# Quark and Lepton Compositeness, Searches for

The latest unpublished results are described in the "Quark and Lepton Compositeness" review.

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## 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. • • •

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| >4.5 | >7.0 | 95 | [2] SCHAEL | 07A | ALEP | $E_{cm}$= 189–209 GeV |
| >5.3 | >6.8 | 95 | ABDALLAH | 06C | DLPH | $E_{cm}$= 130–207 GeV |
| >4.7 | >6.1 | 95 | [3] ABBIENDI | 04G | OPAL | $E_{cm}$= 130–207 GeV |
| >4.3 | >4.9 | 95 | ACCIARRI | 00P | L3 | $E_{cm}$= 130–189 GeV |

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

[2] SCHAEL 07A limits are from $R_c$, $Q_{FB}^{depl}$, and hadronic cross section measurements.

[3] ABBIENDI 04G limits are from $e^+ e^- \rightarrow e^+ e^-$ cross section at $\sqrt{s} = 130$–207 GeV.

## 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 | **>9.5** | 95 | [1] SCHAEL | 07A | ALEP | $E_{cm}$= 189–209 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 | >7.6 | 95 | ABDALLAH | 06C | DLPH | $E_{cm}$= 130–207 GeV |
| >8.1 | >7.3 | 95 | [2] ABBIENDI | 04G | OPAL | $E_{cm}$= 130–207 GeV |

[1] SCHAEL 07A limits are from $R_c$, $Q_{FB}^{depl}$, and hadronic cross section measurements.

[2] ABBIENDI 04G limits are from $e^+ e^- \rightarrow \mu\mu$ cross section at $\sqrt{s} = 130$–207 GeV.

## 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 |
|---|---|---|---|---|---|---|
| **>7.9** | >5.8 | 95 | [1] SCHAEL | 07A | ALEP | $E_{cm}$= 189–209 GeV |
| **>7.9** | >4.6 | 95 | ABDALLAH | 06C | DLPH | $E_{cm}$= 130–207 GeV |
| >4.9 | **>7.2** | 95 | [2] ABBIENDI | 04G | OPAL | $E_{cm}$= 130–207 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >5.4 | >4.7 | 95 | ACCIARRI | 00P | L3 | $E_{cm}$= 130–189 GeV |

[1] SCHAEL 07A limits are from $R_c$, $Q_{FB}^{depl}$, and hadronic cross section measurements.

[2] ABBIENDI 04G limits are from $e^+ e^- \rightarrow \tau\tau$ cross section at $\sqrt{s} = 130$–207 GeV.

## 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 |
|---|---|---|---|---|---|---|
| >7.9 | **> 10.3** | 95 | [1] SCHAEL | 07A | ALEP | $E_{cm}$= 189–209 GeV |
| **>9.1** | >8.2 | 95 | ABDALLAH | 06C | DLPH | $E_{cm}$= 130–207 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >7.7 | >9.5 | 95 | [2] ABBIENDI | 04G | OPAL | $E_{cm}$= 130–207 GeV |
| | | | [3] BABICH | 03 | RVUE | |
| >9.0 | >5.2 | 95 | ACCIARRI | 00P | L3 | $E_{cm}$= 130–189 GeV |

[1] SCHAEL 07A limits are from $R_c$, $Q_{FB}^{depl}$, and hadronic cross section measurements.
[2] ABBIENDI 04G limits are from $e^+e^- \rightarrow \ell^+\ell^-$ cross section at $\sqrt{s}$ = 130–207 GeV.
[3] BABICH 03 obtain a bound $-0.175$ TeV$^{-2}$ $<1/\Lambda^2_{LL} <$ 0.095 TeV$^{-2}$ (95%CL) in a model independent analysis allowing all of $\Lambda_{LL}$, $\Lambda_{LR}$, $\Lambda_{RL}$, $\Lambda_{RR}$ to coexist.

