

# Quark and Lepton Compositeness, Searches for

The latest unpublished results are described in the “Quark and Lepton Compositeness” review.

See the related review(s):

[Searches for Quark and Lepton Compositeness](#)

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

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

$\Lambda_{LL}^+$ (TeV)	$\Lambda_{LL}^-$ (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>8.3	>10.3	95	<sup>1</sup> BOURILKOV	01	RVUE $E_{\text{cm}} = 192\text{--}208$ GeV

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

>4.5	>7.0	95	<sup>2</sup> SCHAEEL	07A	ALEP	$E_{\text{cm}} = 189\text{--}209$ GeV
>5.3	>6.8	95	ABDALLAH	06C	DLPH	$E_{\text{cm}} = 130\text{--}207$ GeV
>4.7	>6.1	95	<sup>3</sup> ABBIENDI	04G	OPAL	$E_{\text{cm}} = 130\text{--}207$ GeV
>4.3	>4.9	95	ACCIARRI	00P	L3	$E_{\text{cm}} = 130\text{--}189$ GeV

<sup>1</sup> A combined analysis of the data from ALEPH, DELPHI, L3, and OPAL.

<sup>2</sup> SCHAEEL 07A limits are from  $R_C$ ,  $Q_{FB}^{depl}$ , and hadronic cross section measurements.

<sup>3</sup> ABBIENDI 04G limits are from  $e^+e^- \rightarrow e^+e^-$  cross section at  $\sqrt{s} = 130\text{--}207$  GeV.

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

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

$\Lambda_{LL}^+$ (TeV)	$\Lambda_{LL}^-$ (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>6.6	<b>&gt;9.5</b>	95	<sup>1</sup> SCHAEEL	07A	ALEP $E_{\text{cm}} = 189\text{--}209$ GeV
<b>&gt;8.5</b>	>3.8	95	ACCIARRI	00P	L3 $E_{\text{cm}} = 130\text{--}189$ GeV

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

>7.3	>7.6	95	ABDALLAH	06C	DLPH $E_{\text{cm}} = 130\text{--}207$ GeV
>8.1	>7.3	95	<sup>2</sup> ABBIENDI	04G	OPAL $E_{\text{cm}} = 130\text{--}207$ GeV

<sup>1</sup> SCHAEEL 07A limits are from  $R_C$ ,  $Q_{FB}^{depl}$ , and hadronic cross section measurements.

<sup>2</sup> ABBIENDI 04G limits are from  $e^+e^- \rightarrow \mu\mu$  cross section at  $\sqrt{s} = 130\text{--}207$  GeV.

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

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

$\Lambda_{LL}^+$ (TeV)	$\Lambda_{LL}^-$ (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;7.9</b>	>5.8	95	<sup>1</sup> SCHAEEL	07A	ALEP $E_{\text{cm}} = 189\text{--}209$ GeV
<b>&gt;7.9</b>	>4.6	95	ABDALLAH	06C	DLPH $E_{\text{cm}} = 130\text{--}207$ GeV
>4.9	<b>&gt;7.2</b>	95	<sup>2</sup> ABBIENDI	04G	OPAL $E_{\text{cm}} = 130\text{--}207$ GeV

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

>5.4	>4.7	95	ACCIARRI	00P	L3 $E_{\text{cm}} = 130\text{--}189$ GeV
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<sup>1</sup> SCHAEEL 07A limits are from  $R_C$ ,  $Q_{FB}^{depl}$ , and hadronic cross section measurements.

<sup>2</sup> ABBIENDI 04G limits are from  $e^+e^- \rightarrow \tau\tau$  cross section at  $\sqrt{s} = 130\text{--}207$  GeV.

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

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

$\Lambda_{LL}^+$ (TeV)	$\Lambda_{LL}^-$ (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>7.9	<b>&gt;10.3</b>	95	<sup>1</sup> SCHAEEL	07A	ALEP $E_{\text{cm}} = 189\text{--}209$ GeV
<b>&gt;9.1</b>	>8.2	95	ABDALLAH	06C	DLPH $E_{\text{cm}} = 130\text{--}207$ GeV

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

>7.7	>9.5	95	<sup>2</sup> ABBIENDI	04G	OPAL $E_{\text{cm}} = 130\text{--}207$ GeV
			<sup>3</sup> BABICH	03	RVUE
>9.0	>5.2	95	ACCIARRI	00P	L3 $E_{\text{cm}} = 130\text{--}189$ GeV

<sup>1</sup> SCHAEL 07A limits are from  $R_c$ ,  $Q_{FB}^{depl}$ , and hadronic cross section measurements.

<sup>2</sup> ABBIENDI 04G limits are from  $e^+e^- \rightarrow \ell^+\ell^-$  cross section at  $\sqrt{s} = 130\text{--}207$  GeV.

<sup>3</sup> BABICH 03 obtain a bound  $-0.175 \text{ TeV}^{-2} < 1/\Lambda_{LL}^2 < 0.095 \text{ TeV}^{-2}$  (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  $\Lambda_{LL}^\pm$  only. For other cases, see each reference.

