Quark and Lepton Compositeness, Searches for

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CONTENTS:

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

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

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>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 $\sqrt{s} = 130\text{–}207$ GeV.

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

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

Λ_{LL}^{+}(TeV)	Λ_{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 $\sqrt{s} = 130\text{–}207$ GeV.

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

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

Λ_{LL}^{+}(TeV)	Λ_{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 $\sqrt{s} = 130\text{–}207$ GeV.

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

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

Λ_{LL}^{+}(TeV)	Λ_{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} $<1/\Lambda_{LL}^2 <$ 0.095 TeV^{-2} (95%CL) in a model independent analysis allowing all of Λ_{LL}, Λ_{LR}, Λ_{RL}, Λ_{RR} to coexist.

SCALE LIMITS for Contact Interactions: Λ($eeqq$)

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

Λ_{LL}^{+}(TeV)	Λ_{LL}^{-}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 9.5	**>12.1**	95	[1] AAD	13E	ATLS	($eeqq$)
> **10.1**	>9.4	95	[2] AAD	12AB	ATLS	($eeqq$)
> 8.4	**>10.2**	95	[3] ABDALLAH	09	DLPH	($eebb$)
> 9.4	**>5.6**	95	[4] SCHAEL	07A	ALEP	($eecc$)
> 9.4	>4.9	95	[3] SCHAEL	07A	ALEP	($eebb$)
>23.3	**>12.5**	95	[5] CHEUNG	01B	RVUE	($eeuu$)
>11.1	**>26.4**	95	[5] CHEUNG	01B	RVUE	($eedd$)
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 4.2	>4.0	95	[6] AARON	11C	H1	($eeqq$)
> 3.8	>3.8	95	[7] ABDALLAH	11	DLPH	($eetc$)
>12.9	>7.2	95	[8] SCHAEL	07A	ALEP	($eeqq$)
> 3.7	>5.9	95	[9] ABULENCIA	06L	CDF	($eeqq$)

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

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

Λ_{LL}^{+}(TeV)	Λ_{LL}^{-}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>9.6	>12.9	95	[1] AAD	13E	ATLS	($\mu\mu qq$) (isosinglet)
>9.5	**> 13.1**	95	[2] CHATRCHYAN	13K	CMS	($\mu\mu qq$) (isosinglet)
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>8.0	>7.0	95	[3] AAD	12AB	ATLS	($\mu\mu qq$) (isosinglet)

[1] AAD 13E limis are from $\mu^+\mu^-$ mass distribution in pp collisions at E_{cm} = 7 TeV.
[2] CHATRCHYAN 13K limis are from $\mu^+\mu^-$ mass distribution in pp collisions at E_{cm} = 7 TeV.
[3] AAD 12AB limis are from $\mu^+\mu^-$ mass distribution in pp collisions at E_{cm} = 7 TeV.

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

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>3.10	90	[1] JODIDIO	86	SPEC	$\Lambda_{LR}^{\pm}(\nu_\mu \nu_e \mu e)$

• • • 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 $\mu^+ \to \overline{\nu}_\mu e^+ \nu_e$. Chirality invariant interactions $L = (g^2/\Lambda^2)$ $[\eta_{LL}\ (\overline{\nu}_{\mu L}\gamma^\alpha\mu_L)\ (\overline{e}_L\gamma_\alpha\nu_{eL}) + \eta_{LR}\ (\overline{\nu}_{\mu L}\gamma^\alpha\nu_{eL})\ (\overline{e}_R\gamma_\alpha\mu_R)]$ with $g^2/4\pi = 1$ and $(\eta_{LL},\eta_{LR}) = (0,\pm1)$ 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 $\Gamma(\tau \to e\nu\nu)$ and assume flavor-dependent contact interactions with $\Lambda(\tau\nu_\tau e\nu_e) \ll \Lambda(\mu\nu_\mu e\nu_e)$.