## 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 |
|---|---|---|---|---|---|---|
| **>16.4** | **>20.7** | 95 | [1] AAD | 14BE | ATLS | $(eeqq)$ |
| > 8.4 | **>10.2** | 95 | [2] ABDALLAH | 09 | DLPH | $(eebb)$ |
| **> 9.4** | **>5.6** | 95 | [3] SCHAEL | 07A | ALEP | $(eecc)$ |
| **> 9.4** | >4.9 | 95 | [2] SCHAEL | 07A | ALEP | $(eebb)$ |
| **>23.3** | **>12.5** | 95 | [4] CHEUNG | 01B | RVUE | $(eeuu)$ |
| **>11.1** | **>26.4** | 95 | [4] CHEUNG | 01B | RVUE | $(eedd)$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >13.5 | >18.3 | 95 | [5] KHACHATRY... | 15AE | CMS | $(eeqq)$ |
| > 9.5 | >12.1 | 95 | [6] AAD | 13E | ATLS | $(eeqq)$ |
| >10.1 | >9.4 | 95 | [7] AAD | 12AB | ATLS | $(eeqq)$ |
| > 4.2 | >4.0 | 95 | [8] AARON | 11C | H1 | $(eeqq)$ |
| > 3.8 | >3.8 | 95 | [9] ABDALLAH | 11 | DLPH | $(eetc)$ |
| >12.9 | >7.2 | 95 | [10] SCHAEL | 07A | ALEP | $(eeqq)$ |
| > 3.7 | >5.9 | 95 | [11] ABULENCIA | 06L | CDF | $(eeqq)$ |

[1] AAD 14BE limits are from $pp$ collisions at $\sqrt{s}$ = 8 TeV. The quoted limit uses a uniform positive prior in $1/\Lambda^2$.
[2] ABDALLAH 09 and SCHAEL 07A limits are from $R_b$, $A^b_{FB}$.
[3] SCHAEL 07A limits are from $R_c$, $Q_{FB}^{depl}$, and hadronic cross section measurements.
[4] CHEUNG 01B is an update of BARGER 98E.
[5] KHACHATRYAN 15AE limit is from $e^+e^-$ mass distribution in $pp$ collisions at $E_{cm}$ = 8 TeV.
[6] AAD 13E limis are from $e^+e^-$ mass distribution in $pp$ collisions at $E_{cm}$ = 7 TeV.
[7] AAD 12AB limis are from $e^+e^-$ mass distribution in $pp$ collisions at $E_{cm}$ = 7 TeV.
[8] AARON 11C limits are from $Q^2$ spectrum measurements of $e^{\pm}p \rightarrow e^{\pm}X$.
[9] ABDALLAH 11 limit is from $e^+e^- \rightarrow t\overline{c}$ cross section. $\Lambda_{LL} = \Lambda_{LR} = \Lambda_{RL} = \Lambda_{RR}$ is assumed.
[10] SCHAEL 07A limit assumes quark flavor universality of the contact interactions.
[11] ABULENCIA 06L limits are from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV.

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

| $\Lambda^+_{LL}$(TeV) | $\Lambda^-_{LL}$(TeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| **>12.5** | **>16.7** | 95 | [1] AAD | 14BE | ATLS | $(\mu\mu qq)$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >12.0 | >15.2 | 95 | [2] KHACHATRY... | 15AE | CMS | $(\mu\mu qq)$ |
| > 9.6 | >12.9 | 95 | [3] AAD | 13E | ATLS | $(\mu\mu qq)$ (isosinglet) |
| > 9.5 | >13.1 | 95 | [4] CHATRCHYAN | 13K | CMS | $(\mu\mu qq)$ (isosinglet) |
| > 8.0 | >7.0 | 95 | [5] AAD | 12AB | ATLS | $(\mu\mu qq)$ (isosinglet) |

[1] AAD 14BE limits are from $p p$ collisions at $\sqrt{s} = 8$ TeV. The quoted limit uses a uniform positive prior in $1/\Lambda^2$.
[2] KHACHATRYAN 15AE limit is from $\mu^+ \mu^-$ mass distribution in $p p$ collisions at $E_{cm} =$ 8 TeV.
[3] AAD 13E limis are from $\mu^+ \mu^-$ mass distribution in $p p$ collisions at $E_{cm} = 7$ TeV.
[4] CHATRCHYAN 13K limis are from $\mu^+ \mu^-$ mass distribution in $p p$ collisions at $E_{cm} =$ 7 TeV.
[5] AAD 12AB limis are from $\mu^+ \mu^-$ mass distribution in $p p$ collisions at $E_{cm} = 7$ TeV.