$\Lambda_{LL}^+$ (TeV)	$\Lambda_{LL}^-$ (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;24</b>	<b>&gt;37</b>	95	<sup>1</sup> AABOUD	17AT ATLS	( <i>eeqq</i> )
> 8.4	<b>&gt;10.2</b>	95	<sup>2</sup> ABDALLAH	09 DLPH	( <i>eebb</i> )
<b>&gt; 9.4</b>	<b>&gt;5.6</b>	95	<sup>3</sup> SCHAEL	07A ALEP	( <i>eecc</i> )
<b>&gt; 9.4</b>	>4.9	95	<sup>2</sup> SCHAEL	07A ALEP	( <i>eebb</i> )
<b>&gt;23.3</b>	<b>&gt;12.5</b>	95	<sup>4</sup> CHEUNG	01B RVUE	( <i>eeuu</i> )
<b>&gt;11.1</b>	<b>&gt;26.4</b>	95	<sup>4</sup> CHEUNG	01B RVUE	( <i>eedd</i> )
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
> 7.1	>7.1	95	<sup>5</sup> AAD	21AU ATLS	( <i>eebs</i> )
>23.5	>26.1	95	<sup>6</sup> AAD	21Q ATLS	( <i>eeqq</i> )
>19.5	>24.0	95	<sup>7</sup> SIRUNYAN	21N CMS	( <i>eeqq</i> )
>23.5	>26.1	95	<sup>8</sup> AAD	20AP ATLS	( <i>eeqq</i> )
> 4.5	>12.8	95	<sup>9</sup> ABRAMOWICZ19	ZEUS	( <i>eeqq</i> )
>16.8	>23.9	95	<sup>10</sup> SIRUNYAN	19AC CMS	( <i>eeqq</i> )
>15.5	>19.5	95	<sup>11</sup> AABOUD	16U ATLS	( <i>eeqq</i> )
>13.5	>18.3	95	<sup>12</sup> KHACHATRY...15AE	CMS	( <i>eeqq</i> )
>16.4	>20.7	95	<sup>13</sup> AAD	14BE ATLS	( <i>eeqq</i> )
> 9.5	>12.1	95	<sup>14</sup> AAD	13E ATLS	( <i>eeqq</i> )
>10.1	>9.4	95	<sup>15</sup> AAD	12AB ATLS	( <i>eeqq</i> )
> 4.2	>4.0	95	<sup>16</sup> AARON	11C H1	( <i>eeqq</i> )
> 3.8	>3.8	95	<sup>17</sup> ABDALLAH	11 DLPH	( <i>eetc</i> )
>12.9	>7.2	95	<sup>18</sup> SCHAEL	07A ALEP	( <i>eeqq</i> )
> 3.7	>5.9	95	<sup>19</sup> ABULENCIA	06L CDF	( <i>eeqq</i> )

<sup>1</sup> AABOUD 17AT limits are from  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit uses a uniform positive prior in  $1/\Lambda^2$ .

<sup>2</sup> ABDALLAH 09 and SCHAEL 07A limits are from  $R_b$ ,  $A_{FB}^b$ .

<sup>3</sup> SCHAEL 07A limits are from  $R_c$ ,  $Q_{FB}^{depl}$ , and hadronic cross section measurements.

<sup>4</sup> CHEUNG 01B is an update of BARGER 98E.

<sup>5</sup> AAD 21AU search for new phenomena in final states with  $e^+e^-$  and one or no  $b$ -tagged jets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limits assume  $g_*^2 = 4\pi$ .

<sup>6</sup> AAD 21Q limits are from  $pp$  collisions at  $\sqrt{s} = 13$  TeV. A frequentist statistical framework is used to remove the prior dependence.

<sup>7</sup> SIRUNYAN 21N limits are from  $e^+e^-$  mass distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>8</sup> AAD 20AP limits are from  $e^+e^-$  mass distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>9</sup> ABRAMOWICZ 19 limits are from  $Q^2$  spectrum measurements of  $e^\pm p \rightarrow e^\pm X$ .

<sup>10</sup> SIRUNYAN 19AC limits are from  $e^+e^-$  mass distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>11</sup> AABOUD 16U limits are from  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit uses a uniform positive prior in  $1/\Lambda^2$ .

- <sup>12</sup> KHACHATRYAN 15AE limit is from  $e^+e^-$  mass distribution in  $pp$  collisions at  $E_{\text{cm}} = 8$  TeV.
- <sup>13</sup> AAD 14BE limits are from  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit uses a uniform positive prior in  $1/\Lambda^2$ .
- <sup>14</sup> AAD 13E limits are from  $e^+e^-$  mass distribution in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV.
- <sup>15</sup> AAD 12AB limits are from  $e^+e^-$  mass distribution in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV.
- <sup>16</sup> AARON 11C limits are from  $Q^2$  spectrum measurements of  $e^\pm p \rightarrow e^\pm X$ .
- <sup>17</sup> ABDALLAH 11 limit is from  $e^+e^- \rightarrow t\bar{c}$  cross section.  $\Lambda_{LL} = \Lambda_{LR} = \Lambda_{RL} = \Lambda_{RR}$  is assumed.
- <sup>18</sup> SCHAEEL 07A limit assumes quark flavor universality of the contact interactions.
- <sup>19</sup> ABULENCIA 06L limits are from  $p\bar{p}$  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
<b>&gt;23.3</b>	<b>&gt;40.0</b>	95	<sup>1</sup> SIRUNYAN	21N CMS	$(\mu\mu qq)$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
> 8.5	>8.5	95	<sup>2</sup> AAD	21AU ATLS	$(\mu\mu bs)$
>22.3	>32.7	95	<sup>3</sup> AAD	21Q ATLS	$(\mu\mu qq)$
>22.3	>32.7	95	<sup>4</sup> AAD	20AP ATLS	$(\mu\mu qq)$
>20.4	>30.4	95	<sup>5</sup> SIRUNYAN	19AC CMS	$(\mu\mu qq)$
>20	>30	95	<sup>6</sup> AABOUD	17AT ATLS	$(\mu\mu qq)$
>15.8	>21.8	95	<sup>7</sup> AABOUD	16U ATLS	$(\mu\mu qq)$
>12.0	>15.2	95	<sup>8</sup> KHACHATRY...	15AE CMS	$(\mu\mu qq)$
>12.5	>16.7	95	<sup>9</sup> AAD	14BE ATLS	$(\mu\mu qq)$
> 9.6	>12.9	95	<sup>10</sup> AAD	13E ATLS	$(\mu\mu qq)$ (isosinglet)
> 9.5	>13.1	95	<sup>11</sup> CHATRCHYAN	13K CMS	$(\mu\mu qq)$ (isosinglet)
> 8.0	>7.0	95	<sup>12</sup> AAD	12AB ATLS	$(\mu\mu qq)$ (isosinglet)

