \rightarrow e^* e^*$ |

[75] From $e^+ e^-$ collisions at $\sqrt{s}$ = 192–202 GeV. $f$=$f'$ is assumed. ACCIARRI 01D also obtain limit for $f$=$-f'$: $m_{e^*} > 93.4$ GeV.

[76] From $e^+ e^-$ collisions at $\sqrt{s}$=161–183 GeV. $f=f'$ is assumed. ABBIENDI 00I also obtain limit for $f=-f'$ ($e^* \rightarrow \nu W$): $m_{e^*} > 86.0$ GeV.

[77] From $e^+ e^-$ collisions at $\sqrt{s}$=189 GeV. $f=f'$ is assumed. ACCIARRI 00E also obtain limit for $f=-f'$ ($e^* \rightarrow \nu W$): $m_{e^*} > 92.6$ GeV.

[78] From $e^+ e^-$ collisions at $\sqrt{s}$= 183 GeV. $f=f'$ is assumed. ABREU 99O also obtain limit for $f=-f'$ ($e^* \rightarrow \nu W$): $m_{e^*} > 81.3$ GeV.

[79] 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.

[80] BARATE 98U obtain limits on the form factor. See their Fig. 14 for limits in mass-form factor plane.

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

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

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

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

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

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

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

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

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

[90] Superseded by DECAMP 92.

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

## 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* |
|---|---|---|---|---|---|
| **>223** | 95 | [92] ADLOFF | 00E | H1 | $ep \rightarrow e^* X$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >202 | | [93] ACCIARRI | 01D | L3 | $e^+e^- \rightarrow ee^*$ |
| | | [94] ABBIENDI | 00I | OPAL | $e^+e^- \rightarrow ee^*$ |
| | | [95] ACCIARRI | 00E | L3 | $e^+e^- \rightarrow ee^*$ |
| | | [96] ABREU | 99O | DLPH | $e^+e^- \rightarrow ee^*$ |
| none 20–170 | 95 | [97] ACCIARRI | 98T | L3 | $e\gamma \rightarrow e^* \rightarrow e\gamma$ |
| | | [98] ACKERSTAFF | 98C | OPAL | $e^+e^- \rightarrow ee^*$ |
| | | [99] BARATE | 98U | ALEP | $e^+e^- \rightarrow ee^*$ |
| | | [100,101] ABREU | 97B | DLPH | $e^+e^- \rightarrow ee^*$ |
| | | [100,102] ACCIARRI | 97G | L3 | $e^+e^- \rightarrow ee^*$ |
| | | [103] ACKERSTAFF | 97 | OPAL | $e^+e^- \rightarrow ee^*$ |
| | | [104] ADLOFF | 97 | H1 | Lepton-flavor violation |
| none 30–200 | 95 | [105] BREITWEG | 97C | ZEUS | $ep \rightarrow e^* X$ |
| | | [106] ABREU | 96K | DLPH | $e^+e^- \rightarrow ee^*$ |
| | | [107] ACCIARRI | 96D | L3 | $e^+e^- \rightarrow ee^*$ |
| | | [108] ALEXANDER | 96Q | OPAL | $e^+e^- \rightarrow ee^*$ |
| | | [109] BUSKULIC | 96W | ALEP | $e^+e^- \rightarrow ee^*$ |
| | | [110] DERRICK | 95B | ZEUS | $ep \rightarrow e^* X$ |
| | | [111] ABT | 93 | H1 | $ep \rightarrow e^* X$ |
| > 86 | 95 | ADRIANI | 93M | L3 | $\lambda_\gamma > 0.04$ |
| > 89 | 95 | ADRIANI | 93M | L3 | $Z \rightarrow ee^*$, $\lambda_Z > 0.5$ |
| | | [112] DERRICK | 93B | ZEUS | Superseded by DERRICK 95B |
| > 88 | 95 | ABREU | 92C | DLPH | $Z \rightarrow ee^*$, $\lambda_Z > 0.5$ |
| > 86 | 95 | ABREU | 92C | DLPH | $e^+e^- \rightarrow ee^*$, $\lambda_\gamma > 0.1$ |
| > 91 | 95 | DECAMP | 92 | ALEP | $Z \rightarrow ee^*$, $\lambda_Z > 1$ |
| > 88 | 95 | [113] ADEVA | 90F | L3 | $Z \rightarrow ee^*$, $\lambda_Z > 0.5$ |
| > 86 | 95 | [113] ADEVA | 90F | L3 | $Z \rightarrow ee^*$, $\lambda_Z > 0.04$ |
| > 87 | 95 | AKRAWY | 90I | OPAL | $Z \rightarrow ee^*$, $\lambda_Z > 0.5$ |
| > 81 | 95 | [114] 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 | [115] ABE | 88B | VNS | $e^+e^- \rightarrow ee^*$ $\lambda_\gamma > 0.04$ |
| > 75 | 95 | [116] ANSARI | 87D | UA2 | $W \rightarrow e^* \nu$; $\lambda_W > 0.7$ |
| > 63 | 95 | [116] ANSARI | 87D | UA2 | $W \rightarrow e^* \nu$; $\lambda_W > 0.2$ |
| > 40 | 95 | [116] ANSARI | 87D | UA2 | $W \rightarrow e^* \nu$; $\lambda_W > 0.09$ |

[92] ADLOFF 00E search for single $e^*$ production in $ep$ collisions with the decays $e^* \to e\gamma$, $eZ$, $\nu W$. $f=f'=\Lambda/m_{e^*}$ is assumed for the $e^*$ coupling. See their Fig. 9 for the exclusion plot in the mass-coupling plane.

[93] ACCIARRI 01D result is from $e^+e^-$ collisions at $\sqrt{s}$ = 192–202 GeV. $f=f'=\Lambda/m_{e^*}$ is assumed for the $e^*$ coupling. See their Fig. 4 for limits in the mass-coupling plane.

[94] ABBIENDI 00I result is from $e^+e^-$ collisions at $\sqrt{s}$=161–183 GeV. See their Fig. 7 for limits in mass-coupling plane.

