

# Heavy Bosons Other Than Higgs Bosons, Searches for

We list here various limits on charged and neutral heavy vector bosons (other than  $W$ 's and  $Z$ 's), heavy scalar bosons (other than Higgs bosons), vector or scalar leptoquarks, and axigluons.

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## MASS LIMITS for $W'$ (Heavy Charged Vector Boson Other Than $W$ ) in Hadron Collider Experiments

Couplings of  $W'$  to quarks and leptons are taken to be identical with those of  $W$ . The following limits are obtained from  $p\bar{p} \rightarrow W'X$  with  $W'$  decaying to the mode indicated in the comments. New decay channels (*e.g.*,  $W' \rightarrow WZ$ ) are assumed to be suppressed. UA1 and UA2 experiments assume that the  $t\bar{b}$  channel is not open.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;786</b>	95	<sup>1</sup> AFFOLDER	01I CDF	$W' \rightarrow e\nu, \mu\nu$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
none 200–480	95	<sup>2</sup> AFFOLDER	02C CDF	$W' \rightarrow WZ$
>660	95	<sup>3</sup> ABE	00 CDF	$W' \rightarrow \mu\nu$
none 300–420	95	<sup>4</sup> ABE	97G CDF	$W' \rightarrow q\bar{q}$
>720	95	<sup>5</sup> ABACHI	96C D0	$W' \rightarrow e\nu$
>610	95	<sup>6</sup> ABACHI	95E D0	$W' \rightarrow e\nu, \tau\nu$
>652	95	<sup>7</sup> ABE	95M CDF	$W' \rightarrow e\nu$
>251	90	<sup>8</sup> ALITTI	93 UA2	$W' \rightarrow q\bar{q}$
none 260–600	95	<sup>9</sup> RIZZO	93 RVUE	$W' \rightarrow q\bar{q}$
>220	90	<sup>10</sup> ALBAJAR	89 UA1	$W' \rightarrow e\nu$
>209	90	<sup>11</sup> ANSARI	87D UA2	$W' \rightarrow e\nu$

<sup>1</sup> AFFOLDER 01I combine a new bound on  $W' \rightarrow e\nu$  of 754 GeV with the bound of ABE 00 on  $W' \rightarrow \mu\nu$  to obtain quoted bound.

<sup>2</sup> The quoted limit is obtained assuming  $W'WZ$  coupling strength is the same as the ordinary  $WWZ$  coupling strength in the Standard Model. See their Fig. 2 for the limits on the production cross sections as a function of the  $W'$  width.

<sup>3</sup> ABE 00 assume that the neutrino from  $W'$  decay is stable and has a mass significantly less than  $m_{W'}$ .

<sup>4</sup> ABE 97G search for new particle decaying to dijets.

<sup>5</sup> For bounds on  $W_R$  with nonzero right-handed mass, see Fig. 5 from ABACHI 96C.

<sup>6</sup> ABACHI 95E assume that the decay  $W' \rightarrow WZ$  is suppressed and that the neutrino from  $W'$  decay is stable and has a mass significantly less  $m_{W'}$ .

<sup>7</sup> ABE 95M assume that the decay  $W' \rightarrow WZ$  is suppressed and the (right-handed) neutrino is light, noninteracting, and stable. If  $m_\nu=60$  GeV, for example, the effect on the mass limit is negligible.

<sup>8</sup> ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes  $\Gamma(W')/m_{W'} = \Gamma(W)/m_W$  and  $B(W' \rightarrow jj) = 2/3$ . This corresponds to  $W_R$  with  $m_{\nu_R} > m_{W_R}$  (no leptonic decay) and  $W_R \rightarrow t\bar{b}$  allowed. See their Fig. 4 for limits in the  $m_{W'}-B(q\bar{q})$  plane.

<sup>9</sup> RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed  $K$  factor.

<sup>10</sup> ALBAJAR 89 cross section limit at 630 GeV is  $\sigma(W') B(e\nu) < 4.1$  pb (90% CL).

<sup>11</sup> See Fig. 5 of ANSARI 87D for the excluded region in the  $m_{W'} - [(g_{W'q})^2 B(W' \rightarrow e\bar{\nu})]$  plane. Note that the quantity  $(g_{W'q})^2 B(W' \rightarrow e\bar{\nu})$  is normalized to unity for the standard  $W$  couplings.