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

| *VALUE* (TeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>3.10** | 90 | [1] 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 | | [2] DIAZCRUZ | 94 | RVUE | $\Lambda^{+}_{LL}(\tau \nu_\tau e \nu_e)$ |
| >8.1 | | [2] DIAZCRUZ | 94 | RVUE | $\Lambda^{-}_{LL}(\tau \nu_\tau e \nu_e)$ |
| >4.1 | | [3] DIAZCRUZ | 94 | RVUE | $\Lambda^{+}_{LL}(\tau \nu_\tau \mu \nu_\mu)$ |
| >6.5 | | [3] DIAZCRUZ | 94 | RVUE | $\Lambda^{-}_{LL}(\tau \nu_\tau \mu \nu_\mu)$ |

[1] 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.
[2] DIAZCRUZ 94 limits are from $\Gamma(\tau \rightarrow e \nu \nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau \nu_\tau e \nu_e) \ll \Lambda(\mu \nu_\mu e \nu_e)$.
[3] 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: $\Lambda(e \nu q q)$

| *VALUE* (TeV) | *CL%* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| **>2.81** | 95 | [1] AFFOLDER | 01I | CDF |

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

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

| *VALUE* (TeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| >8.1 | 95 | [1] AAD | 15L | ATLS | $p p$ dijet angl. $\Lambda^{+}_{LL}$ |
| **>9.0** | 95 | [2] KHACHATRY... | 15J | CMS | $p p$ dijet angl. $\Lambda^{+}_{LL}$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [3] AAD | 15BY | ATLS | $p p \rightarrow t \overline{t} t \overline{t}$ |
| >5 | 95 | [4] FABBRICHESI | 14 | RVUE | $q \overline{q} t \overline{t}$ |
| >7.6 | 95 | [5] AAD | 13D | ATLS | $p p \rightarrow$ dijet angl. |
| >9.9 | 95 | [6] CHATRCHYAN | 13AN | CMS | $p p \rightarrow$ dijet.; $\Lambda^{+}_{LL}$ |
| >7.5 | 95 | [7] CHATRCHYAN | 12Z | CMS | $p p \rightarrow$ dijet angl.; $\Lambda^{+}_{LL}$ |

[1] AAD 15L limit is from dijet angular distribution in $pp$ collisions at $E_{cm}$ = 8 TeV. $u$, $d$, and $s$ quarks are assumed to be composite. They also obtain $\Lambda^{-}_{LL} > 12.0$ TeV.

[2] KHACHATRYAN 15J limit is from dijet angular distribution in $pp$ collisions at $E_{cm}$ = 8 TeV. $u$, $d$, $s$, $c$, and $b$ quarks are assumed to be composite. They also obtain $\Lambda^{-}_{LL} >$ 11.7 TeV.

[3] AAD 15BY obtain limit on the $t_R$ compositeness $2\pi\Lambda^{2}_{RR} < 15.1\ \text{TeV}^{-2}$ at 95% CL from the $t\overline{t}t\overline{t}$ production in the $pp$ collisions at $E_{cm}$ = 8 TeV.

[4] FABBRICHESI 14 obtain bounds on chromoelectric and chromomagnetic form factors of the top-quark using $pp \rightarrow t\overline{t}$ and $p\overline{p} \rightarrow t\overline{t}$ cross sections. The quoted limit on the $q\overline{q}t\overline{t}$ contact interaction is derived from their bound on the chromoelectric form factor.