[95] ACCIARRI 00E result is from $e^+e^-$ collisions at $\sqrt{s}$=189 GeV. See their Fig. 3 for limits in mass-coupling plane.

[96] ABREU 99O result is from $e^+e^-$ collisions at $\sqrt{s}$= 183 GeV. See their Figs. 4 and 5 for the exclusion limit in the mass-coupling plane.

[97] ACCIARRI 98T search for single $e^*$ production in quasi-real Compton scattering. The limit is for $|\lambda| > 1.0 \times 10^{-1}$ and non-chiral coupling of $e^*$. See their Fig. 7 for the exclusion plot in the mass-coupling plane.

[98] 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.

[99] BARATE 98U is from $e^+e^-$ collision at $\sqrt{s}=M_Z$. See their Fig. 12 for limits in mass-coupling plane

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

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

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

[103] 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.

[104] ADLOFF 97 search for single $e^*$ production in $ep$ collisions with the decays $e^* \to e\gamma$, $eZ$, $\nu W$. 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.

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

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

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

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

[113] Superseded by ADRIANI 93M.

[114] Superseded by DECAMP 92.

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

[116] ANSARI 87D is at $E_{\rm cm}$ = 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 and ACHARD 02D are for nonchiral coupling with $\eta_L = \eta_R = 1$. We choose the chiral coupling limit as the best liimit and list it in the Summary Table.

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

| VALUE (GeV) | CL% | | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **>310** | 95 | | ACHARD | 02D | L3 | $\sqrt{s}$= 192–209 GeV |
| >311 | 95 | | ABREU | 00A | DLPH | $\sqrt{s}$= 189–202 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >283 | 95 | [117] | ACCIARRI | 00G | L3 | $\sqrt{s}$= 183–189 GeV |
| >306 | 95 | | ABBIENDI | 99P | OPAL | $\sqrt{s}$= 189 GeV |
| >231 | 95 | | ABREU | 98J | DLPH | $\sqrt{s}$= 130–183 GeV |
| >194 | 95 | | ACKERSTAFF | 98 | OPAL | $\sqrt{s}$= 130–172 GeV |
| >227 | 95 | | ACKER..,K... | 98B | OPAL | $\sqrt{s}$= 183 GeV |
| >250 | 95 | | BARATE | 98J | ALEP | $\sqrt{s}$= 183 GeV |
| >160 | 95 | [118] | BARATE | 98U | ALEP | |
| >210 | 95 | [119] | ACCIARRI | 97W | L3 | $\sqrt{s}$= 161, 172 GeV |
| >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 | |
| | | [120] | BUSKULIC | 93Q | ALEP | |
| >127 | 95 | [121] | ADRIANI | 92B | L3 | |
| >114 | 95 | [122] | BARDADIN-... | 92 | RVUE | |
| > 99 | 95 | | DECAMP | 92 | ALEP | |
| | | [123] | 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 | [124] | ABE | 89J | VNS | $\eta_L$=1, $\eta_R$=0 |
| > 90.2 | 95 | | ADACHI | 89B | TOPZ | |
| > 65 | 95 | | KIM | 89 | AMY | |

[117] ACCIARRI 00G also obtain a limit on $e^*$ with chiral coupling, $m_{e^*} > 213$ GeV.

[118] BARATE 98U is from $e^+e^-$ collision at $\sqrt{s}$=$M_Z$. See their Fig. 5 for limits in mass-coupling plane

[119] ACCIARRI 97W also obtain a limit on $e^*$ with chiral coupling, $m_{e^*} > 157$ GeV (95%CL).

[120] 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 $m_{e^*}$.

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

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

[123] 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.

[124] 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. • • • | | | | |
| | [125] DORENBOS... | 89 | CHRM | $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ and $\nu_\mu e \to \nu_\mu e$ |
| | [126] GRIFOLS | 86 | THEO | $\nu_\mu e \to \nu_\mu e$ |
| | [127] RENARD | 82 | THEO | $g-2$ of electron |

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

[126] 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.

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

# MASS LIMITS for Excited $\mu$ ($\mu^*$)

## Limits for Excited $\mu$ ($\mu^*$) from Pair Production

These limits are obtained from $e^+ e^- \to \mu^{*+} \mu^{*-}$ and thus rely only on the (electroweak) charge of $\mu^*$. Form factor effects are ignored unless noted. For the case of limits from $Z$ decay, the $\mu^*$ coupling is assumed to be of sequential type. All limits assume a dominant $\mu^* \to \mu\gamma$ 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 |
|---|---|---|---|---|---|
| **>100.2** | 95 | [128] ACCIARRI | 01D | L3 | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| > 91.3 | 95 | [129] ABBIENDI | 00I | OPAL | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| > 94.2 | 95 | [130] ACCIARRI | 00E | L3 | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| > 90.7 | 95 | [131] ABREU | 99O | DLPH | Homodoublet type |
| > 85.3 | 95 | [132] ACKERSTAFF | 98C | OPAL | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| | | [133] BARATE | 98U | ALEP | $Z \to \mu^* \mu^*$ |
| > 79.6 | 95 | [134,135] ABREU | 97B | DLPH | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| > 78.4 | 95 | [134,136] ABREU | 97B | DLPH | $e^+ e^- \to \mu^* \mu^*$ Sequential type |
| > 79.9 | 95 | [134] ACCIARRI | 97G | L3 | $e^+ e^- \to \mu^* \mu^*$ Sequential type |
| > 80.0 | 95 | [134,137] ACKERSTAFF | 97 | OPAL | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| > 62.6 | 95 | [138] ABREU | 96K | DLPH | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| > 64.9 | 95 | [139] ACCIARRI | 96D | L3 | $e^+ e^- \to \mu^* \mu^*$ Sequential type |
| > 66.8 | 95 | [139] ALEXANDER | 96Q | OPAL | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| > 65.4 | 95 | [139] 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 | [140] | BARDADIN-... | 92 | RVUE | $\Gamma(Z)$ |
| $>26.1$ | 95 | [141] | DECAMP | 92 | ALEP | $Z \to \mu^* \mu^*$; $\Gamma(Z)$ |
| $>46.1$ | 95 | | DECAMP | 92 | ALEP | $Z \to \mu^* \mu^*$ |
| $>33$ | 95 | [141] | ABREU | 91F | DLPH | $Z \to \mu^* \mu^*$; $\Gamma(Z)$ |
| $>45.3$ | 95 | [142] | ADEVA | 90F | L3 | $Z \to \mu^* \mu^*$ |
| $>44.9$ | 95 | | AKRAWY | 90I | OPAL | $Z \to \mu^* \mu^*$ |
| $>44.6$ | 95 | [143] | 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 | $e^+ e^- \to \mu^* \mu^*$ |

[128] From $e^+ e^-$ collisions at $\sqrt{s}$ = 192–202 GeV. $f$=$f'$ is assumed. ACCIARRI 01D also obtain limit for $f$=$-f'$: $m_{\mu^*} > 93.4$ GeV.