- <sup>1</sup> SIRUNYAN 21N limits are from  $\mu^+\mu^-$  mass distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>2</sup> AAD 21AU search for new phenomena in final states with  $\mu^+\mu^-$  and one or no  $b$ -tagged jets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limits assume  $g_*^2 = 4\pi$ .
- <sup>3</sup> AAD 21Q limits are from  $pp$  collisions at  $\sqrt{s} = 13$  TeV. A frequentist statistical framework is used to remove the prior dependence.
- <sup>4</sup> AAD 20AP limits are from  $\mu^+\mu^-$  mass distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>5</sup> SIRUNYAN 19AC limits are from  $\mu^+\mu^-$  mass distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>6</sup> AABOUD 17AT limits are from  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit uses a uniform positive prior in  $1/\Lambda^2$ .
- <sup>7</sup> AABOUD 16U limits are from  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit uses a uniform positive prior in  $1/\Lambda^2$ .
- <sup>8</sup> KHACHATRYAN 15AE limit is from  $\mu^+\mu^-$  mass distribution in  $pp$  collisions at  $E_{\text{cm}} = 8$  TeV.
- <sup>9</sup> AAD 14BE limits are from  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit uses a uniform positive prior in  $1/\Lambda^2$ .
- <sup>10</sup> AAD 13E limits are from  $\mu^+\mu^-$  mass distribution in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV.
- <sup>11</sup> CHATRCHYAN 13K limits are from  $\mu^+\mu^-$  mass distribution in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV.
- <sup>12</sup> AAD 12AB limits are from  $\mu^+\mu^-$  mass distribution in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV.

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

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;3.10</b>	90	<sup>1</sup> 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		<sup>2</sup> DIAZCRUZ	94	RVUE $\Lambda_{LL}^+(\tau\nu_{\tau}e\nu_e)$
>8.1		<sup>2</sup> DIAZCRUZ	94	RVUE $\Lambda_{LL}^-(\tau\nu_{\tau}e\nu_e)$
>4.1		<sup>3</sup> DIAZCRUZ	94	RVUE $\Lambda_{LL}^+(\tau\nu_{\tau}\mu\nu_{\mu})$
>6.5		<sup>3</sup> DIAZCRUZ	94	RVUE $\Lambda_{LL}^-(\tau\nu_{\tau}\mu\nu_{\mu})$

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

<sup>2</sup> DIAZCRUZ 94 limits are from  $\Gamma(\tau \rightarrow e\nu\nu)$  and assume flavor-dependent contact interactions with  $\Lambda(\tau\nu_{\tau}e\nu_e) \ll \Lambda(\mu\nu_{\mu}e\nu_e)$ .

<sup>3</sup> 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	COMMENT
<b>&gt;2.81</b>	95	<sup>1</sup> AFFOLDER	01i	CDF

<sup>1</sup> AFFOLDER 00i bound is for a scalar interaction  $\bar{q}_R q_L \bar{\nu} e_L$ .

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

$\Lambda_{LL}^+$ (TeV)	$\Lambda_{LL}^-$ (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;13.1 none</b>	<b>17.4–29.5</b>	<b>&gt;21.8</b>	<sup>1</sup> AABOUD	17AK ATLS	$pp$ dijet angl.
• • •			We do not use the following data for averages, fits, limits, etc. • • •		
>12.8	>17.5	95	<sup>2</sup> AABOUD	18AV ATLS	$pp \rightarrow t\bar{t}t\bar{t}$
>11.5	>14.7	95	<sup>3</sup> SIRUNYAN	18DD CMS	$pp$ dijet angl.
>12.0	>17.5	95	<sup>4</sup> SIRUNYAN	17F CMS	$pp$ dijet angl.
			<sup>5</sup> AAD	16S ATLS	$pp$ dijet angl.
			<sup>6</sup> AAD	15AR ATLS	$pp \rightarrow t\bar{t}t\bar{t}$
			<sup>7</sup> AAD	15BY ATLS	$pp \rightarrow t\bar{t}t\bar{t}$
> 8.1	>12.0	95	<sup>8</sup> AAD	15L ATLS	$pp$ dijet angl.
> 9.0	>11.7	95	<sup>9</sup> KHACHATRY...15J	CMS	$pp$ dijet angl.
> 5		95	<sup>10</sup> FABBRICHESI 14	RVUE	$q\bar{q}t\bar{t}$

<sup>1</sup> AABOUD 17AK limit is from dijet angular distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $u$ ,  $d$ , and  $s$  quarks are assumed to be composite.