[5] AAD 13D limit is from dijet angular distribution in $pp$ collisions at $E_{cm}$ = 7 TeV. The constant prior in $1/\Lambda^4$ is applied.

[6] CHATRCHYAN 13AN limit is from inclusive jet $p_T$ spectrum in $pp$ collisions at $E_{cm}$ = 7 TeV. They also obtain $\Lambda^{-}_{LL} > 14.3$ TeV.

[7] CHATRCHYAN 12Z limit is from dijet angular distribution in $pp$ collisions at $E_{cm}$ = 7 TeV. They also obtain $\Lambda^{-}_{LL} > 10.5$ TeV.

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

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 | [1] MCFARLAND 98 | CCFR | $\nu N$ scattering |

[1] 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** S1 (1992)).

| VALUE (GeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **>103.2** | 95 | [1] ABBIENDI | 02G | OPAL | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >102.8 | 95 | [2] ACHARD | 03B | L3 | $e^+e^- \rightarrow e^*e^*$ Homodoublet type |

[1] From $e^+e^-$ collisions at $\sqrt{s}$ = 183–209 GeV. $f = f'$ is assumed.
[2] From $e^+e^-$ collisions at $\sqrt{s}$ = 189–209 GeV. $f = f'$ is assumed. ACHARD 03B also obtain limit for $f = -f'$: $m_{e^*} > 96.6$ GeV.

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

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

For limits prior to 1987, see our 1992 edition (Physical Review **D45** S1 (1992)).

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>3000** | 95 | [1] AAD | 15AP | ATLS | $pp \to e^{(*)}e^*X$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >2200 | 95 | [2] AAD | 13BB | ATLS | $pp \to ee^*X$ |
| >1900 | 95 | [3] CHATRCHYAN | 13AE | CMS | $pp \to ee^*X$ |
| >1870 | 95 | [4] AAD | 12AZ | ATLS | $pp \to e^{(*)}e^*X$ |
| >1070 | 95 | [5] CHATRCHYAN | 11X | CMS | $pp \to ee^*X$ |

[1] AAD 15AP search for $e^*$ production in evens with three or more charged leptons in $pp$ collisions at $\sqrt{s} = 8$ TeV. The quoted limit assumes $\Lambda = m_{e^*}$, $f = f' = 1$. The contact interaction is included in the $e^*$ production and decay amplitudes.
[2] AAD 13BB search for single $e^*$ production in $pp$ collisions with $e^* \to e\gamma$ decay. $f = f' = 1$, and $e^*$ production via contact interaction with $\Lambda = m_{e^*}$ are assumed.
[3] CHATRCHYAN 13AE search for single $e^*$ production in $pp$ collisions with $e^* \to e\gamma$ decay. $f = f' = 1$, and $e^*$ production via contact interaction with $\Lambda = m_{e^*}$ are assumed.
[4] AAD 12AZ search for $e^*$ production via four-fermion contact interaction in $pp$ collisions with $e^* \to e\gamma$ decay. The quoted limit assumes $\Lambda = m_{e^*}$. See their Fig. 8 for the exclusion plot in the mass-coupling plane.
[5] CHATRCHYAN 11X search for single $e^*$ production in $pp$ collisions with the decay $e^* \to e\gamma$. $f = f' = \Lambda/m_{e^*}$ is assumed. See their Fig. 2 for the exclusion plot in the mass-coupling plane.

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

These limits are derived from indirect effects due to $e^*$ exchange in the $t$ channel and depend on transition magnetic coupling between $e$ and $e^*$. All limits are for $\lambda_\gamma = 1$. All limits except ABE 89J and ACHARD 02D are for nonchiral coupling with $\eta_L = \eta_R = 1$. We choose the chiral coupling limit as the best limit and list it in the Summary Table.

For limits prior to 1987, see our 1992 edition (Physical Review **D45** S1 (1992)).