## $W_R$ (Right-Handed $W$ Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91.  $g_R = g_L$  assumed. [Limits in the section MASS LIMITS for  $W'$  below are also valid for  $W_R$  if  $m_{\nu_R} \ll m_{W_R}$ .] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B. Limits on the  $W_L$ - $W_R$  mixing angle  $\zeta$  are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 715	90	<sup>12</sup> CZAKON	99	RVUE Electroweak
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 310	90	<sup>13</sup> THOMAS	01	CNTR $\beta^+$ decay
> 137	95	<sup>14</sup> ACKERSTAFF	99D	OPAL $\tau$ decay
> 1400	68	<sup>15</sup> BARENBOIM	98	RVUE Electroweak, $Z$ - $Z'$ mixing
> 549	68	<sup>16</sup> BARENBOIM	97	RVUE $\mu$ decay
> 220	95	<sup>17</sup> STAHL	97	RVUE $\tau$ decay
> 220	90	<sup>18</sup> ALLET	96	CNTR $\beta^+$ decay
> 281	90	<sup>19</sup> KUZNETSOV	95	CNTR Polarized neutron decay
> 282	90	<sup>20</sup> KUZNETSOV	94B	CNTR Polarized neutron decay
> 439	90	<sup>21</sup> BHATTACH...	93	RVUE $Z$ - $Z'$ mixing
> 250	90	<sup>22</sup> SEVERIJNS	93	CNTR $\beta^+$ decay
		<sup>23</sup> IMAZATO	92	CNTR $K^+$ decay
> 475	90	<sup>24</sup> POLAK	92B	RVUE $\mu$ decay
> 240	90	<sup>25</sup> AQUINO	91	RVUE Neutron decay
> 496	90	<sup>25</sup> AQUINO	91	RVUE Neutron and muon decay
> 700		<sup>26</sup> COLANGELO	91	THEO $m_{K_L^0} - m_{K_S^0}$
> 477	90	<sup>27</sup> POLAK	91	RVUE $\mu$ decay
[none 540–23000]		<sup>28</sup> BARBIERI	89B	ASTR SN 1987A; light $\nu_R$
> 300	90	<sup>29</sup> LANGACKER	89B	RVUE General
> 160	90	<sup>30</sup> BALKE	88	CNTR $\mu \rightarrow e\nu\bar{\nu}$
> 406	90	<sup>31</sup> JODIDIO	86	ELEC Any $\zeta$
> 482	90	<sup>31</sup> JODIDIO	86	ELEC $\zeta = 0$
> 800		MOHAPATRA	86	RVUE $SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	<sup>32</sup> STOKER	85	ELEC Any $\zeta$
> 475	95	<sup>32</sup> STOKER	85	ELEC $\zeta < 0.041$
		<sup>33</sup> BERGSMA	83	CHRM $\nu_\mu e \rightarrow \mu\nu_e$
> 380	90	<sup>34</sup> CARR	83	ELEC $\mu^+$ decay
> 1600		<sup>35</sup> BEALL	82	THEO $m_{K_L^0} - m_{K_S^0}$
[> 4000]		STEIGMAN	79	COSM Nucleosynthesis; light $\nu_R$