<sup>2</sup> AABOUD 18AV obtain limit on  $t_R$  compositeness  $2\pi/\Lambda_{RR}^2 < 1.6 \text{ TeV}^{-2}$  at 95% CL from  $t\bar{t}t\bar{t}$  production in the  $pp$  collisions at  $E_{\text{cm}} = 13$  TeV.

<sup>3</sup> SIRUNYAN 18DD limit is from dijet angular distribution in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>4</sup> SIRUNYAN 17F limit is from dijet angular cross sections in  $pp$  collisions at  $E_{\text{cm}} = 13$  TeV. All quarks are assumed to be composite.

- <sup>5</sup> AAD 16S limit is from dijet angular selections in  $pp$  collisions at  $E_{\text{cm}} = 13$  TeV.  $u$ ,  $d$ , and  $s$  quarks are assumed to be composite.
- <sup>6</sup> AAD 15AR obtain limit on the  $t_R$  compositeness  $2\pi/\Lambda_{RR}^2 < 6.6$  TeV<sup>-2</sup> at 95% CL from the  $t\bar{t}t\bar{t}$  production in the  $pp$  collisions at  $E_{\text{cm}} = 8$  TeV.
- <sup>7</sup> AAD 15BY obtain limit on the  $t_R$  compositeness  $2\pi/\Lambda_{RR}^2 < 15.1$  TeV<sup>-2</sup> at 95% CL from the  $t\bar{t}t\bar{t}$  production in the  $pp$  collisions at  $E_{\text{cm}} = 8$  TeV.
- <sup>8</sup> AAD 15L limit is from dijet angular distribution in  $pp$  collisions at  $E_{\text{cm}} = 8$  TeV.  $u$ ,  $d$ , and  $s$  quarks are assumed to be composite.
- <sup>9</sup> KHACHATRYAN 15J limit is from dijet angular distribution in  $pp$  collisions at  $E_{\text{cm}} = 8$  TeV.  $u$ ,  $d$ ,  $s$ ,  $c$ , and  $b$  quarks are assumed to be composite.
- <sup>10</sup> FABBRICHESI 14 obtain bounds on chromoelectric and chromomagnetic form factors of the top-quark using  $pp \rightarrow t\bar{t}$  and  $p\bar{p} \rightarrow t\bar{t}$  cross sections. The quoted limit on the  $q\bar{q}t\bar{t}$  contact interaction is derived from their bound on the chromoelectric form factor.

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

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

$\Lambda_{LL}^+$ (TeV)	$\Lambda_{LL}^-$ (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;5.0</b>	<b>&gt;5.4</b>	95	<sup>1</sup> MCFARLAND 98	CCFR	$\nu N$ scattering

<sup>1</sup> 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
<b>&gt;103.2</b>	95	<sup>1</sup> 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	<sup>2</sup> ACHARD 03B	L3	$e^+e^- \rightarrow e^*e^*$ Homodoublet type

<sup>1</sup> From  $e^+e^-$  collisions at  $\sqrt{s} = 183\text{--}209$  GeV.  $f = f'$  is assumed.

<sup>2</sup> From  $e^+e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  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
>5600	95	<sup>1</sup> SIRUNYAN	20AJ CMS	$pp \rightarrow ee^*X$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>4800	95	<sup>2</sup> AABOUD	19AZ ATLS	$pp \rightarrow ee^*X$
>3900	95	<sup>3</sup> SIRUNYAN	19Z CMS	$pp \rightarrow ee^*X$
>2450	95	<sup>4</sup> KHACHATRYAN	16AQ CMS	$pp \rightarrow ee^*X$
>3000	95	<sup>5</sup> AAD	15AP ATLS	$pp \rightarrow e^{(*)}e^*X$
>2200	95	<sup>6</sup> AAD	13BB ATLS	$pp \rightarrow ee^*X$
>1900	95	<sup>7</sup> CHATRCHYAN	13AE CMS	$pp \rightarrow ee^*X$
>1870	95	<sup>8</sup> AAD	12AZ ATLS	$pp \rightarrow e^{(*)}e^*X$

<sup>1</sup> SIRUNYAN 20AJ search for  $e^*$  production in  $2e2j$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit assumes  $\Lambda = m_{e^*}$ ,  $f = f' = 1$ . The contact interaction is included. See their Fig.11 for exclusion limits in  $m_{e^*} - \Lambda$  plane.

<sup>2</sup> AABOUD 19AZ search for single  $e^*$  production in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is from  $e^* \rightarrow eq\bar{q}$  and  $e^* \rightarrow \nu W$  decays assuming  $f = f' = 1$  and  $m_{e^*} = \Lambda$ . The contact interaction is included in  $e^*$  production and decay amplitudes. See their Fig.6 for exclusion limits in  $m_{e^*} - \Lambda$  plane.

<sup>3</sup> SIRUNYAN 19Z search for  $e^*$  production in  $ll\gamma$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit assumes  $\Lambda = m_{e^*}$ ,  $f = f' = 1$ . The contact interaction is included in the  $e^*$  production and decay amplitudes.

<sup>4</sup> KHACHATRYAN 16AQ search for single  $e^*$  production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above is from the  $e^* \rightarrow e\gamma$  search channel assuming  $f = f' = 1$ ,  $m_{e^*} = \Lambda$ . See their Table 7 for limits in other search channels or with different assumptions.

<sup>5</sup> 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.