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>356** | 95 | [1] ABDALLAH | 04N | DLPH | $\sqrt{s}$= 161–208 GeV |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >310 | 95 | ACHARD | 02D | L3 | $\sqrt{s}$= 192–209 GeV |

[1] ABDALLAH 04N also obtain a limit on the excited electron mass with $ee^*$ chiral coupling, $m_{e^*} > 295$ GeV at 95% CL.

### 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. • • • | | | | |
| | [1] DORENBOS... | 89 | CHRM | $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$, $\nu_\mu e \to \nu_\mu e$ |
| | [2] GRIFOLS | 86 | THEO | $\nu_\mu e \to \nu_\mu e$ |
| | [3] RENARD | 82 | THEO | $g-2$ of electron |

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

[2] 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.

[3] 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** S1 (1992)).

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>103.2** | 95 | [1] ABBIENDI | 02G | OPAL | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >102.8 | 95 | [2] ACHARD | 03B | L3 | $e^+ e^- \to \mu^* \mu^*$ Homodoublet type |

[1] From $e^+ e^-$ collisions at $\sqrt{s} = 183$–$209$ GeV. $f = f'$ is assumed.

[2] From $e^+ e^-$ collisions at $\sqrt{s} = 189$–$209$ GeV. $f = f'$ is assumed. ACHARD 03B also obtain limit for $f = -f'$: $m_{\mu^*} > 96.6$ GeV.

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

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

For limits prior to 1987, see our 1992 edition (Physical Review **D45** S1 (1992)).

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>3000** | 95 | [1] AAD | 15AP | ATLS | $pp \to \mu^{(*)} \mu^* X$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >2200 | 95 | [2] AAD | 13BB | ATLS | $pp \to \mu \mu^* X$ |
| >1900 | 95 | [3] CHATRCHYAN | 13AE | CMS | $pp \to \mu \mu^* X$ |
| >1750 | 95 | [4] AAD | 12AZ | ATLS | $pp \to \mu^{(*)} \mu^* X$ |
| >1090 | 95 | [5] CHATRCHYAN | 11X | CMS | $pp \to \mu \mu^* X$ |

[1] AAD 15AP search for $\mu^*$ production in evens with three or more charged leptons in $pp$ collisions at $\sqrt{s} = 8$ TeV. The quoted limit assumes $\Lambda = m_{\mu^*}$, $f = f' = 1$. The contact interaction is included in the $\mu^*$ production and decay amplitudes.
[2] AAD 13BB search for single $\mu^*$ production in $pp$ collisions with $\mu^* \rightarrow \mu\gamma$ decay. $f = f' = 1$, and $\mu^*$ production via contact interaction with $\Lambda = m_{\mu^*}$ are assumed.
[3] CHATRCHYAN 13AE search for single $\mu^*$ production in $pp$ collisions with $\mu^* \rightarrow \mu\gamma$ decay. $f = f' = 1$, and $\mu^*$ production via contact interaction with $\Lambda = m_{\mu^*}$ are assumed.
[4] AAD 12AZ search for $\mu^*$ production via four-fermion contact interaction in $pp$ collisions with $\mu^* \rightarrow \mu\gamma$ decay. The quoted limit assumes $\Lambda = m_{\mu^*}$. See their Fig. 8 for the exclusion plot in the mass-coupling plane.
[5] CHATRCHYAN 11X search for single $\mu^*$ production in $pp$ collisions with the decay $\mu^* \rightarrow \mu\gamma$. $f = f' = \Lambda/m_{\mu^*}$ is assumed. See their Fig. 2 for the exclusion plot in the mass-coupling plane.

## 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. • • • | | | | |
| | [1] RENARD | 82 | THEO | $g-2$ of muon |

[1] 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** S1 (1992)).

| VALUE (GeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **>103.2** | 95 | [1] ABBIENDI | 02G | OPAL | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >102.8 | 95 | [2] ACHARD | 03B | L3 | $e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type |

[1] From $e^+e^-$ collisions at $\sqrt{s} = 183$–$209$ GeV. $f = f'$ is assumed.
[2] From $e^+e^-$ collisions at $\sqrt{s} = 189$–$209$ GeV. $f = f'$ is assumed. ACHARD 03B also obtain limit for $f = -f'$: $m_{\tau^*} > 96.6$ GeV.