- 12 CZAKON 99 perform a simultaneous fit to charged and neutral sectors.
- 13 THOMAS 01 limit is from measurement of  $\beta^+$  polarization in decay of polarized  $^{12}\text{N}$ . The listed limit assumes no mixing.
- 14 ACKERSTAFF 99D limit is from  $\tau$  decay parameters. Limit increase to 145 GeV for zero mixing.
- 15 BARENBOIM 98 assumes minimal left-right model with Higgs of  $\text{SU}(2)_R$  in  $\text{SU}(2)_L$  doublet. For Higgs in  $\text{SU}(2)_L$  triplet,  $m_{W_R} > 1100$  GeV. Bound calculated from effect of corresponding  $Z_{LR}$  on electroweak data through  $Z-Z_{LR}$  mixing.
- 16 The quoted limit is from  $\mu$  decay parameters. BARENBOIM 97 also evaluate limit from  $K_L-K_S$  mass difference.
- 17 STAHL 97 limit is from fit to  $\tau$ -decay parameters.
- 18 ALLET 96 measured polarization-asymmetry correlaton in  $^{12}\text{N}\beta^+$  decay. The listed limit assumes zero  $L$ - $R$  mixing.
- 19 KUZNETSOV 95 limit is from measurements of the asymmetry  $\langle \vec{p}_\nu \cdot \sigma_n \rangle$  in the  $\beta$  decay of polarized neutrons. Zero mixing assumed. See also KUZNETSOV 94B.
- 20 KUZNETSOV 94B limit is from measurements of the asymmetry  $\langle \vec{p}_\nu \cdot \sigma_n \rangle$  in the  $\beta$  decay of polarized neutrons. Zero mixing assumed.
- 21 BHATTACHARYYA 93 uses  $Z$ - $Z'$  mixing limit from LEP '90 data, assuming a specific Higgs sector of  $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)$  gauge model. The limit is for  $m_t = 200$  GeV and slightly improves for smaller  $m_t$ .
- 22 SEVERIJNS 93 measured polarization-asymmetry correlation in  $^{107}\text{In}\beta^+$  decay. The listed limit assumes zero  $L$ - $R$  mixing. Value quoted here is from SEVERIJNS 94 erratum.
- 23 IMAZATO 92 measure positron asymmetry in  $K^+ \rightarrow \mu^+ \nu_\mu$  decay and obtain  $\xi P_\mu > 0.990$  (90%CL). If  $W_R$  couples to  $u\bar{s}$  with full weak strength ( $V_{us}^R = 1$ ), the result corresponds to  $m_{W_R} > 653$  GeV. See their Fig. 4 for  $m_{W_R}$  limits for general  $|V_{us}^R|^2 = 1 - |V_{ud}^R|^2$ .
- 24 POLAK 92B limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming  $\zeta = 0$ . Supersedes POLAK 91.
- 25 AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right symmetry assumed. Stronger of the two limits also includes muon decay results.
- 26 COLANGELO 91 limit uses hadronic matrix elements evaluated by QCD sum rule and is less restrictive than BEALL 82 limit which uses vacuum saturation approximation. Manifest left-right symmetry assumed.
- 27 POLAK 91 limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming  $\zeta = 0$ . Superseded by POLAK 92B.
- 28 BARBIERI 89B limit holds for  $m_{\nu_R} \leq 10$  MeV.
- 29 LANGACKER 89B limit is for any  $\nu_R$  mass (either Dirac or Majorana) and for a general class of right-handed quark mixing matrices.
- 30 BALKE 88 limit is for  $m_{\nu_{eR}} = 0$  and  $m_{\nu_{\mu R}} \leq 50$  MeV. Limits come from precise measurements of the muon decay asymmetry as a function of the positron energy.
- 31 JODIDIO 86 is the same TRIUMF experiment as STOKER 85 (and CARR 83); however, it uses a different technique. The results given here are combined results of the two techniques. The technique here involves precise measurement of the end-point  $e^+$  spectrum in the decay of the highly polarized  $\mu^+$ .
- 32 STOKER 85 is same TRIUMF experiment as CARR 83. Here they measure the decay  $e^+$  spectrum asymmetry above 46 MeV/ $c$  using a muon-spin-rotation technique. Assumed a light right-handed neutrino. Quoted limits are from combining with CARR 83.
- 33 BERGSMA 83 set limit  $m_{W_2}/m_{W_1} > 1.9$  at CL = 90%.

- <sup>34</sup> CARR 83 is TRIUMF experiment with a highly polarized  $\mu^+$  beam. Looked for deviation from  $V-A$  at the high momentum end of the decay  $e^+$  energy spectrum. Limit from previous world-average muon polarization parameter is  $m_{W_R} > 240$  GeV. Assumes a light right-handed neutrino.
- <sup>35</sup> BEALL 82 limit is obtained assuming that  $W_R$  contribution to  $K_L^0-K_S^0$  mass difference is smaller than the standard one, neglecting the top quark contributions. Manifest left-right symmetry assumed.

### Limit on $W_L$ - $W_R$ Mixing Angle $\zeta$

Lighter mass eigenstate  $W_1 = W_L \cos \zeta - W_R \sin \zeta$ . Light  $\nu_R$  assumed unless noted.

Values in brackets are from cosmological and astrophysical considerations.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
< 0.12	95	<sup>36</sup> ACKERSTAFF 99D	OPAL	$\tau$ decay
< 0.013	90	<sup>37</sup> CZAKON 99	RVUE	Electroweak
< 0.0333		<sup>38</sup> BARENBOIM 97	RVUE	$\mu$ decay
< 0.04	90	<sup>39</sup> MISHRA 92	CCFR	$\nu N$ scattering
-0.0006 to 0.0028	90	<sup>40</sup> AQUINO 91	RVUE	
[none 0.00001-0.02]		<sup>41</sup> BARBIERI 89B	ASTR	SN 1987A
< 0.040	90	<sup>42</sup> JODIDIO 86	ELEC	$\mu$ decay
-0.056 to 0.040	90	<sup>42</sup> JODIDIO 86	ELEC	$\mu$ decay

- <sup>36</sup> ACKERSTAFF 99D limit is from  $\tau$  decay parameters.
- <sup>37</sup> CZAKON 99 perform a simultaneous fit to charged and neutral sectors.
- <sup>38</sup> The quoted limit is from  $\mu$  decay parameters. BARENBOIM 97 also evaluate limit from  $K_L-K_S$  mass difference.
- <sup>39</sup> MISHRA 92 limit is from the absence of extra large- $x$ , large- $y$   $\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X$  events at Tevatron, assuming left-handed  $\nu$  and right-handed  $\bar{\nu}$  in the neutrino beam. The result gives  $\zeta^2(1-2m_{W_1}^2/m_{W_2}^2) < 0.0015$ . The limit is independent of  $\nu_R$  mass.
- <sup>40</sup> AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right asymmetry is assumed.
- <sup>41</sup> BARBIERI 89B limit holds for  $m_{\nu_R} \leq 10$  MeV.
- <sup>42</sup> First JODIDIO 86 result assumes  $m_{W_R} = \infty$ , second is for unconstrained  $m_{W_R}$ .