<sup>6</sup> AAD 13BB search for single  $e^*$  production in  $pp$  collisions with  $e^* \rightarrow e\gamma$  decay.  $f = f' = 1$ , and  $e^*$  production via contact interaction with  $\Lambda = m_{e^*}$  are assumed.

<sup>7</sup> CHATRCHYAN 13AE search for single  $e^*$  production in  $pp$  collisions with  $e^* \rightarrow e\gamma$  decay.  $f = f' = 1$ , and  $e^*$  production via contact interaction with  $\Lambda = m_{e^*}$  are assumed.

<sup>8</sup> AAD 12AZ search for  $e^*$  production via four-fermion contact interaction in  $pp$  collisions with  $e^* \rightarrow e\gamma$  decay. The quoted limit assumes  $\Lambda = m_{e^*}$ . See their Fig. 8 for the exclusion plot in the mass-coupling plane.

## 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 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	<sup>1</sup> ABDALLAH	04N DLPH	$\sqrt{s}=161\text{--}208$ GeV

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

>310	95	ACHARD	02D L3	$\sqrt{s}=192\text{--}209$ GeV
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<sup>1</sup> 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
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• • • We do not use the following data for averages, fits, limits, etc. • • •

<sup>1</sup> DORENBOS...	89	CHRM	$\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e, \nu_\mu e \rightarrow \nu_\mu e$
<sup>2</sup> GRIFOLS	86	THEO	$\nu_\mu e \rightarrow \nu_\mu e$
<sup>3</sup> RENARD	82	THEO	$g-2$ of electron

<sup>1</sup> DORENBOSCH 89 obtain the limit  $\lambda_\gamma^2 \Lambda_{\text{cut}}^2 / m_{e^*}^2 < 2.6$  (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.

<sup>2</sup> GRIFOLS 86 uses  $\nu_\mu e \rightarrow \nu_\mu e$  and  $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$  data from CHARM Collaboration to derive mass limits which depend on the scale of compositeness.

<sup>3</sup> 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  $e^+ e^- \rightarrow \mu^{*+} \mu^{*-}$  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  $\mu^* \rightarrow \mu\gamma$  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	<sup>1</sup> 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	<sup>2</sup> ACHARD	03B L3	$e^+ e^- \rightarrow \mu^* \mu^*$ Homodoublet type
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<sup>1</sup> From  $e^+ e^-$  collisions at  $\sqrt{s} = 183\text{--}209$  GeV.  $f = f'$  is assumed.

<sup>2</sup> From  $e^+ e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  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  $e^+e^- \rightarrow \mu^*\mu$  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** S1 (1992)).

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;5700</b>	95	<sup>1</sup> SIRUNYAN	20AJ CMS	$pp \rightarrow \mu\mu^* X$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>3800	95	<sup>2</sup> SIRUNYAN	19Z CMS	$pp \rightarrow \mu\mu^* X$
>2800	95	<sup>3</sup> AAD	16BMATLS	$pp \rightarrow \mu\mu^* X$
>2470	95	<sup>4</sup> KHACHATRYAN	16AQ CMS	$pp \rightarrow \mu\mu^* X$
>3000	95	<sup>5</sup> AAD	15AP ATLS	$pp \rightarrow \mu^{(*)}\mu^* X$
>2200	95	<sup>6</sup> AAD	13BB ATLS	$pp \rightarrow \mu\mu^* X$
>1900	95	<sup>7</sup> CHATRCHYAN	13AE CMS	$pp \rightarrow \mu\mu^* X$
>1750	95	<sup>8</sup> AAD	12AZ ATLS	$pp \rightarrow \mu^{(*)}\mu^* X$

<sup>1</sup> SIRUNYAN 20AJ search for  $\mu^*$  production in  $2\mu 2j$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit assumes  $\Lambda = m_{\mu^*}$ ,  $f = f' = 1$ . The contact interaction is included. See their Fig.11 for exclusion limits in  $m_{\mu^*}$ - $\Lambda$  plane.

<sup>2</sup> SIRUNYAN 19Z search for  $\mu^*$  production in  $ll\gamma$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit assumes  $\Lambda = m_{\mu^*}$ ,  $f = f' = 1$ . The contact interaction is included in the  $\mu^*$  production and decay amplitudes.

<sup>3</sup> AAD 16BM search for  $\mu^*$  production in  $\mu\mu jj$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. Both the production and decay are assumed to occur via a contact interaction with  $\Lambda = m_{\mu^*}$ .

<sup>4</sup> KHACHATRYAN 16AQ search for single  $\mu^*$  production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above is from the  $\mu^* \rightarrow \mu\gamma$  search channel assuming  $f = f' = 1$ ,  $m_{\mu^*} = \Lambda$ . See their Table 7 for limits in other search channels or with different assumptions.

<sup>5</sup> AAD 15AP search for  $\mu^*$  production in events 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.

<sup>6</sup> 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.

<sup>7</sup> 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.

<sup>8</sup> 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.

## 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. ● ● ●			
	<sup>1</sup> RENARD	82	THEO $g-2$ of muon

<sup>1</sup>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
<b>&gt;103.2</b>	95	<sup>1</sup> 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	<sup>2</sup> ACHARD	03B L3	$e^+e^- \rightarrow \tau^*\tau^*$ Homodoublet type

<sup>1</sup>From  $e^+e^-$  collisions at  $\sqrt{s} = 183\text{--}209$  GeV.  $f = f'$  is assumed.