## 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 |
|---|---|---|---|---|---|
| **>2500** | 95 | [1] AAD | 15AP | ATLS | $pp \rightarrow \tau^{(*)}\tau^* X$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| > 180 | 95 | [2] ACHARD | 03B | L3 | $e^+e^- \rightarrow \tau\tau^*$ |
| > 185 | 95 | [3] ABBIENDI | 02G | OPAL | $e^+e^- \rightarrow \tau\tau^*$ |

[1] AAD 15AP search for $\tau^*$ production in events with three or more charged leptons in $pp$ collisions at $\sqrt{s} = 8$ TeV. The quoted limit assumes $\Lambda = m_{\tau^*}$, $f = f' = 1$. The contact interaction is included in the $\tau^*$ production and decay amplitudes.

[2] ACHARD 03B result is from $e^+e^-$ collisions at $\sqrt{s} = 189$–$209$ GeV. $f = f' = \Lambda/m_{\tau^*}$ is assumed. See their Fig. 4 for the exclusion plot in the mass-coupling plane.

[3] ABBIENDI 02G result is from $e^+e^-$ collisions at $\sqrt{s} = 183$–$209$ GeV. $f = f' = \Lambda/m_{\tau^*}$ is assumed for $\tau^*$ coupling. See their Fig. 4c for the exclusion limit in the mass-coupling plane.

# 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* |
|---|---|---|---|---|---|
| **>1600** | 95 | [1] AAD | 15AP | ATLS | $pp \rightarrow \nu^*\nu^* X$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [2] ABBIENDI | 04N | OPAL | |
| > 102.6 | 95 | [3] ACHARD | 03B | L3 | $e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type |

[1] AAD 15AP search for $\nu^*$ pair production in evens with three or more charged leptons in $pp$ collisions at $\sqrt{s} = 8$ TeV. The quoted limit assumes $\Lambda = m_{\nu^*}$, $f = f' = 1$. The contact interaction is included in the $\nu^*$ production and decay amplitudes.

[2] From $e^+e^-$ collisions at $\sqrt{s} = 192$–$209$ GeV, ABBIENDI 04N obtain limit on $\sigma(e^+e^- \rightarrow \nu^*\nu^*)$ $B^2(\nu^* \rightarrow \nu\gamma)$. See their Fig.2. The limit ranges from 20 to 45 fb for $m_{\nu^*} > 45$ GeV.

[3] From $e^+e^-$ collisions at $\sqrt{s} = 189$–$209$ GeV. $f = -f'$ is assumed. ACHARD 03B also obtain limit for $f = f'$: $m_{\nu_e^*} > 101.7$ GeV, $m_{\nu_\mu^*} > 101.8$ GeV, and $m_{\nu_\tau^*} > 92.9$ GeV. See their Fig. 4 for the exclusion plot in the mass-coupling plane.

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

These limits are from $e^+e^- \rightarrow \nu\nu^*$, $Z \rightarrow \nu\nu^*$, or $ep \rightarrow \nu^* X$ 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* |
|---|---|---|---|---|---|
| **>213** | 95 | [1] AARON | 08 | H1 | $ep \rightarrow \nu^* X$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >190 | 95 | [2] ACHARD | 03B | L3 | $e^+e^- \rightarrow \nu\nu^*$ |
| none 50–150 | 95 | [3] ADLOFF | 02 | H1 | $ep \rightarrow \nu^* X$ |
| >158 | 95 | [4] CHEKANOV | 02D | ZEUS | $ep \rightarrow \nu^* X$ |

[1] AARON 08 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. 3 and Fig. 4 for the exclusion plots in the mass-coupling plane.