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### MASS LIMITS for $Z'$ (Heavy Neutral Vector Boson Other Than $Z$ )

#### Limits for $Z'_{SM}$

$Z'_{SM}$  is assumed to have couplings with quarks and leptons which are identical to those of  $Z$ , and decays only to known fermions.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> <b>1500</b>	95	<sup>43</sup> CHEUNG 01B	RVUE	Electroweak
> <b>690</b>	95	<sup>44</sup> ABE 97S	CDF	$p\bar{p}; Z'_{SM} \rightarrow e^+e^-, \mu^+\mu^-$

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

> 670	95	45	ABAZOV	01B	D0	$p\bar{p}; Z'_{SM} \rightarrow e^+e^-$
> 710	95	46	ABREU	00S	DLPH	$e^+e^-$
> 898	95	47	BARATE	00I	ALEP	$e^+e^-$
> 809	95	48	ERLER	99	RVUE	Electroweak
> 490	95		ABACHI	96D	D0	$p\bar{p}; Z'_{SM} \rightarrow e^+e^-$
> 398	95	49	VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
> 237	90	50	ALITTI	93	UA2	$p\bar{p}; Z'_{SM} \rightarrow q\bar{q}$
none 260–600	95	51	RIZZO	93	RVUE	$p\bar{p}; Z_{SM} \rightarrow q\bar{q}$
> 426	90	52	ABE	90F	VNS	$e^+e^-$

<sup>43</sup> CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.

<sup>44</sup> ABE 97S find  $\sigma(Z') \times B(e^+e^-, \mu^+\mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s} = 1.8$  TeV.

<sup>45</sup> ABAZOV 01B search for resonances in  $p\bar{p} \rightarrow e^+e^-$  at  $\sqrt{s} = 1.8$  TeV. They find  $\sigma \cdot B(Z' \rightarrow ee) < 0.06$  pb for  $M_{Z'} > 500$  GeV.

<sup>46</sup> ABREU 00S uses LEP data at  $\sqrt{s} = 90$  to 189 GeV.

<sup>47</sup> BARATE 00I search for deviations in cross section and asymmetries in  $e^+e^- \rightarrow$  fermions at  $\sqrt{s} = 90$  to 183 GeV. Assume  $\theta = 0$ . Bounds in the mass-mixing plane are shown in their Figure 18.

<sup>48</sup> ERLER 99 give 90%CL limit on the  $Z$ - $Z'$  mixing  $-0.0041 < \theta < 0.0003$ .  $\rho_0 = 1$  is assumed.

<sup>49</sup> VILAIN 94B assume  $m_t = 150$  GeV.

<sup>50</sup> ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes  $B(Z' \rightarrow q\bar{q}) = 0.7$ . See their Fig. 5 for limits in the  $m_{Z'} - B(q\bar{q})$  plane.

<sup>51</sup> RIZZO 93 analyses CDF limit on possible two-jet resonances.

<sup>52</sup> ABE 90F use data for  $R, R_{\ell\ell},$  and  $A_{\ell\ell}$ . They fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.

### Limits for $Z_{LR}$

$Z_{LR}$  is the extra neutral boson in left-right symmetric models.  $g_L = g_R$  is assumed unless noted. Values in parentheses assume stronger constraint on the Higgs sector, usually motivated by specific left-right symmetric models (see the Note on the  $W'$ ). Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino. Direct search bounds assume decays to Standard Model fermions only, unless noted.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;860</b>	95	53 CHEUNG	01B RVUE	Electroweak
<b>&gt;630</b>	95	54 ABE	97S CDF	$p\bar{p}; Z'_{LR} \rightarrow e^+e^-, \mu^+\mu^-$

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

>380	95	55	ABREU	00S	DLPH	$e^+e^-$
>436	95	56	BARATE	00I	ALEP	$e^+e^-$
>550	95	57	CHAY	00	RVUE	Electroweak
		58	ERLER	00	RVUE	Cs
		59	CASALBUONI	99	RVUE	Cs
(> 1205)	90	60	CZAKON	99	RVUE	Electroweak
>564	95	61	ERLER	99	RVUE	Electroweak