[129] From $e^+ e^-$ collisions at $\sqrt{s}$=161–183 GeV. $f=f'$ is assumed. ABBIENDI 00I also obtain limit for $f=-f'$ ($\mu^* \to \nu W$): $m_{\mu^*} > 86.0$ GeV.

[130] From $e^+ e^-$ collisions at $\sqrt{s}$=189 GeV. $f=f'$ is assumed. ACCIARRI 00E also obtain limit for $f=-f'$ ($\mu^* \to \nu W$): $m_{\mu^*} > 92.6$ GeV.

[131] From $e^+ e^-$ collisions at $\sqrt{s}$= 183 GeV. $f=f'$ is assumed. ABREU 99O also obtain limit for $f=-f'$ ($\mu^* \to \nu W$): $m_{\mu^*} > 81.3$ GeV.

[132] 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.

[133] BARATE 98U obtain limits on the form factor. See their Fig. 14 for limits in mass-form factor plane.

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

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

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

[137] ACKERSTAFF 97 also obtain limit from charged current decay mode $\mu^* \to \nu W$, $m_{\nu^*_\mu} > 77.1$ GeV.

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

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

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

[141] Limit is independent of $\mu^*$ decay mode.

[142] Superseded by ADRIANI 93M.

[143] Superseded by DECAMP 92.

## Limits for Excited $\mu$ ($\mu^*$) from Single Production

These limits are from $e^+e^- \rightarrow \mu^*\mu$ and depend on transition magnetic coupling between $\mu$ and $\mu^*$. All limits assume $\mu^* \rightarrow \mu\gamma$ 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 |
|---|---|---|---|---|---|
| **>178** | 95 | [144] ACCIARRI | 01D | L3 | $e^+e^- \rightarrow \mu\mu^*$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [145] ABBIENDI | 00I | OPAL | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [146] ACCIARRI | 00E | L3 | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [147] ABREU | 99O | DLPH | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [148] ACKERSTAFF | 98C | OPAL | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [149] BARATE | 98U | ALEP | $Z \rightarrow \mu\mu^*$ |
| | | [150,151] ABREU | 97B | DLPH | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [150,152] ACCIARRI | 97G | L3 | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [153] ACKERSTAFF | 97 | OPAL | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [154] ABREU | 96K | DLPH | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [155] ACCIARRI | 96D | L3 | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [156] ALEXANDER | 96Q | OPAL | $e^+e^- \rightarrow \mu\mu^*$ |
| | | [157] BUSKULIC | 96W | ALEP | $e^+e^- \rightarrow \mu\mu^*$ |
| > 89 | 95 | ADRIANI | 93M | L3 | $Z \rightarrow \mu\mu^*$, $\lambda_Z > 0.5$ |
| > 88 | 95 | ABREU | 92C | DLPH | $Z \rightarrow \mu\mu^*$, $\lambda_Z > 0.5$ |
| > 91 | 95 | DECAMP | 92 | ALEP | $Z \rightarrow \mu\mu^*$, $\lambda_Z >1$ |
| > 85 | 95 | [158] ADEVA | 90F | L3 | $Z \rightarrow \mu\mu^*$, $\lambda_Z > 1$ |
| > 75 | 95 | [158] ADEVA | 90F | L3 | $Z \rightarrow \mu\mu^*$, $\lambda_Z > 0.1$ |
| > 87 | 95 | AKRAWY | 90I | OPAL | $Z \rightarrow \mu\mu^*$, $\lambda_Z >1$ |
| > 80 | 95 | [159] DECAMP | 90G | ALEP | $e^+e^- \rightarrow \mu\mu^*$, $\lambda_Z=1$ |
| > 50 | 95 | ADACHI | 89B | TOPZ | $e^+e^- \rightarrow \mu\mu^*$, $\lambda_\gamma=0.7$ |
| > 46 | 95 | KIM | 89 | AMY | $e^+e^- \rightarrow \mu\mu^*$, $\lambda_\gamma=0.2$ |

[144] ACCIARRI 01D result is from $e^+e^-$ collisions at $\sqrt{s}$ = 192–202 GeV. $f=f'=\Lambda/m_{\mu^*}$ is assumed for the $\mu^*$ coupling. See their Fig. 4 for limits in the mass-coupling plane.

[145] ABBIENDI 00I result is from $e^+e^-$ collisions at $\sqrt{s}$=161–183 GeV. See their Fig. 7 for limits in mass-coupling plane.

[146] ACCIARRI 00E result is from $e^+e^-$ collisions at $\sqrt{s}$=189 GeV. See their Fig. 3 for limits in mass-coupling plane.

[147] ABREU 99O result is from $e^+e^-$ collisions at $\sqrt{s}$= 183 GeV. See their Figs. 4 and 5 for the exclusion limit in the mass-coupling plane.

[148] 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.

[149] BARATE 98U obtain limits on the $Z\mu\mu^*$ coupling. See their Fig. 12 for limits in mass-coupling plane

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

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

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

[153] 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.

[154] 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.
[155] 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.
[156] 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.
[157] 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.
[158] Superseded by ADRIANI 93M.
[159] Superseded by DECAMP 92.