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

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

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: $\Lambda(qqqq)$

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
>9.9	95	[1] CHATRCHYAN	13AN	CMS	$pp \to$ dijet.; Λ^+_{LL}
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>7.6	95	[2] AAD	13D	ATLS	$pp \to$ dijet angl.
>7.5	95	[3] CHATRCHYAN	12Z	CMS	$pp \to$ dijet angl.; Λ^+_{LL}
>3.4	95	[4] AAD	11	ATLS	$pp \to$ dijet; Λ^+_{LL}
>5.6	95	[5] KHACHATRY...	11F	CMS	$pp \to$ dijet angl.; Λ^+_{LL}

[1] 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.

[2] 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.

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

[4] AAD 11 limit is from dijet angular distribution and dijet centrality ratio in pp collisions at E_{cm} = 7 TeV.

[5] KHACHATRYAN 11F limit is from dijet angular distribution in pp collisions at E_{cm} = 7 TeV. They also obtain $\Lambda^-_{LL} > 6.7$ TeV.

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

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

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>5.0	**>5.4**	95	[1] MCFARLAND 98	CCFR	νN 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 λ have assumed transition couplings which are chirality violating ($\eta_L = \eta_R$). However they can be interpreted as limits for chirality-conserving interactions after multiplying the coupling value λ by $\sqrt{2}$; see Note.

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

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

These limits are obtained from $e^+e^- \rightarrow e^{*+}e^{*-}$ and thus rely only on the (electroweak) charge of e^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the e^* coupling is assumed to be of sequential type. Possible t channel contribution from transition magnetic coupling is neglected. All limits assume 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 $e^+e^- \rightarrow e^*e$, $W \rightarrow e^*\nu$, 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** S1 (1992)).

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>2200	95	[1] AAD 13BB	ATLS	$pp \rightarrow ee^*X$

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

>1900	95	[2] CHATRCHYAN	13AE	CMS	$p p \to e e^* X$
>1870	95	[3] AAD	12AZ	ATLS	$p p \to e^{(*)} e^* X$
>1070	95	[4] CHATRCHYAN	11X	CMS	$p p \to e e^* X$
> 272	95	[5] AARON	08A	H1	$e p \to e^* X$
		[6] ABAZOV	08H	D0	$p \overline{p} \to e^* e$
> 209	95	[7] ACOSTA	05B	CDF	$p \overline{p} \to e^* X$
> 206	95	[8] ACHARD	03B	L3	$e^+ e^- \to e e^*$
> 208	95	[9] ABBIENDI	02G	OPAL	$e^+ e^- \to e e^*$
> 228	95	[10] CHEKANOV	02D	ZEUS	$e p \to e^* X$

[1] AAD 13BB search for single e^* production in $p p$ collisions with $e^* \to e\gamma$ decay. $f = f' = 1$, and e^* production via contact interaction with $\Lambda = m_{e^*}$ are assumed.

[2] CHATRCHYAN 13AE search for single e^* production in $p p$ collisions with $e^* \to e\gamma$ decay. $f = f' = 1$, and e^* production via contact interaction with $\Lambda = m_{e^*}$ are assumed.

[3] AAD 12AZ search for e^* production via four-fermion contact interaction in $p p$ 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.

[4] CHATRCHYAN 11X search for single e^* production in $p p$ 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.

[5] AARON 08A search for single e^* production in $e p$ collisions with the decays $e^* \to e\gamma$, $e Z$, νW. The quoted limit assumes $f = f' = \Lambda/m_{e^*}$. See their Fig. 3 and Fig. 4 for the exclusion plots in the mass-coupling plane.

[6] ABAZOV 08H search for single e^* production in $p\overline{p}$ collisions with the decays $e^* \to e\gamma$. The e^* production is assumed to be described by an effective four-fermion interaction. See their Fig. 5 for the exclusion plot in the mass-coupling plane.

[7] ACOSTA 05B search for single e^* production in $p\overline{p}$ collisions with the decays $e^* \to e\gamma$. $f = f' = \Lambda/m_{e^*}$ is assumed for the e^* coupling. See their Fig.3 for the exclusion limit in the mass-coupling plane.