(> 1673)	95	62 ERLER	99 RVUE	Electroweak
(> 1700)	68	63 BARENBOIM	98 RVUE	Electroweak
>244	95	64 CONRAD	98 RVUE	$\nu_\mu N$ scattering
>253	95	65 VILAIN	94B CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
none 200–600	95	66 RIZZO	93 RVUE	$p\bar{p}; Z_{LR} \rightarrow q\bar{q}$
[> 2000]		WALKER	91 COSM	Nucleosynthesis; light $\nu_R$
none 200–500		67 GRIFOLS	90 ASTR	SN 1987A; light $\nu_R$
none 350–2400		68 BARBIERI	89B ASTR	SN 1987A; light $\nu_R$

<sup>53</sup> CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.

<sup>54</sup> ABE 97S find  $\sigma(Z') \times B(e^+ e^-, \mu^+ \mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s} = 1.8$  TeV.

<sup>55</sup> ABREU 00S give 95%CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0018$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 90$  to 189 GeV.

<sup>56</sup> BARATE 00i search for deviations in cross section and asymmetries in  $e^+ e^- \rightarrow$  fermions at  $\sqrt{s} = 90$  to 183 GeV. Assume  $\theta = 0$ . Bounds in the mass-mixing plane are shown in their Figure 18.

<sup>57</sup> CHAY 00 also find  $-0.0003 < \theta < 0.0019$ . For  $g_R$  free,  $m_{Z'} > 430$  GeV.

<sup>58</sup> ERLER 00 discuss the possibility that a discrepancy between the observed and predicted values of  $Q_W(C_s)$  is due to the exchange of  $Z'$ . The data are better described in a certain class of the  $Z'$  models including  $Z_{LR}$  and  $Z_\chi$ .

<sup>59</sup> CASALBUONI 99 discuss the discrepancy between the observed and predicted values of  $Q_W(C_s)$ . It is shown that the data are better described in a class of models including the  $Z_{LR}$  model.

<sup>60</sup> CZAKON 99 perform a simultaneous fit to charged and neutral sectors. Assumes manifest left-right symmetric model. Finds  $|\theta| < 0.0042$ .

<sup>61</sup> ERLER 99 give 90%CL limit on the  $Z$ - $Z'$  mixing  $-0.0009 < \theta < 0.0017$ .

<sup>62</sup> ERLER 99 assumes 2 Higgs doublets, transforming as 10 of  $SO(10)$ , embedded in  $E_6$ .

<sup>63</sup> BARENBOIM 98 also gives 68% CL limits on the  $Z$ - $Z'$  mixing  $-0.0005 < \theta < 0.0033$ . Assumes Higgs sector of minimal left-right model.

<sup>64</sup> CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.

<sup>65</sup> VILAIN 94B assume  $m_t = 150$  GeV and  $\theta = 0$ . See Fig. 2 for limit contours in the mass-mixing plane.

<sup>66</sup> RIZZO 93 analyses CDF limit on possible two-jet resonances.

<sup>67</sup> GRIFOLS 90 limit holds for  $m_{\nu_R} \lesssim 1$  MeV. A specific Higgs sector is assumed. See also GRIFOLS 90D, RIZZO 91.

<sup>68</sup> BARBIERI 89B limit holds for  $m_{\nu_R} \leq 10$  MeV. Bounds depend on assumed supernova core temperature.

### Limits for $Z_\chi$

$Z_\chi$  is the extra neutral boson in  $SO(10) \rightarrow SU(5) \times U(1)_\chi$ .  $g_\chi = e/\cos\theta_W$  is assumed unless otherwise stated. We list limits with the assumption  $\rho = 1$  but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;680</b>	95	<sup>69</sup> CHEUNG	01B RVUE	Electroweak
<b>&gt;595</b>	95	<sup>70</sup> ABE	97S CDF	$p\bar{p}; Z'_\chi \rightarrow e^+ e^-, \mu^+ \mu^-$

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

>440	95	71	ABREU	00s	DLPH	$e^+e^-$
>533	95	72	BARATE	00i	ALEP	$e^+e^-$
>554	95	73	CHO	00	RVUE	Electroweak
		74	ERLER	00	RVUE	Cs
		75	ROSNER	00	RVUE	Cs
>545	95	76	ERLER	99	RVUE	Electroweak
(> 1368)	95	77	ERLER	99	RVUE	Electroweak
>215	95	78	CONRAD	98	RVUE	$\nu_\mu N$ scattering
>190	95	79	ARIMA	97	VNS	Bhabha scattering
>262	95	80	VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
[>1470]		81	FARAGGI	91	COSM	Nucleosynthesis; light $\nu_R$
>231	90	82	ABE	90F	VNS	$e^+e^-$
[> 1140]		83	GONZALEZ-G.	90D	COSM	Nucleosynthesis; light $\nu_R$
[> 2100]		84	GRIFOLS	90	ASTR	SN 1987A; light $\nu_R$

<sup>69</sup> CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.