<sup>2</sup>From  $e^+e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  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  $\lambda\text{--}m_{\tau^*}$  plane. See the original papers.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;4600</b>	95	<sup>1</sup> AAD	23BJ ATLS	$pp \rightarrow \tau\tau^*$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>2500	95	<sup>2</sup> AAD	15AP ATLS	$pp \rightarrow \tau^{(*)}\tau^*X$
> 180	95	<sup>3</sup> ACHARD	03B L3	$e^+e^- \rightarrow \tau\tau^*$
> 185	95	<sup>4</sup> ABBIENDI	02G OPAL	$e^+e^- \rightarrow \tau\tau^*$

<sup>1</sup>AAD 23BJ search for  $\tau^*$  produced in association with  $\tau$  and decaying into  $\tau q\bar{q}$  via a contact interaction with  $g_{\text{contact}}^2 = (4\pi)^2$ . The limit quoted above assumes  $\Lambda = m_{\tau^*}$ .

<sup>2</sup>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.

<sup>3</sup>ACHARD 03B result is from  $e^+e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  GeV.  $f = f' = \Lambda/m_{\tau^*}$  is assumed. See their Fig. 4 for the exclusion plot in the mass-coupling plane.

<sup>4</sup>ABBIENDI 02G result is from  $e^+e^-$  collisions at  $\sqrt{s} = 183\text{--}209$  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	<sup>1</sup> AAD	15AP ATLS	$pp \rightarrow \nu^*\nu^*X$
		<sup>2</sup> ABBIENDI	04N OPAL	
> 102.6	95	<sup>3</sup> ACHARD	03B L3	$e^+e^- \rightarrow \nu^*\nu^*$ Homodoublet type

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

<sup>1</sup> 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.

<sup>2</sup> From  $e^+e^-$  collisions at  $\sqrt{s} = 192\text{--}209$  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.

<sup>3</sup> From  $e^+e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  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	<sup>1</sup> AARON	08 H1	$ep \rightarrow \nu^*X$
>6000	95	<sup>2</sup> TUMASYAN	23AL CMS	$pp \rightarrow \ell\nu^* \rightarrow \ell\ell qq, \ell = e$
> 190	95	<sup>3</sup> ACHARD	03B L3	$e^+e^- \rightarrow \nu\nu^*$
none 50–150	95	<sup>4</sup> ADLOFF	02 H1	$ep \rightarrow \nu^*X$
> 158	95	<sup>5</sup> CHEKANOV	02D ZEUS	$ep \rightarrow \nu^*X$

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

<sup>1</sup> 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.

<sup>2</sup> TUMASYAN 23AL search for Majorana excited neutrino  $\nu^*$  produced and decaying via gauge and contact interactions. The limit quoted above is for  $\ell = e$  with  $\Lambda = M_{\nu^*}$ . The limit becomes  $M_{\nu^*} > 6.1$  TeV for  $\ell = \mu$ .

<sup>3</sup> ACHARD 03B result is from  $e^+e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  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.

<sup>4</sup> 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.

<sup>5</sup> 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  $e^+e^- \rightarrow q^*\bar{q}^*$  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
<b>&gt;338</b>	95	<sup>1</sup> AALTONEN 10H	CDF	$q^* \rightarrow tW^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 700–1200	95	<sup>2</sup> SIRUNYAN 18V	CMS	$pp \rightarrow t_{3/2}^* \bar{t}_{3/2}^* \rightarrow t\bar{t}gg$
		<sup>3</sup> BARATE 98U	ALEP	$Z \rightarrow q^*q^*$
> 45.6	95	<sup>4</sup> ADRIANI 93M	L3	$u$ or $d$ type, $Z \rightarrow q^*q^*$
> 41.7	95	<sup>5</sup> BARDADIN-...	92 RVUE	$u$ -type, $\Gamma(Z)$
> 44.7	95	<sup>5</sup> BARDADIN-...	92 RVUE	$d$ -type, $\Gamma(Z)$
> 40.6	95	<sup>6</sup> DECAMP 92	ALEP	$u$ -type, $\Gamma(Z)$
> 44.2	95	<sup>6</sup> DECAMP 92	ALEP	$d$ -type, $\Gamma(Z)$
> 45	95	<sup>7</sup> DECAMP 92	ALEP	$u$ or $d$ type, $Z \rightarrow q^*q^*$
> 45	95	<sup>6</sup> ABREU 91F	DLPH	$u$ -type, $\Gamma(Z)$
> 45	95	<sup>6</sup> ABREU 91F	DLPH	$d$ -type, $\Gamma(Z)$

<sup>1</sup> AALTONEN 10H obtain limits on the  $q^*q^*$  production cross section in  $p\bar{p}$  collisions. See their Fig. 3.

<sup>2</sup> SIRUNYAN 18V search for pair production of spin 3/2 excited top quarks.  $B(t_{3/2}^* \rightarrow tg) = 1$  is assumed.

<sup>3</sup> BARATE 98U obtain limits on the form factor. See their Fig. 16 for limits in mass-form factor plane.

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

<sup>5</sup> BARDADIN-OTWINOWSKA 92 limit based on  $\Delta\Gamma(Z) < 36$  MeV.

<sup>6</sup> These limits are independent of decay modes.