### Indirect Limits for Excited $\mu$ ($\mu^*$)

These limits make use of loop effects involving $\mu^*$ 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. • • • | | | | |
| | [160] RENARD | 82 | THEO | $g-2$ of muon |

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

## MASS LIMITS for Excited $\tau$ ($\tau^*$)

### Limits for Excited $\tau$ ($\tau^*$) from Pair Production

These limits are obtained from $e^+e^- \rightarrow \tau^{*+}\tau^{*-}$ and thus rely only on the (electroweak) charge of $\tau^*$. Form factor effects are ignored unless noted. For the case of limits from $Z$ decay, the $\tau^*$ coupling is assumed to be of sequential type. All limits assume a dominant $\tau^* \rightarrow \tau\gamma$ 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* |
|---|---|---|---|---|---|
| **>99.8** | 95 | [161] ACCIARRI | 01D | L3 | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >91.2 | 95 | [162] ABBIENDI | 00I | OPAL | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| >94.2 | 95 | [163] ACCIARRI | 00E | L3 | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| >89.7 | 95 | [164] ABREU | 99O | DLPH | Homodoublet type |
| >84.6 | 95 | [165] ACKERSTAFF | 98C | OPAL | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| | | [166] BARATE | 98U | ALEP | $Z \rightarrow \tau^*\tau^*$ |
| >79.4 | 95 | [167,168] ABREU | 97B | DLPH | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| >77.4 | 95 | [167,169] ABREU | 97B | DLPH | $e^+e^- \rightarrow \tau^*\tau^*$ Sequential type |
| >79.3 | 95 | [167] ACCIARRI | 97G | L3 | $e^+e^- \rightarrow \tau^*\tau^*$ Sequential type |
| >79.1 | 95 | [167,170] ACKERSTAFF | 97 | OPAL | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| >62.2 | 95 | [171] ABREU | 96K | DLPH | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| >64.2 | 95 | [172] ACCIARRI | 96D | L3 | $e^+e^- \rightarrow \tau^*\tau^*$ Sequential type |
| >65.3 | 95 | [172] ALEXANDER | 96Q | OPAL | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| >64.8 | 95 | [172] BUSKULIC | 96W | ALEP | $e^+e^- \rightarrow \tau^*\tau^*$ Sequential type |

| | | | | | |
|---|---|---|---|---|---|
| >45.6 | 95 | ADRIANI | 93M | L3 | $Z \to \tau^* \tau^*$ |
| >45.3 | 95 | ABREU | 92C | DLPH | $Z \to \tau^* \tau^*$ |
| >29.8 | 95 | [173] BARDADIN-... | 92 | RVUE | $\Gamma(Z)$ |
| >26.1 | 95 | [174] DECAMP | 92 | ALEP | $Z \to \tau^* \tau^*$; $\Gamma(Z)$ |
| >46.0 | 95 | DECAMP | 92 | ALEP | $Z \to \tau^* \tau^*$ |
| >33 | 95 | [174] ABREU | 91F | DLPH | $Z \to \tau^* \tau^*$; $\Gamma(Z)$ |
| >45.5 | 95 | [175] ADEVA | 90L | L3 | $Z \to \tau^* \tau^*$ |
| >44.9 | 95 | AKRAWY | 90I | OPAL | $Z \to \tau^* \tau^*$ |
| >41.2 | 95 | [176] DECAMP | 90G | ALEP | $e^+ e^- \to \tau^* \tau^*$ |
| >29.0 | 95 | ADACHI | 89B | TOPZ | $e^+ e^- \to \tau^* \tau^*$ |

[161] From $e^+ e^-$ collisions at $\sqrt{s}$ = 192–202 GeV. $f$=$f'$ is assumed. ACCIARRI 01D also obtain limit for $f$=$-f'$: $m_{\tau^*} > 93.4$ GeV.

[162] From $e^+ e^-$ collisions at $\sqrt{s}$=161–183 GeV. $f$=$f'$ is assumed. ABBIENDI 00I also obtain limit for $f$=$-f'$ ($\tau^* \to \nu W$): $m_{\tau^*} > 86.0$ GeV.

[163] From $e^+ e^-$ collisions at $\sqrt{s}$=189 GeV. $f$=$f'$ is assumed. ACCIARRI 00E also obtain limit for $f$=$-f'$ ($\tau^* \to \nu W$): $m_{\tau^*} > 92.6$ GeV.

[164] From $e^+ e^-$ collisions at $\sqrt{s}$= 183 GeV. $f$=$f'$ is assumed. ABREU 99O also obtain limit for $f$=$-f'$ ($\tau^* \to \nu W$): $m_{\tau^*} > 81.3$ GeV.

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

[166] BARATE 98U obtain limits on the form factor. See their Fig. 14 for limits in mass-form factor plane.

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

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

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

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

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

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

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

[174] Limit is independent of $\tau^*$ decay mode.

[175] Superseded by ADRIANI 93M.

[176] Superseded by DECAMP 92.

## Limits for Excited $\tau$ ($\tau^*$) from Single Production

These limits are from $e^+e^- \rightarrow \tau^*\tau$ and depend on transition magnetic coupling between $\tau$ and $\tau^*$. 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 |
|---|---|---|---|---|---|
| **>173** | 95 | [177] ACCIARRI | 01D | L3 | $e^+e^- \rightarrow \tau\tau^*$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [178] ABBIENDI | 00I | OPAL | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [179] ACCIARRI | 00E | L3 | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [180] ABREU | 99O | DLPH | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [181] ACKERSTAFF | 98C | OPAL | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [182] BARATE | 98U | ALEP | $Z \rightarrow \tau\tau^*$ |
| | | [183,184] ABREU | 97B | DLPH | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [183,185] ACCIARRI | 97G | L3 | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [186] ACKERSTAFF | 97 | OPAL | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [187] ABREU | 96K | DLPH | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [188] ACCIARRI | 96D | L3 | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [189] ALEXANDER | 96Q | OPAL | $e^+e^- \rightarrow \tau\tau^*$ |
| | | [190] BUSKULIC | 96W | ALEP | $e^+e^- \rightarrow \tau\tau^*$ |
| > 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 | $Z \rightarrow \tau\tau^*$, $\lambda_Z > 0.18$ |
| > 88 | 95 | [191] ADEVA | 90L | L3 | $Z \rightarrow \tau\tau^*$, $\lambda_Z > 1$ |
| > 86.5 | 95 | AKRAWY | 90I | OPAL | $Z \rightarrow \tau\tau^*$, $\lambda_Z > 1$ |
| > 59 | 95 | [192] DECAMP | 90G | ALEP | $Z \rightarrow \tau\tau^*$, $\lambda_Z = 1$ |
| > 40 | 95 | [193] BARTEL | 86 | JADE | $e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 1$ |
| > 41.4 | 95 | [194] BEHREND | 86 | CELL | $e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 1$ |
| > 40.8 | 95 | [194] BEHREND | 86 | CELL | $e^+e^- \rightarrow \tau\tau^*$, $\lambda_\gamma = 0.7$ |