<sup>70</sup> ABE 97s find  $\sigma(Z') \times B(e^+e^-, \mu^+\mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s} = 1.8$  TeV.

<sup>71</sup> ABREU 00s give 95%CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0017$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 90$  to 189 GeV.

<sup>72</sup> BARATE 00i search for deviations in cross section and asymmetries in  $e^+e^- \rightarrow$  fermions at  $\sqrt{s} = 90$  to 183 GeV. Assume  $\theta = 0$ . Bounds in the mass-mixing plane are shown in their Figure 18.

<sup>73</sup> CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H = 100$  GeV. See Fig. 3 for limits in the mass-mixing plane.

<sup>74</sup> ERLER 00 discuss the possibility that a discrepancy between the observed and predicted values of  $Q_W(\text{Cs})$  is due to the exchange of  $Z'$ . The data are better described in a certain class of the  $Z'$  models including  $Z_{LR}$  and  $Z_\chi$ .

<sup>75</sup> ROSNER 00 discusses the possibility that a discrepancy between the observed and predicted values of  $Q_W(\text{Cs})$  is due to the exchange of  $Z'$ . The data are better described in a certain class of the  $Z'$  models including  $Z_\chi$ .

<sup>76</sup> ERLER 99 give 90%CL limit on the  $Z$ - $Z'$  mixing  $-0.0020 < \theta < 0.0015$ .

<sup>77</sup> ERLER 99 assumes 2 Higgs doublets, transforming as 10 of  $SO(10)$ , embedded in  $E_6$ .

<sup>78</sup> CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.

<sup>79</sup>  $Z$ - $Z'$  mixing is assumed to be zero.  $\sqrt{s} = 57.77$  GeV.

<sup>80</sup> VILAIN 94B assume  $m_t = 150$  GeV and  $\theta = 0$ . See Fig. 2 for limit contours in the mass-mixing plane.

<sup>81</sup> FARAGGI 91 limit assumes the nucleosynthesis bound on the effective number of neutrinos  $\Delta N_\nu < 0.5$  and is valid for  $m_{\nu_R} < 1$  MeV.

<sup>82</sup> ABE 90F use data for  $R$ ,  $R_{\ell\ell}$ , and  $A_{\ell\ell}$ . ABE 90F fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.

<sup>83</sup> Assumes the nucleosynthesis bound on the effective number of light neutrinos ( $\delta N_\nu < 1$ ) and that  $\nu_R$  is light ( $\lesssim 1$  MeV).

<sup>84</sup> GRIFOLS 90 limit holds for  $m_{\nu_R} \lesssim 1$  MeV. See also GRIFOLS 90D, RIZZO 91.

### Limits for $Z_\psi$

$Z_\psi$  is the extra neutral boson in  $E_6 \rightarrow SO(10) \times U(1)_\psi$ .  $g_\psi = e/\cos\theta_W$  is assumed unless otherwise stated. We list limits with the assumption  $\rho = 1$  but with no further constraints on the Higgs sector. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>350	95	85 ABREU	00S DLPH	$e^+e^-$
>590	95	86 ABE	97S CDF	$p\bar{p}; Z'_\psi \rightarrow e^+e^-, \mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>294	95	87 BARATE	00I ALEP	$e^+e^-$
>137	95	88 CHO	00 RVUE	Electroweak
>146	95	89 ERLER	99 RVUE	Electroweak
> 54	95	90 CONRAD	98 RVUE	$\nu_\mu N$ scattering
>135	95	91 VILAIN	94B CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
>105	90	92 ABE	90F VNS	$e^+e^-$
[> 160]		93 GONZALEZ-G.	90D COSM	Nucleosynthesis; light $\nu_R$
[> 2000]		94 GRIFOLS	90D ASTR	SN 1987A; light $\nu_R$

<sup>85</sup> ABREU 00S give 95%CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0018$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s}=90$  to 189 GeV.

<sup>86</sup> ABE 97S find  $\sigma(Z') \times B(e^+e^-, \mu^+\mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s}=1.8$  TeV.

<sup>87</sup> BARATE 00I search for deviations in cross section and asymmetries in  $e^+e^- \rightarrow$  fermions at  $\sqrt{s}=90$  to 183 GeV. Assume  $\theta=0$ . Bounds in the mass-mixing plane are shown in their Figure 18.

<sup>88</sup> CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H=100$  GeV. See Fig. 3 for limits in the mass-mixing plane.