<sup>7</sup> 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  $e^+e^- \rightarrow q^*\bar{q}$ ,  $p\bar{p} \rightarrow q^*X$ , 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
<b>&gt;6700 (CL = 95%) OUR LIMIT</b>				
none 1800–2500	95	<sup>1</sup> TUMASYAN 23AF	CMS	$pp \rightarrow b^*X$ , $b^* \rightarrow bg$
none 1000–6000	95	<sup>2</sup> TUMASYAN 23BC	CMS	$pp \rightarrow q^*X$ , $q^* \rightarrow q\gamma$
none 1000–2200	95	<sup>3</sup> TUMASYAN 23BC	CMS	$pp \rightarrow b^*X$ , $b^* \rightarrow b\gamma$
<b>none 2000–6700</b>	95	<sup>4</sup> AAD 20T	ATLS	$pp \rightarrow q^*X$ , $q^* \rightarrow qg$
none 1250–3200	95	<sup>4</sup> AAD 20T	ATLS	$pp \rightarrow b^*X$ , $b^* \rightarrow bg, b\gamma, bZ, tW$
none 1800–6300	95	<sup>5</sup> SIRUNYAN 20AI	CMS	$pp \rightarrow q^*X$ , $q^* \rightarrow qg$
none 1500–2600	95	<sup>6</sup> AABOUD 18AB	ATLS	$pp \rightarrow b^*X$ , $b^* \rightarrow bg$

none 1500–5300	95	7	AABOUD	18BA ATLS	$pp \rightarrow q^* X, q^* \rightarrow q\gamma$
none 1000–5500	95	8	SIRUNYAN	18AG CMS	$pp \rightarrow q^* X, q^* \rightarrow q\gamma$
none 1000–1800	95	9	SIRUNYAN	18AG CMS	$pp \rightarrow b^* X, b^* \rightarrow b\gamma$
none 600–6000	95	10	SIRUNYAN	18BO CMS	$pp \rightarrow q^* X, q^* \rightarrow qg$
none 1200–5000	95	11	SIRUNYAN	18P CMS	$pp \rightarrow q^* X, q^* \rightarrow qW$
none 1200–4700	95	11	SIRUNYAN	18P CMS	$pp \rightarrow q^* X, q^* \rightarrow qZ$
>6000	95	12	AABOUD	17AK ATLS	$pp \rightarrow q^* X, q^* \rightarrow qg$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
none 700–3000	95	13	TUMASYAN	22O CMS	$pp \rightarrow b^* X, b^* \rightarrow tW$
>2600	95	14	SIRUNYAN	21AG CMS	$pp \rightarrow b^* X, b^* \rightarrow tW$
none 600–5400	95	15	KHACHATRY...17W	CMS	$pp \rightarrow q^* X, q^* \rightarrow qg$
none 1100–2100	95	16	AABOUD	16 ATLS	$pp \rightarrow b^* X, b^* \rightarrow bg$
>1500	95	17	AAD	16AH ATLS	$pp \rightarrow b^* X, b^* \rightarrow tW$
>4400	95	18	AAD	16AI ATLS	$pp \rightarrow q^* X, q^* \rightarrow q\gamma$
		19	AAD	16AV ATLS	$pp \rightarrow q^* X, q^* \rightarrow Wb$
>5200	95	20	AAD	16S ATLS	$pp \rightarrow q^* X, q^* \rightarrow qg$
>1390	95	21	KHACHATRY...16I	CMS	$pp \rightarrow b^* X, b^* \rightarrow tW$
>5000	95	22	KHACHATRY...16K	CMS	$pp \rightarrow q^* X, q^* \rightarrow qg$
none 500–1600	95	23	KHACHATRY...16L	CMS	$pp \rightarrow q^* X, q^* \rightarrow qg$
>4060	95	24	AAD	15V ATLS	$pp \rightarrow q^* X, q^* \rightarrow qg$
>3500	95	25	KHACHATRY...15V	CMS	$pp \rightarrow q^* X, q^* \rightarrow qg$
>3500	95	26	AAD	14A ATLS	$pp \rightarrow q^* X, q^* \rightarrow q\gamma$
>3200	95	27	KHACHATRY...14	CMS	$pp \rightarrow q^* X, q^* \rightarrow qW$
>2900	95	28	KHACHATRY...14	CMS	$pp \rightarrow q^* X, q^* \rightarrow qZ$
none 700–3500	95	29	KHACHATRY...14J	CMS	$pp \rightarrow q^* X, q^* \rightarrow q\gamma$
>2380	95	30	CHATRCHYAN 13AJ	CMS	$pp \rightarrow q^* X, q^* \rightarrow qW$
>2150	95	31	CHATRCHYAN 13AJ	CMS	$pp \rightarrow q^* X, q^* \rightarrow qZ$

<sup>1</sup> TUMASYAN 23AF limit quoted above assumes  $bg \rightarrow b^*$  production. The limit becomes  $m_{b^*} > 4$  TeV if contact interaction is included in the  $b^*$  production cross section. See their Fig. 5 for limits on  $\sigma \cdot B$ .

<sup>2</sup> TUMASYAN 23BC search for excited light flavor quark  $q^*$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $f = 1.0$  is assumed.

<sup>3</sup> TUMASYAN 23BC search for excited  $b$  quark  $b^*$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $b^*$  production via gauge interactions and  $f = 1.0$  are assumed. The limit becomes  $m_{b^*} > 3.8$  TeV if contact interaction is included in the  $b^*$  production cross section.

<sup>4</sup> AAD 20T search for resonances decaying into dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .

<sup>5</sup> SIRUNYAN 20AI search for resonances decaying into dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .

<sup>6</sup> AABOUD 18AB assume  $\Lambda = m_{b^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $b^*$  production and decay amplitudes.