[2] ACHARD 03B result is from $e^+e^-$ collisions at $\sqrt{s} = 189$–$209$ GeV. The quoted limit is for $\nu_e^*$. $f = -f' = \Lambda/m_{\nu^*}$ is assumed. See their Fig. 4 for the exclusion plot in the mass-coupling plane.

[3] ADLOFF 02 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. 1 for the exclusion plots in the mass-coupling plane.

[4] CHEKANOV 02D search for single $\nu^*$ production in $ep$ collisions with the decays $\nu^* \rightarrow \nu\gamma$, $\nu Z$, $eW$. $f = -f' = \Lambda/m_{\nu^*}$ is assumed for the $e^*$ coupling. CHEKANOV 02D also obtain limit for $f = f' = \Lambda/m_{\nu^*}$: $m_{\nu^*}$ >135 GeV. See their Fig. 5c and Fig. 5d for the exclusion plot in the mass-coupling plane.

## MASS LIMITS for Excited $q$ ($q^*$)

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

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

| VALUE (GeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **>338** | 95 | [1] AALTONEN | 10H | CDF | $q^* \rightarrow tW^-$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >655 | 95 | [2] AAD | 14AZ | ATLS | $T \rightarrow tZ$ |
| | | [3] BARATE | 98U | ALEP | $Z \rightarrow q^*q^*$ |
| > 45.6 | 95 | [4] ADRIANI | 93M | L3 | $u$ or $d$ type, $Z \rightarrow q^*q^*$ |
| > 41.7 | 95 | [5] BARDADIN-... | 92 | RVUE | $u$-type, $\Gamma(Z)$ |
| > 44.7 | 95 | [5] BARDADIN-... | 92 | RVUE | $d$-type, $\Gamma(Z)$ |
| > 40.6 | 95 | [6] DECAMP | 92 | ALEP | $u$-type, $\Gamma(Z)$ |
| > 44.2 | 95 | [6] DECAMP | 92 | ALEP | $d$-type, $\Gamma(Z)$ |
| > 45 | 95 | [7] DECAMP | 92 | ALEP | $u$ or $d$ type, $Z \rightarrow q^*q^*$ |
| > 45 | 95 | [6] ABREU | 91F | DLPH | $u$-type, $\Gamma(Z)$ |
| > 45 | 95 | [6] ABREU | 91F | DLPH | $d$-type, $\Gamma(Z)$ |

[1] AALTONEN 10H obtain limits on the $q^*q^*$ production cross section in $p\overline{p}$ collisions. See their Fig. 3.

[2] AAD 14AZ quoted limit is for heavy SU(2) singlet quark $T$.

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

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

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

[6] These limits are independent of decay modes.

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

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

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

| VALUE (GeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **>4060** | 95 | [1] AAD | 15V | ATLS | $pp \rightarrow q^*X$, $q^* \rightarrow qg$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >1390 | 95 | [2] KHACHATRY... | 16I | CMS | $pp \rightarrow b^*X$, $b^* \rightarrow tW$ |
| >3500 | 95 | [3] KHACHATRY... | 15V | CMS | $pp \rightarrow q^*X$, $q^* \rightarrow qg$ |
| >3500 | 95 | [4] AAD | 14A | ATLS | $pp \rightarrow q^*X$, $q^* \rightarrow q\gamma$ |
| >3200 | 95 | [5] KHACHATRY... | 14 | CMS | $pp \rightarrow q^*X$, $q^* \rightarrow qW$ |
| >2900 | 95 | [6] KHACHATRY... | 14 | CMS | $pp \rightarrow q^*X$, $q^* \rightarrow qZ$ |

| | | | | | |
|---|---|---|---|---|---|
| none 700–3500 | 95 | [7] KHACHATRY... | 14J | CMS | $pp \to q^* X$, $q^* \to q\gamma$ |
| $>$ 870 | 95 | [8] AAD | 13AF | ATLS | $pp \to b^* X$, $b^* \to tW$ |
| $>$1940 | 95 | [9] CHATRCHYAN | 13AI | CMS | $pp \to q^* X$, $q^* \to qZ, qW$ |
| $>$2380 | 95 | [10] CHATRCHYAN | 13AJ | CMS | $pp \to q^* X$, $q^* \to qW$ |
| $>$2150 | 95 | [11] CHATRCHYAN | 13AJ | CMS | $pp \to q^* X$, $q^* \to qZ$ |
| | | [12] ABAZOV | 11F | D0 | $p\overline{p} \to q^* X$, $q^* \to qZ, qW$ |