<sup>89</sup> ERLER 99 give 90%CL limit on the  $Z$ - $Z'$  mixing  $-0.0013 < \theta < 0.0024$ .

<sup>90</sup> CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.

<sup>91</sup> VILAIN 94B assume  $m_t = 150$  GeV and  $\theta=0$ . See Fig. 2 for limit contours in the mass-mixing plane.

<sup>92</sup> ABE 90F use data for  $R$ ,  $R_{\ell\ell}$ , and  $A_{\ell\ell}$ . ABE 90F fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.

<sup>93</sup> Assumes the nucleosynthesis bound on the effective number of light neutrinos ( $\delta N_\nu < 1$ ) and that  $\nu_R$  is light ( $\lesssim 1$  MeV).

<sup>94</sup> GRIFOLS 90D limit holds for  $m_{\nu_R} \lesssim 1$  MeV. See also RIZZO 91.

### Limits for $Z_\eta$

$Z_\eta$  is the extra neutral boson in  $E_6$  models, corresponding to  $Q_\eta = \sqrt{3/8} Q_\chi - \sqrt{5/8} Q_\psi$ .  $g_\eta = e/\cos\theta_W$  is assumed unless otherwise stated. We list limits with the assumption  $\rho = 1$  but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>619	95	95 CHO	00 RVUE	Electroweak
>620	95	96 ABE	97S CDF	$p\bar{p}; Z'_\eta \rightarrow e^+e^-, \mu^+\mu^-$



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

>310	95	97 ABREU	00S DLPH	$e^+e^-$
>329	95	98 BARATE	00I ALEP	$e^+e^-$
>365	95	99 ERLER	99 RVUE	Electroweak
> 87	95	100 CONRAD	98 RVUE	$\nu_\mu N$ scattering
>100	95	101 VILAIN	94B CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
>125	90	102 ABE	90F VNS	$e^+e^-$
[> 820]		103 GONZALEZ-G.	90D COSM	Nucleosynthesis; light $\nu_R$
[> 3300]		104 GRIFOLS	90 ASTR	SN 1987A; light $\nu_R$
[> 1040]		103 LOPEZ	90 COSM	Nucleosynthesis; light $\nu_R$

<sup>95</sup> CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H=100$  GeV. See Fig. 3 for limits in the mass-mixing plane.

<sup>96</sup> ABE 97S find  $\sigma(Z') \times B(e^+e^-, \mu^+\mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s}=1.8$  TeV.

<sup>97</sup> ABREU 00S give 95%CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0024$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s}=90$  to 189 GeV.

<sup>98</sup> BARATE 00I search for deviations in cross section and asymmetries in  $e^+e^- \rightarrow$  fermions at  $\sqrt{s}=90$  to 183 GeV. Assume  $\theta=0$ . Bounds in the mass-mixing plane are shown in their Figure 18.

<sup>99</sup> ERLER 99 give 90%CL limit on the  $Z$ - $Z'$  mixing  $-0.0062 < \theta < 0.0011$ .

<sup>100</sup> CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.

<sup>101</sup> VILAIN 94B assume  $m_t = 150$  GeV and  $\theta=0$ . See Fig. 2 for limit contours in the mass-mixing plane.

<sup>102</sup> ABE 90F use data for  $R$ ,  $R_{\ell\ell}$ , and  $A_{\ell\ell}$ . ABE 90F fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.

<sup>103</sup> These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ( $\delta N_\nu < 1$ ) constrains  $Z'$  masses if  $\nu_R$  is light ( $\lesssim 1$  MeV).

<sup>104</sup> GRIFOLS 90 limit holds for  $m_{\nu_R} \lesssim 1$  MeV. See also GRIFOLS 90D, RIZZO 91.

### Limits for other $Z'$

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • We do not use the following data for averages, fits, limits, etc. • • •

105	CHO	00	RVUE	$E_6$ -motivated
106	CHO	98	RVUE	$E_6$ -motivated
107	ABE	97G	CDF	$Z' \rightarrow \bar{q}q$

<sup>105</sup> CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H=100$  GeV. See Fig. 2 for limits in general  $E_6$ -motivated models.

<sup>106</sup> CHO 98 study constraints on four-Fermi contact interactions obtained from low-energy electroweak experiments, assuming no  $Z$ - $Z'$  mixing.

<sup>107</sup> Search for  $Z'$  decaying to dijets at  $\sqrt{s}=1.8$  TeV. For  $Z'$  with electromagnetic strength coupling, no bound is obtained.

## Indirect Constraints on Kaluza-Klein Gauge Bosons

Bounds on a Kaluza-Klein excitation of the  $Z$  boson or photon in  $d=1$  extra dimension. These bounds can also be interpreted as a lower bound on  $1/R$ , the size of the extra dimension. Unless otherwise stated, bounds assume all fermions live on a single brane and all gauge fields occupy the  $4+d$ -dimensional bulk.