[177] ACCIARRI 01D result is from $e^+e^-$ collisions at $\sqrt{s}$ = 192–202 GeV. $f = f' = \Lambda/m_{\tau^*}$ is assumed for the $\tau^*$ coupling. See their Fig. 4 for limits in the mass-coupling plane.

[178] ABBIENDI 00I result is from $e^+e^-$ collisions at $\sqrt{s}$=161–183 GeV. See their Fig. 7 for limits in mass-coupling plane.

[179] ACCIARRI 00E result is from $e^+e^-$ collisions at $\sqrt{s}$=189 GeV. See their Fig. 3 for limits in mass-coupling plane.

[180] ABREU 99O result is from $e^+e^-$ collisions at $\sqrt{s}$= 183 GeV. See their Figs. 4 and 5 for the exclusion limit in the mass-coupling plane.

[181] 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.

[182] BARATE 98U obtain limits on the $Z\tau\tau^*$ coupling. See their Fig. 12 for limits in mass-coupling plane

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

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

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

[186] 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.

[187] 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.

[188] 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.

[189] 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.

[190] 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.

[191] Superseded by ADRIANI 93M.

[192] Superseded by DECAMP 92.

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

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

## MASS LIMITS for Excited Neutrino ($\nu^*$)

### Limits for Excited $\nu$ ($\nu^*$) from Pair Production

These limits are obtained from $e^+e^- \rightarrow \nu^*\nu^*$ and thus rely only on the (electroweak) charge of $\nu^*$. Form factor effects are ignored unless noted. The $\nu^*$ coupling is assumed to be of sequential type unless otherwise noted. All limits assume a dominant $\nu^* \rightarrow \nu\gamma$ decay except the limits from $\Gamma(Z)$.

| VALUE (GeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **>99.4** | 95 | [195] ACCIARRI | 01D | L3 | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >91.2 | 95 | [196] ABBIENDI | 00I | OPAL | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |
| | | [197] ABBIENDI,G | 00D | OPAL | |
| >94.1 | 95 | [198] ACCIARRI | 00E | L3 | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |
| | | [199] ABBIENDI | 99F | OPAL | |
| >90.0 | 95 | [200] ABREU | 99O | DLPH | Homodoublet type |
| >84.9 | 95 | [201] ACKERSTAFF | 98C | OPAL | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |
| | | [202] BARATE | 98U | ALEP | $Z \rightarrow \nu^*\nu^*$ |
| >77.6 | 95 | [203,204] ABREU | 97B | DLPH | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |
| >64.4 | 95 | [203,205] ABREU | 97B | DLPH | $e^+e^- \rightarrow \nu^*\nu^*$ Sequential type |
| >71.2 | 95 | [203,206] ACCIARRI | 97G | L3 | $e^+e^- \rightarrow \nu^*\nu^*$ Sequential type |
| >77.8 | 95 | [203,207] ACKERSTAFF | 97 | OPAL | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |
| >61.4 | 95 | [208,209] ACCIARRI | 96D | L3 | $e^+e^- \rightarrow \nu^*\nu^*$ Sequential type |
| >65.0 | 95 | [210,211] ALEXANDER | 96Q | OPAL | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |
| >63.6 | 95 | [208] BUSKULIC | 96W | ALEP | $e^+e^- \rightarrow \nu^*\nu^*$ Sequential type |
| >43.7 | 95 | [212] BARDADIN-... | 92 | RVUE | $\Gamma(Z)$ |
| >47 | 95 | [213] DECAMP | 92 | ALEP | |
| >42.6 | 95 | [214] DECAMP | 92 | ALEP | $\Gamma(Z)$ |
| >35.4 | 95 | [215,216] DECAMP | 90O | ALEP | $\Gamma(Z)$ |
| >46 | 95 | [216,217] DECAMP | 90O | ALEP | |

[195] From $e^+e^-$ collisions at $\sqrt{s}$ = 192–202 GeV. $f$=$f'$ is assumed. ACCIARRI 01D also obtain limit for $f$=$-f'$: $m_{\nu_e^*}$ > 99.1 GeV, $m_{\nu_\mu^*}$ > 99.3 GeV, $m_{\nu_\tau^*}$ > 90.5 GeV.

[196] From $e^+e^-$ collisions at $\sqrt{s}$=161–183 GeV. $f$=$-f'$ (photonic decay) is assumed. ABBIENDI 00I also obtain limit for $f$=$f'$ ($\nu^* \rightarrow \ell W$): $m_{\nu_e^*}$ > 91.1 GeV, $m_{\nu_\mu^*}$ > 91.1 GeV, $m_{\nu_\tau^*}$ > 83.1 GeV.

[197] From $e^+ e^-$ collisions at $\sqrt{s}$= 189 GeV. ABBIENDI,G 00D obtain limit on $\sigma(e^+ e^- \rightarrow \nu^* \nu^*)\mathrm{B}(\nu^* \rightarrow \nu\gamma)^2$. See their Fig. 14. The limit ranges from 50 to 80 fb for $\sqrt{s}/2$= 95 GeV$>m_{\nu^*}>$45 GeV.