[8] ACHARD 03B result is from $e^+ e^-$ collisions at $\sqrt{s} = 189$–209 GeV. See their Fig. 4 for the exclusion plot in the mass-coupling plane.

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

[10] CHEKANOV 02D search for single e^* production in $e p$ collisions with the decays $e^* \to e\gamma$, $e Z$, νW. $f = f' = \Lambda/m_{e^*}$ is assumed for the e^* coupling. See their Fig. 5a 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 $e e^*$ 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	$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$, $\nu_\mu e \rightarrow \nu_\mu e$
	[2] GRIFOLS	86	THEO	$\nu_\mu e \rightarrow \nu_\mu e$
	[3] RENARD	82	THEO	$g-2$ of electron

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

[2] GRIFOLS 86 uses $\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$ 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 μ^*. See figures 2 and 3 of the paper.

MASS LIMITS for Excited μ (μ^*)

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

These limits are obtained from $e^+ e^- \rightarrow \mu^{*+} \mu^{*-}$ and thus rely only on the (electroweak) charge of μ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the μ^* coupling is assumed to be of sequential type. All limits assume a dominant $\mu^* \rightarrow \mu\gamma$ 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	$e^+ e^- \rightarrow \mu^* \mu^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>102.8	95	[2] ACHARD	03B	L3	$e^+ e^- \rightarrow \mu^* \mu^*$ 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 μ (μ^*) from Single Production

These limits are from $e^+ e^- \rightarrow \mu^* \mu$ and depend on transition magnetic coupling between μ and μ^*. 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** S1 (1992)).

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>2200	95	[1] AAD	13BB	ATLS	$p p \rightarrow \mu \mu^* X$

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

>1900	95	[2] CHATRCHYAN	13AE	CMS	$pp \to \mu\mu^* X$
>1750	95	[3] AAD	12AZ	ATLS	$pp \to \mu^{(*)}\mu^* X$
>1090	95	[4] CHATRCHYAN	11X	CMS	$pp \to \mu\mu^* X$
> 180	95	[5] ACHARD	03B	L3	$e^+e^- \to \mu\mu^*$
> 190	95	[6] ABBIENDI	02G	OPAL	$e^+e^- \to \mu\mu^*$

[1] AAD 13BB search for single μ^* production in pp collisions with $\mu^* \to \mu\gamma$ decay. $f = f' = 1$, and μ^* production via contact interaction with $\Lambda = m_{\mu^*}$ are assumed.

[2] CHATRCHYAN 13AE search for single μ^* production in pp collisions with $\mu^* \to \mu\gamma$ decay. $f = f' = 1$, and μ^* production via contact interaction with $\Lambda = m_{\mu^*}$ are assumed.

[3] AAD 12AZ search for μ^* production via four-fermion contact interaction in pp collisions with $\mu^* \to \mu\gamma$ decay. The quoted limit assumes $\Lambda = m_{\mu^*}$. See their Fig. 8 for the exclusion plot in the mass-coupling plane.

[4] CHATRCHYAN 11X search for single μ^* production in pp collisions with the decay $\mu^* \to \mu\gamma$. $f = f' = \Lambda/m_{\mu^*}$ is assumed. See their Fig. 2 for the exclusion plot in the mass-coupling plane.

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

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

Indirect Limits for Excited μ (μ^*)

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

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

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

MASS LIMITS for Excited τ (τ^*)

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

These limits are obtained from $e^+e^- \to \tau^{*+}\tau^{*-}$ and thus rely only on the (electroweak) charge of τ^*. Form factor effects are ignored unless noted. For the case of limits from Z decay, the τ^* coupling is assumed to be of sequential type. All limits assume a dominant $\tau^* \to \tau\gamma$ 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	$e^+e^- \to \tau^*\tau^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>102.8	95	[2] ACHARD	03B	L3	$e^+e^- \to \tau^*\tau^*$ 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 τ (τ^*) from Single Production

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>185	95	[1] ABBIENDI	02G	OPAL	$e^+e^- \rightarrow \tau\tau^*$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>180	95	[2] ACHARD	03B	L3	$e^+e^- \rightarrow \tau\tau^*$

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

[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.