[1] AAD 15V assume $\Lambda = m_{q^*}$, $f_s = f = f' = 1$. The contact interactions are not included in $q^*$ production and decay amplitudes.

[2] KHACHATRYAN 16I search for $b^*$ decaying to $tW$ in $pp$ collisions at $\sqrt{s} = 8$ TeV. $\kappa^b_L = g_L = 1$, $\kappa^b_R = g_R = 0$ are assumed. See their Fig. 8 for limits on $\sigma \cdot B$.

[3] KHACHATRYAN 15V assume $\Lambda = m_{q^*}$, $f_s = f = f' = 1$. The contact interactions are not included in $q^*$ production and decay amplitudes.

[4] AAD 14A assume $\Lambda = m_{q^*}$, $f_s = f = f' = 1$.

[5] KHACHATRYAN 14 use the hadronic decay of $W$, assuming $\Lambda = m_{q^*}$, $f_s = f = f' = 1$.

[6] KHACHATRYAN 14 use the hadronic decay of $Z$, assuming $\Lambda = m_{q^*}$, $f_s = f = f' = 1$.

[7] KHACHATRYAN 14J assume $f_s = f = f' = \Lambda \,/\, m_{q^*}$.

[8] AAD 13AF search for $b^*$ decaying to $tW$ in $pp$ collisions at $\sqrt{s} = 7$ TeV. $\kappa^b_L = g_L = 1$, $\kappa^b_R = g_R = 0$ are assumed. See their Fig.6 for limits on $\sigma \cdot B$.

[9] CHATRCHYAN 13AI assume $q^*$ production via $qg$ fusion and $\Lambda = m_{q^*}$, $f_s = f = f' = 1$. For $q^*$ production via $qg$ fusion and via contact interactions, the limit becomes $m_{q^*} >$ 2220 GeV.

[10] CHATRCHYAN 13AJ use the hadronic decay of $W$.

[11] CHATRCHYAN 13AJ use the hadronic decay of $Z$.

[12] ABAZOV 11F search for vectorlike quarks decaying to $W$+jet and $Z$+jet in $p\overline{p}$ collisions. See their Fig. 3 and Fig. 4 for the limits on $\sigma \cdot$ B.

## MASS LIMITS for Color Sextet Quarks ($q_6$)

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>84** | 95 | [1] ABE | 89D | CDF | $p\overline{p} \to q_6 \overline{q}_6$ |

[1] 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 | [1] 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. • • • | | | | | |
| | | [2] ABT | 93 | H1 | $e_8$: $ep \to e_8 X$ |

[1] 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.

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

## MASS LIMITS for Color Octet Neutrinos ($\nu_8$)

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>110** | 90 | [1] 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 | [2] KIM | 90 | AMY | $\nu_8$: $e^+ e^- \rightarrow$ acoplanar jets |
| none 9–21.9 | 95 | [3] BARTEL | 87B | JADE | $\nu_8$: $e^+ e^- \rightarrow$ acoplanar jets |

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

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

[3] BARTEL 87B is at $E_{cm}$ = 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 $SU(2)_L \times U(1)_Y$ quantum numbers.

## MASS LIMITS for $W_8$ (Color Octet $W$ Boson)

| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [1] ALBAJAR | 89 | UA1 | $p\overline{p} \rightarrow W_8 X$, $W_8 \rightarrow Wg$ |

[1] 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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