[198] From $e^+ e^-$ collisions at $\sqrt{s}$=189 GeV. $f=-f'$ (photonic decay) is assumed. ACCIARRI 00E also obtain limit for $f=f'$ ($\nu^* \rightarrow \ell W$): $m_{\nu_e^*} > 93.9$ GeV, $m_{\nu_\mu^*} > 94.0$ GeV, $m_{\nu_\tau^*} > 91.5$ GeV.

[199] From $e^+ e^-$ collisions at $\sqrt{s}$= 130–183 GeV, ABBIENDI 99F obtain limit on $\sigma(e^+ e^- \rightarrow \nu^* \nu^*)$ $\mathrm{B}(\nu^* \rightarrow \nu\gamma)^2$. See their Fig. 13. The limit ranges from 0.094 to 0.14 pb for $\sqrt{s}/2 > m_{\nu^*} > 45$ GeV.

[200] From $e^+ e^-$ collisions at $\sqrt{s}$= 183 GeV. $f=-f'$ is assumed. ABREU 99O also obtain limit for $f=f'$: $m_{\nu_{e^*}} > 87.3$ GeV, $m_{\nu_{\mu^*}} > 88.0$ GeV, $m_{\nu_{\tau^*}} > 81.0$ GeV.

[201] 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.

[202] BARATE 98U obtain limits on the form factor. See their Fig. 14 for limits in mass-form factor plane.

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

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

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

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

[207] 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.

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

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

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

[211] 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.

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

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

[214] Limit is for Dirac $\nu^*$. The limit is 34.6 GeV for Majorana $\nu^*$, 45.4 GeV for homodoublet $\nu^*$.

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

[216] Superseded by DECAMP 92.

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

## Limits for Excited $\nu$ ($\nu^*$) from Single Production

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

| VALUE (GeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **>171** | 95 | [218] ACCIARRI | 01D | L3 | $e^+e^- \to \nu\nu^*$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| none 50–150 | 95 | [219] ADLOFF | 02 | H1 | $ep \to \nu^* X$ |
| | | [220] ABBIENDI | 00I | OPAL | $e^+e^- \to \nu\nu^*$ |
| | | [221] ABBIENDI,G | 00D | OPAL | |
| | | [222] ACCIARRI | 00E | L3 | $e^+e^- \to \nu\nu^*$ |
| >114 | 95 | [223] ADLOFF | 00E | H1 | $ep \to \nu^* X$ |
| | | [224] ABBIENDI | 99F | OPAL | |
| | | [225] ABREU | 99O | DLPH | $e^+e^- \to \nu\nu^*$ |
| | | [226] ACKERSTAFF | 98C | OPAL | $e^+e^- \to \nu^*\nu^*$ Homodoublet type |
| | | [227] BARATE | 98U | ALEP | $Z \to \nu\nu^*$ |
| | | [228,229] ABREU | 97B | DLPH | $e^+e^- \to \nu\nu^*$ |
| | | [230] ABREU | 97I | DLPH | $\nu^* \to \ell W$, $\nu Z$ |
| | | [231] ABREU | 97J | DLPH | $\nu^* \to \nu\gamma$ |
| | | [228,232] ACCIARRI | 97G | L3 | $e^+e^- \to \nu\nu^*$ |
| | | [233] ACKERSTAFF | 97 | OPAL | $e^+e^- \to \nu\nu^*$ |
| | | [234] ADLOFF | 97 | H1 | Lepton-flavor violation |
| none 40–96 | 95 | [235] BREITWEG | 97C | ZEUS | $ep \to \nu^* X$ |
| | | [236] ACCIARRI | 96D | L3 | $e^+e^- \to \nu\nu^*$ |
| | | [237] ALEXANDER | 96Q | OPAL | $e^+e^- \to \nu\nu^*$ |
| | | [238] BUSKULIC | 96W | ALEP | $e^+e^- \to \nu\nu^*$ |
| | | [239] DERRICK | 95B | ZEUS | $ep \to \nu^* X$ |
| | | [240] ABT | 93 | H1 | $ep \to \nu^* X$ |
| > 91 | 95 | ADRIANI | 93M | L3 | $\lambda_Z > 1$, $\nu^* \to \nu\gamma$ |
| > 89 | 95 | ADRIANI | 93M | L3 | $\lambda_Z > 1$, $\nu_e^* \to eW$ |
| > 87 | 95 | ADRIANI | 93M | L3 | $\lambda_Z > 0.1$, $\nu^* \to \nu\gamma$ |
| > 74 | 95 | ADRIANI | 93M | L3 | $\lambda_Z > 0.1$, $\nu_e^* \to eW$ |
| | | [241] BARDADIN-... | 92 | RVUE | |
| > 91 | 95 | [242] DECAMP | 92 | ALEP | $\lambda_Z > 1$ |
| > 74 | 95 | [242] DECAMP | 92 | ALEP | $\lambda_Z > 0.034$ |
| > 91 | 95 | [243,244] ADEVA | 90O | L3 | $\lambda_Z > 1$ |
| > 83 | 95 | [244] ADEVA | 90O | L3 | $\lambda_Z > 0.1$, $\nu^* \to \nu\gamma$ |
| > 74 | 95 | [244] ADEVA | 90O | L3 | $\lambda_Z > 0.1$, $\nu_e^* \to eW$ |
| > 90 | 95 | [245,246] DECAMP | 90O | ALEP | $\lambda_Z > 1$ |
| > 74.7 | 95 | [245,246] DECAMP | 90O | ALEP | $\lambda_Z > 0.06$ |

[218] ACCIARRI 01D search for $\nu\nu^*$ production in $e^+e^-$ collisions at $\sqrt{s}$ = 192–202 GeV with decays $\nu^* \to \nu\gamma$, $\nu^* \to eW$. $f = -f' = \Lambda/m_{\nu^*}$ is assumed for the $\nu^*$ coupling. See their Fig. 4 for limits in the mass-coupling plane.

[219] ADLOFF 02 search for single $\nu^*$ production in $ep$ collisions with the decays $\nu^* \to \nu\gamma$, $\nu Z$, $eW$. The quoted limit assumes $f = -f' = \Lambda/m_{\nu^*}$. See their Fig. 1 for the exclusion plots in the mass-coupling plane.