MASS LIMITS for Excited Neutrino (ν^*)

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

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>102.6	95	[1] ACHARD	03B	L3	$e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[2] ABBIENDI	04N	OPAL	

[1] 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.

[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.

Limits for Excited ν (ν^*) 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 ν/e and ν^*. Assumptions about ν^* 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 ν^* production in ep collisions with the decays $\nu^* \to \nu\gamma$, νZ, 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 ν^*_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 ν^* production in ep collisions with the decays $\nu^* \to \nu\gamma$, νZ, 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 ν^* production in ep collisions with the decays $\nu^* \to \nu\gamma$, νZ, eW. $f = -f' = \Lambda/m_{\nu^*}$ is assumed for the e^* coupling. CHEKANOV 02D also obtain limit for $f = f' = \Lambda/m_{\nu^*}$: m_{ν^*} >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 $e^+e^- \to q^*\overline{q}^*$ 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
>338	95	[1] AALTONEN	10H	CDF	$q^* \to tW^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[2] BARATE	98U	ALEP	$Z \to q^* q^*$
> 45.6	95	[3] ADRIANI	93M	L3	u or d type, $Z \to q^* q^*$
> 41.7	95	[4] BARDADIN-...	92	RVUE	u-type, $\Gamma(Z)$
> 44.7	95	[4] BARDADIN-...	92	RVUE	d-type, $\Gamma(Z)$
> 40.6	95	[5] DECAMP	92	ALEP	u-type, $\Gamma(Z)$
> 44.2	95	[5] DECAMP	92	ALEP	d-type, $\Gamma(Z)$
> 45	95	[6] DECAMP	92	ALEP	u or d type, $Z \to q^* q^*$
> 45	95	[5] ABREU	91F	DLPH	u-type, $\Gamma(Z)$
> 45	95	[5] 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] BARATE 98U obtain limits on the form factor. See their Fig. 16 for limits in mass-form factor plane.
[3] ADRIANI 93M limit is valid for B($q^* \to qg$)> 0.25 (0.17) for up (down) type.
[4] BARDADIN-OTWINOWSKA 92 limit based on $\Delta\Gamma(Z)$<36 MeV.
[5] These limits are independent of decay modes.
[6] Limit is for B($q^* \to qg$)+B($q^* \to q\gamma$)=1.

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

These limits are from $e^+e^- \to q^*\overline{q}$, $p\overline{p} \to q^*X$, or $pp \to q^*X$ 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
>3500	95	[1] AAD	14A	ATLS	$pp \to q^*X$, $q^* \to q\gamma$

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

$>$ 870	95	[2] AAD	13AF	ATLS	$pp \to b^* X,\ b^* \to tW$
$>$3320	95	[3] CHATRCHYAN	13A	CMS	$pp \to q^* X,\ q^* \to qg$
$>$1940	95	[4] CHATRCHYAN	13AI	CMS	$pp \to q^* X,\ q^* \to qZ, qW$
$>$2380	95	[5] CHATRCHYAN	13AJ	CMS	$pp \to q^* X,\ q^* \to qW$
$>$2150	95	[6] CHATRCHYAN	13AJ	CMS	$pp \to q^* X,\ q^* \to qZ$
none 1000–3190	95	[7] CHATRCHYAN	13AS	CMS	$pp \to q^* X,\ q^* \to qg$
$>$2460	95	[8] AAD	12AO	ATLS	$pp \to q^* X,\ q^* \to q\gamma$
$>$2990	95	[9] AAD	12S	ATLS	$pp \to q^* X,\ q^* \to qg$
		[10] ABAZOV	11F	D0	$p\overline{p} \to q^* X,\ q^* \to qZ, qW$
$>$2490	95	[11] CHATRCHYAN	11Y	CMS	$pp \to q^* X,\ q^* \to qg$

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

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

[3] CHATRCHYAN 13A assume $\Lambda = m_{q^*}$.