<sup>7</sup> AABOUD 18BA search for first-generation excited quarks ( $u^*$  and  $d^*$ ) with degenerate mass, assuming  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes.

<sup>8</sup> SIRUNYAN 18AG search for first-generation excited quarks ( $u^*$  and  $d^*$ ) with degenerate mass, assuming  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .

<sup>9</sup> SIRUNYAN 18AG search for excited  $b$  quark assuming  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .

- 10 SIRUNYAN 18B0 assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes.
- 11 SIRUNYAN 18P use the hadronic decay of  $W$  or  $Z$ , assuming  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .
- 12 AABOUD 17AK assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes. Only the decay of  $q^* \rightarrow g u$  and  $q^* \rightarrow g d$  is simulated as the benchmark signals in the analysis.
- 13 TUMASYAN 220 search for  $b^*$  decaying to  $tW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above assumes  $\kappa_L^b = g_L = 1$ ,  $\kappa_R^b = g_R = 0$ . The limit becomes  $m_{b^*} > 3.0$  TeV ( $> 3.2$  TeV) if we assume  $\kappa_L^b = g_L = 0$ ,  $\kappa_R^b = g_R = 1$  ( $\kappa_L^b = g_L = 1$ ,  $\kappa_R^b = g_R = 1$ ). See their Fig. 3 for limits on  $\sigma \cdot B$ .
- 14 SIRUNYAN 21AG search for  $b^*$  decaying to  $tW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above assumes  $\kappa_L^b = g_L = 1$ ,  $\kappa_R^b = g_R = 0$ . The limit becomes  $m_{b^*} > 2.8$  TeV ( $> 3.1$  TeV) if we assume  $\kappa_L^b = g_L = 0$ ,  $\kappa_R^b = g_R = 1$  ( $\kappa_L^b = g_L = \kappa_R^b = g_R = 1$ ). See their Fig. 5 for limits on  $\sigma \cdot B$ .
- 15 KHACHATRYAN 17W assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes.
- 16 AABOUD 16 assume  $\Lambda = m_{b^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in the  $b^*$  production and decay amplitudes.
- 17 AAD 16AH search for  $b^*$  decaying to  $tW$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.  $f_g = f_L = f_R = 1$  are assumed. See their Fig. 12b for limits on  $\sigma \cdot B$ .
- 18 AAD 16AI assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .
- 19 AAD 16AV search for single production of vector-like quarks decaying to  $Wb$  in  $pp$  collisions. See their Fig. 8 for the limits on couplings and mixings.
- 20 AAD 16S assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes.
- 21 KHACHATRYAN 16I search for  $b^*$  decaying to  $tW$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.  $\kappa_L^b = g_L = 1$ ,  $\kappa_R^b = g_R = 0$  are assumed. See their Fig. 8 for limits on  $\sigma \cdot B$ .
- 22 KHACHATRYAN 16K assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes.
- 23 KHACHATRYAN 16L search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV using the data scouting technique which increases the sensitivity to the low mass resonances.
- 24 AAD 15V assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes.
- 25 KHACHATRYAN 15V assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ . The contact interactions are not included in  $q^*$  production and decay amplitudes.
- 26 AAD 14A assume  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .
- 27 KHACHATRYAN 14 use the hadronic decay of  $W$ , assuming  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .
- 28 KHACHATRYAN 14 use the hadronic decay of  $Z$ , assuming  $\Lambda = m_{q^*}$ ,  $f_S = f = f' = 1$ .
- 29 KHACHATRYAN 14J assume  $f_S = f = f' = \Lambda / m_{q^*}$ .
- 30 CHATRCHYAN 13AJ use the hadronic decay of  $W$ .
- 31 CHATRCHYAN 13AJ use the hadronic decay of  $Z$ .

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

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;84</b>	95	<sup>1</sup> ABE	89D CDF	$p\bar{p} \rightarrow q_6\bar{q}_6$

<sup>1</sup> 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 ( $l_8$ )**

$$\lambda \equiv m_{l_8}/\Lambda$$

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;86</b>	95	<sup>1</sup> ABE	89D CDF	Stable $l_8$ : $p\bar{p} \rightarrow l_8\bar{l}_8$

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

<sup>2</sup> ABT 93 H1  $e_8$ :  $e p \rightarrow e_8 X$

<sup>1</sup> 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.

<sup>2</sup> ABT 93 search for  $e_8$  production via  $e$ -gluon fusion in  $e p$  collisions with  $e_8 \rightarrow e g$ . 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 ( $\nu_8$ )**

$$\lambda \equiv m_{\nu_8}/\Lambda$$

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;110</b>	90	<sup>1</sup> BARGER	89 RVUE	$\nu_8$ : $p\bar{p} \rightarrow \nu_8\bar{\nu}_8$

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

none 3.8–29.8 95 <sup>2</sup> KIM 90 AMY  $\nu_8$ :  $e^+e^- \rightarrow$  acoplanar jets

none 9–21.9 95 <sup>3</sup> BARTEL 87B JADE  $\nu_8$ :  $e^+e^- \rightarrow$  acoplanar jets

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

<sup>2</sup> KIM 90 is at  $E_{cm} = 50-60.8$  GeV. The same assumptions as in BARTEL 87B are used.

<sup>3</sup> 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
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• • • We do not use the following data for averages, fits, limits, etc. • • •

<sup>1</sup> ALBAJAR 89 UA1  $p\bar{p} \rightarrow W_8 X$ ,  $W_8 \rightarrow W g$

<sup>1</sup> 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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