[220] ABBIENDI 00I result is from $e^+e^-$ collisions at $\sqrt{s}$=161–183 GeV. See their Fig. 7 for limits in mass-coupling plane.

[221] From $e^+ e^-$ collisions at $\sqrt{s}$= 189 GeV. ABBIENDI,G 00D obtain limit on $\sigma(e^+ e^- \rightarrow \nu^* \nu^*)$B$(\nu^* \rightarrow \nu\gamma)^2$. See their Fig. 11.

[222] ACCIARRI 00E result is from $e^+ e^-$ collisions at $\sqrt{s}$=189 GeV. See their Fig. 3 for limits in mass-coupling plane.

[223] ADLOFF 00E search for single $\nu^*$ production in $ep$ collisions with the decays $\nu^* \rightarrow \nu\gamma$, $\nu Z$, $eW$. The quoted limit assumes $f$=$-f'$=$\Lambda/m_{\nu^*}$. See their Fig. 10 for the exclusion plot in the mass-coupling plane.

[224] From $e^+ e^-$ collisions at $\sqrt{s}$= 130–183 GeV, ABBIENDI 99F obtain limit on $\sigma(e^+ e^- \rightarrow \nu\nu^*)$ B$(\nu^* \rightarrow \nu\gamma)$. See their Fig. 8.

[225] ABREU 99O result is from $e^+ e^-$ collisions at $\sqrt{s}$= 183 GeV. See their Figs. 4 and 5 for the exclusion limit in the mass-coupling plane.

[226] 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.

[227] BARATE 98U obtain limits on the $Z\nu\nu^*$ coupling. See their Fig. 13 for limits in mass-coupling plane

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

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

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

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

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

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

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

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

[236] 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.

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

[238] 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.

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

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

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

[242] 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 $\nu^*$, B$(\nu^* \rightarrow \nu\gamma) = 1$.

[243] Limit is either for $\nu^* \rightarrow \nu\gamma$ or $\nu^* \rightarrow eW$.

[244] Superseded by ADRIANI 93M.

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

[246] 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 | [247] ADRIANI | 93M | L3 | $u$ or $d$ type, $Z \to q^* q^*$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [248] BARATE | 98U | ALEP | $Z \to q^* q^*$ |
| | | [249] ADRIANI | 92F | L3 | $Z \to q^* q^*$ |
| >41.7 | 95 | [250] BARDADIN-... | 92 | RVUE | $u$-type, $\Gamma(Z)$ |
| >44.7 | 95 | [250] BARDADIN-... | 92 | RVUE | $d$-type, $\Gamma(Z)$ |
| >40.6 | 95 | [251] DECAMP | 92 | ALEP | $u$-type, $\Gamma(Z)$ |
| >44.2 | 95 | [251] DECAMP | 92 | ALEP | $d$-type, $\Gamma(Z)$ |
| >45 | 95 | [252] DECAMP | 92 | ALEP | $u$ or $d$ type, $Z \to q^* q^*$ |
| >45 | 95 | [251] ABREU | 91F | DLPH | $u$-type, $\Gamma(Z)$ |
| >45 | 95 | [251] ABREU | 91F | DLPH | $d$-type, $\Gamma(Z)$ |
| >21.1 | 95 | [253] BEHREND | 86C | CELL | $e(q^*) = -1/3$, $q^* \to qg$ |
| >22.3 | 95 | [253] BEHREND | 86C | CELL | $e(q^*) = 2/3$, $q^* \to qg$ |
| >22.5 | 95 | [253] BEHREND | 86C | CELL | $e(q^*) = -1/3$, $q^* \to q\gamma$ |
| >23.2 | 95 | [253] BEHREND | 86C | CELL | $e(q^*) = 2/3$, $q^* \to q\gamma$ |

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

[248] BARATE 98U obtain limits on the form factor. See their Fig. 16 for limits in mass-form factor plane.

[249] 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.

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

[251] These limits are independent of decay modes.

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

[253] 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, none 580–760 (CL = 95%) OUR EVALUATION** | | | | | |
| none 200–520 and **580–760** | 95 | [254] ABE | 97G | CDF | $p\overline{p} \to q^* X$, $q^* \to 2$ jets |
| **none 80–570** | 95 | [255] ABE | 95N | CDF | $p\overline{p} \to q^* X$, $q^* \to qg$ $q\gamma$, $qW$ |
| **>288** | 90 | [256] ALITTI | 93 | UA2 | $p\overline{p} \to q^* X$, $q^* \to qg$ |

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

| | | | | | |
|---|---|---|---|---|---|
| >188 | 95 | [257] ADLOFF | 00E | H1 | $ep \rightarrow q^* X$ |
| | | [258] ABREU | 99O | DLPH | $e^+ e^- \rightarrow q q^*$ |
| | | [259] BARATE | 98U | ALEP | $Z \rightarrow q q^*$ |
| | | [260] ADLOFF | 97 | H1 | Lepton-flavor violation |
| none 40–169 | 95 | [261] BREITWEG | 97C | ZEUS | $ep \rightarrow q^* X$ |
| | | [262] DERRICK | 95B | ZEUS | $ep \rightarrow q^* X$ |
| none 80–540 | 95 | [263] ABE | 94 | CDF | $p\overline{p} \rightarrow q^* X$, $q^* \rightarrow q\gamma$, $qW$ |
| > 79 | 95 | [264] ADRIANI | 93M | L3 | $\lambda_Z$(L3)> 0.06 |
| | | [265] ABREU | 92D | DLPH | $Z \rightarrow q q^*$ |
| | | [266] ADRIANI | 92F | L3 | $Z \rightarrow q q^*$ |
| > 75 | 95 | [264] DECAMP | 92 | ALEP | $Z \rightarrow q q^*$, $\lambda_Z$ >1 |
| > 88 | 95 | [267] DECAMP | 92 | ALEP | $Z \rightarrow q q^*$, $\lambda_Z$ >1 |
| > 86 | 95 | [267] AKRAWY | 90J | OPAL | $Z \rightarrow q q^*$, $\lambda_Z$ > 1.2 |
| | | [268] ALBAJAR | 89 | UA1 | $p\overline{p} \rightarrow q^* X$, $q^* \rightarrow qW$ |
| > 39 | 95 | [269] BEHREND | 86C | CELL | $e^+ e^- \rightarrow q^* \overline{q}$ ($q^* \rightarrow qg, q\gamma$), $\lambda_\gamma$=1 |

[254] ABE 97G search for new particle decaying to dijets.