[4] 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.

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

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

[7] CHATRCHYAN 13AS assume $\Lambda = m_{q^*}$.

[8] AAD 12AO assume $\Lambda = m_{q^*}$, $f_s = f = f' = 1$.

[9] AAD 12S assume $\Lambda = m_{q^*}$.

[10] 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.

[11] CHATRCHYAN 11Y assume degenerate q^* with $f_s = \Lambda/m_{q^*}$.

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 (ℓ_8)

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>86	95	[1] ABE	89D	CDF	Stable ℓ_8: $p\overline{p} \to \ell_8 \overline{\ell}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[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}–Λ plane for m_{e_8} = 35–220 GeV.

MASS LIMITS for Color Octet Neutrinos (ν_8)

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>110	90	[1] BARGER	89	RVUE	ν_8: $p\overline{p} \rightarrow \nu_8 \overline{\nu}_8$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 3.8–29.8	95	[2] KIM	90	AMY	ν_8: $e^+ e^- \rightarrow$ acoplanar jets
none 9–21.9	95	[3] BARTEL	87B	JADE	ν_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 $E_{\rm cm}$ = 50–60.8 GeV. The same assumptions as in BARTEL 87B are used.

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

MASS LIMITS for W_8 (Color Octet W Boson)

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

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

REFERENCES FOR Searches for Quark and Lepton Compositeness

AAD	14A	PL B728 562	G. Aad et al.	(ATLAS Collab.)
AAD	13AF	PL B721 171	G. Aad et al.	(ATLAS Collab.)
AAD	13BB	NJP 15 093011	G. Aad et al.	(ATLAS Collab.)
AAD	13D	JHEP 1301 029	G. Aad et al.	(ATLAS Collab.)
AAD	13E	PR D87 015010	G. Aad et al.	(ATLAS Collab.)
CHATRCHYAN	13A	JHEP 1301 013	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	13AE	PL B720 309	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	13AI	PL B722 28	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	13AJ	PL B723 280	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	13AN	PR D87 052017	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	13AS	PR D87 114015	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	13K	PR D87 032001	S. Chatrchyan et al.	(CMS Collab.)
AAD	12AB	PL B712 40	G. Aad et al.	(ATLAS Collab.)
AAD	12AO	PRL 108 211802	G. Aad et al.	(ATLAS Collab.)
AAD	12AZ	PR D85 072003	G. Aad et al.	(ATLAS Collab.)
AAD	12S	PL B708 37	G. Aad et al.	(ATLAS Collab.)
CHATRCHYAN	12Z	JHEP 1205 055	S. Chatrchyan et al.	(CMS Collab.)
AAD	11	PL B694 327	G. Aad et al.	(ATLAS Collab.)
AARON	11C	PL B705 52	F. D. Aaron et al.	(H1 Collab.)
ABAZOV	11F	PRL 106 081801	V.M. Abazov et al.	(D0 Collab.)
ABDALLAH	11	EPJ C71 1555	J. Abdallah et al.	(DELPHI Collab.)
CHATRCHYAN	11X	PL B704 143	S. Chatrchyan et al.	(CMS Collab.)