[255] 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.

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

[257] ADLOFF 00E search for single $q^*$ production in $ep$ collisions with the decays $q^* \rightarrow q\gamma$, $qZ$, $qW$. $f_s$=0 and $f$=$f'$=$\Lambda/m_{q^*}$ is assumed for the $q^*$ coupling. See their Fig. 11 for the exclusion plot in the mass-coupling plane.

[258] ABREU 99O result is from $e^+ e^-$ collisions at $\sqrt{s}$= 183 GeV. See their Fig. 6 for the exclusion limit in the mass-coupling plane.

[259] BARATE 98U obtain limits on the $Zqq^*$ coupling. See their Fig. 16 for limits in mass-coupling plane

[260] 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.

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

[262] 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.

[263] ABE 94 search for resonances in jet-$\gamma$ 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.

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

[265] 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.

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

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

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

[269] BEHREND 86C has $E_{\text{cm}}$ = 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 | [270] ABE | 89D | CDF | $p\overline{p} \to q_6 \overline{q}_6$ |

[270] 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 ($\ell_8$)

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>86** | 95 | [271] ABE | 89D | CDF | Stable $\ell_8$: $p\overline{p} \to \ell_8 \overline{\ell}_8$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [272] ABT | 93 | H1 | $e_8$: $ep \to e_8 X$ |
| none 3.0–30.3 | 95 | [273] KIM | 90 | AMY | $e_8$: $e^+e^- \to ee+$ jets |
| none 3.5–30.3 | 95 | [273] KIM | 90 | AMY | $\mu_8$: $e^+e^- \to \mu\mu+$ jets |
| | | [274] KIM | 90 | AMY | $e_8$: $e^+e^- \to gg$; $R$ |
| >19.8 | 95 | [275] BARTEL | 87B | JADE | $e_8$, $\mu_8$, $\tau_8$: $e^+e^-$; $R$ |
| none 5–23.2 | 95 | [275] BARTEL | 87B | JADE | $\mu_8$: $e^+e^- \to \mu\mu+$ jets |
| | | [276] BARTEL | 85K | JADE | $e_8$: $e^+e^- \to gg$; $R$ |

[271] 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.

[272] 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 $m_{e_8}$–$\Lambda$ plane for $m_{e_8}$ = 35–220 GeV.

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

[274] 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.

[275] BARTEL 87B is at $E_{\text{cm}}$ = 46.3–46.78 GeV. The limits assume $\ell_8$ pair production cross sections to be eight times larger than those of the corresponding heavy lepton pair production.

[276] 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 ($\nu_8$)

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>110** | 90 | [277] BARGER | 89 | RVUE | $\nu_8$: $p\overline{p} \rightarrow \nu_8\overline{\nu}_8$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| none 3.8–29.8 | 95 | [278] KIM | 90 | AMY | $\nu_8$: $e^+e^- \rightarrow$ acoplanar jets |
| none 9–21.9 | 95 | [279] BARTEL | 87B | JADE | $\nu_8$: $e^+e^- \rightarrow$ acoplanar jets |

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

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

[279] BARTEL 87B is at $E_{\rm cm}$ = 46.3–46.78 GeV. The limit assumes the $\nu_8$ 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 $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ 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. • • • | | | | |
| | [280] ALBAJAR | 89 | UA1 | $p\overline{p} \rightarrow W_8 X$, $W_8 \rightarrow W g$ |

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

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| ARNISON | 86D | PL B177 244 | G.T.J. Arnison *et al.* | (UA1 Collab.) |
| BARTEL | 86 | ZPHY C31 359 | W. Bartel *et al.* | (JADE Collab.) |
| BARTEL | 86C | ZPHY C30 371 | W. Bartel *et al.* | (JADE Collab.) |
| BEHREND | 86 | PL 168B 420 | H.J. Behrend *et al.* | (CELLO Collab.) |
| BEHREND | 86C | PL B181 178 | H.J. Behrend *et al.* | (CELLO Collab.) |
| DERRICK | 86 | PL 166B 463 | M. Derrick *et al.* | (HRS Collab.) |
| Also | 86B | PR D34 3286 | M. Derrick *et al.* | (HRS Collab.) |
| DERRICK | 86B | PR D34 3286 | M. Derrick *et al.* | (HRS Collab.) |
| GRIFOLS | 86 | PL 168B 264 | J.A. Grifols, S. Peris | (BARC) |
| JODIDIO | 86 | PR D34 1967 | A. Jodidio *et al.* | (LBL, NWES, TRIU) |
| Also | 88 | PR D37 237 erratum | A. Jodidio *et al.* | (LBL, NWES, TRIU) |
| APPEL | 85 | PL 160B 349 | J.A. Appel *et al.* | (UA2 Collab.) |
| BARTEL | 85K | PL 160B 337 | W. Bartel *et al.* | (JADE Collab.) |
| BERGER | 85 | ZPHY C28 1 | C. Berger *et al.* | (PLUTO Collab.) |
| BERGER | 85B | ZPHY C27 341 | C. Berger *et al.* | (PLUTO Collab.) |
| BAGNAIA | 84C | PL 138B 430 | P. Bagnaia *et al.* | (UA2 Collab.) |
| BARTEL | 84D | PL 146B 437 | W. Bartel *et al.* | (JADE Collab.) |
| BARTEL | 84E | PL 146B 121 | W. Bartel *et al.* | (JADE Collab.) |
| EICHTEN | 84 | RMP 56 579 | E. Eichten *et al.* | (FNAL, LBL, OSU) |
| ALTHOFF | 83C | PL 126B 493 | M. Althoff *et al.* | (TASSO Collab.) |
| RENARD | 82 | PL 116B 264 | F.M. Renard | (CERN) |