CHATRCHYAN	11Y	PL B704 123	S. Chatrchyan *et al.*	(CMS Collab.)
KHACHATRY...	11F	PRL 106 201804	V. Khachatryan *et al.*	(CMS Collab.)
AALTONEN	10H	PRL 104 091801	T. Aaltonen *et al.*	(CDF Collab.)
ABDALLAH	09	EPJ C60 1	J. Abdallah *et al.*	(DELPHI Collab.)
AARON	08	PL B663 382	F.D. Aaron *et al.*	(H1 Collab.)
AARON	08A	PL B666 131	F.D. Aaron *et al.*	(H1 Collab.)
ABAZOV	08H	PR D77 091102	V.M. Abazov *et al.*	(D0 Collab.)
SCHAEL	07A	EPJ C49 411	S. Schael *et al.*	(ALEPH Collab.)
ABDALLAH	06C	EPJ C45 589	J. Abdallah *et al.*	(DELPHI Collab.)
ABULENCIA	06L	PRL 96 211801	A. Abulencia *et al.*	(CDF Collab.)
ACOSTA	05B	PRL 94 101802	D. Acosta *et al.*	(CDF Collab.)
ABBIENDI	04G	EPJ C33 173	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	04N	PL B602 167	G. Abbiendi *et al.*	(OPAL Collab.)
ABDALLAH	04N	EPJ C37 405	J. Abdallah *et al.*	(DELPHI Collab.)
ACHARD	03B	PL B568 23	P. Achard *et al.*	(L3 Collab.)
BABICH	03	EPJ C29 103	A.A. Babich *et al.*	
ABBIENDI	02G	PL B544 57	G. Abbiendi *et al.*	(OPAL Collab.)
ACHARD	02D	PL B531 28	P. Achard *et al.*	(L3 Collab.)
ADLOFF	02	PL B525 9	C. Adloff *et al.*	(H1 Collab.)
CHEKANOV	02D	PL B549 32	S. Chekanov *et al.*	(ZEUS Collab.)
AFFOLDER	01I	PRL 87 231803	T. Affolder *et al.*	(CDF Collab.)
BOURILKOV	01	PR D64 071701	D. Bourilkov	
CHEUNG	01B	PL B517 167	K. Cheung	
ACCIARRI	00P	PL B489 81	M. Acciarri *et al.*	(L3 Collab.)
AFFOLDER	00I	PR D62 012004	T. Affolder *et al.*	(CDF Collab.)
BARATE	98U	EPJ C4 571	R. Barate *et al.*	(ALEPH Collab.)
BARGER	98E	PR D57 391	V. Barger *et al.*	
MCFARLAND	98	EPJ C1 509	K.S. McFarland *et al.*	(CCFR/NuTeV Collab.)
DIAZCRUZ	94	PR D49 R2149	J.L. Diaz Cruz, O.A. Sampayo	(CINV)
ABT	93	NP B396 3	I. Abt *et al.*	(H1 Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani *et al.*	(L3 Collab.)
BARDADIN-...	92	ZPHY C55 163	M. Bardadin-Otwinowska	(CLER)
DECAMP	92	PRPL 216 253	D. Decamp *et al.*	(ALEPH Collab.)
PDG	92	PR D45 S1	K. Hikasa *et al.*	(KEK, LBL, BOST+)
ABREU	91F	NP B367 511	P. Abreu *et al.*	(DELPHI Collab.)
KIM	90	PL B240 243	G.N. Kim *et al.*	(AMY Collab.)
ABE	89B	PRL 62 1825	F. Abe *et al.*	(CDF Collab.)
ABE	89D	PRL 63 1447	F. Abe *et al.*	(CDF Collab.)
ABE	89J	ZPHY C45 175	K. Abe *et al.*	(VENUS Collab.)
ALBAJAR	89	ZPHY C44 15	C. Albajar *et al.*	(UA1 Collab.)
BARGER	89	PL B220 464	V. Barger *et al.*	(WISC, KEK)
DORENBOS...	89	ZPHY C41 567	J. Dorenbosch *et al.*	(CHARM Collab.)
BARTEL	87B	ZPHY C36 15	W. Bartel *et al.*	(JADE 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		PR D37 237 (erratum)	A. Jodidio *et al.*	(LBL, NWES, TRIU)
EICHTEN	84	RMP 56 579	E. Eichten *et al.*	(FNAL, LBL, OSU)
RENARD	82	PL 116B 264	F.M. Renard	(CERN)