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 3.3	95	108 CORNET	00 RVUE	$e\nu qq'$
>5000		109 DELGADO	00 RVUE	$\epsilon_K$
> 2.6	95	110 DELGADO	00 RVUE	Electroweak
> 3.3	95	111 RIZZO	00 RVUE	Electroweak
> 2.9	95	112 MARCIANO	99 RVUE	Electroweak
> 2.5	95	113 MASIP	99 RVUE	Electroweak
> 1.6	90	114 NATH	99 RVUE	Electroweak
> 3.4	95	115 STRUMIA	99 RVUE	Electroweak

108 Bound is derived from limits on  $e\nu qq'$  contact interaction, using data from HERA and the Tevatron.

109 Bound holds only if first two generations of quarks lives on separate branes. If quark mixing is not complex, then bound lowers to 400 TeV from  $\Delta m_K$ .

110 See Figs. 1 and 2 of DELGADO 00 for several model variations. Special boundary conditions can be found which permit KK states down to 950 GeV and that agree with the measurement of  $Q_W(C_s)$ . Quoted bound assumes all Higgs bosons confined to brane; placing one Higgs doublet in the bulk lowers bound to 2.3 TeV.

111 Bound is derived from global electroweak analysis assuming the Higgs field is trapped on the matter brane. If the Higgs propagates in the bulk, the bound increases to 3.8 TeV.

112 Bound is derived from global electroweak analysis but considering only presence of the KK  $W$  bosons.

113 Global electroweak analysis used to obtain bound independent of position of Higgs on brane or in bulk.

114 Bounds from effect of KK states on  $G_F$ ,  $\alpha$ ,  $M_W$ , and  $M_Z$ . Hard cutoff at string scale determined using gauge coupling unification. Limits for  $d=2,3,4$  rise to 3.5, 5.7, and 7.8 TeV.

115 Bound obtained for Higgs confined to the matter brane with  $m_H=500$  GeV. For Higgs in the bulk, the bound increases to 3.5 TeV.

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### MASS LIMITS for Leptoquarks from Pair Production

These limits rely only on the color or electroweak charge of the leptoquark.

VALUE (GeV)	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
>200	95		116 ABBOTT	00C D0	Second generation
<b>&gt;148</b>	95		117 AFFOLDER	00K CDF	Third generation
<b>&gt;202</b>	95		118 ABE	98S CDF	Second generation
<b>&gt;242</b>	95		119 GROSS-PILCH.98		First generation

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

> 98	95	120	ABAZOV	02 D0	All generatrions
>225	95	121	ABAZOV	01D D0	First generation
> 85.8	95	122	ABBIENDI	00M OPAL	First generation
> 85.5	95	122	ABBIENDI	00M OPAL	Second generation
> 82.7	95	122	ABBIENDI	00M OPAL	Third generation
>123	95	123	AFFOLDER	00K CDF	Second generation
>160	95	124	ABBOTT	99J D0	Second generation
>225	95	125	ABBOTT	98E D0	First generation
> 94	95	126	ABBOTT	98J D0	Third generation
> 99	95	127	ABE	97F CDF	Third generation
>213	95	128	ABE	97X CDF	First generation
> 45.5	95	129,130	ABREU	93J DLPH	First + second genera- tion
> 44.4	95	131	ADRIANI	93M L3	First generation
> 44.5	95	131	ADRIANI	93M L3	Second generation
> 45	95	131	DECAMP	92 ALEP	Third generation
none 8.9–22.6	95	132	KIM	90 AMY	First generation
none 10.2–23.2	95	132	KIM	90 AMY	Second generation
none 5–20.8	95	133	BARTEL	87B JADE	
none 7–20.5	95	2 134	BEHREND	86B CELL	

116 ABBOTT 00C search for scalar leptoquarks using  $\mu\mu jj$ ,  $\mu\nu jj$ , and  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The limit above assumes  $B(\mu q)=1$ . For  $B(\mu q)=0.5$  and 0, the bound becomes 180 and 79 GeV respectively. Bounds for vector leptoquarks are also given.

117 AFFOLDER 00K search for scalar leptoquark using  $\nu\nu bb$  events in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The quoted limit assumes  $B(\nu b)=1$ . Bounds for vector leptoquarks are also given.

118 ABE 98S search for scalar leptoquarks using  $\mu\mu jj$  events in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The limit is for  $B(\mu q)=1$ . For  $B(\mu q)=B(\nu q)=0.5$ , the limit is  $> 160$  GeV.

119 GROSS-PILCHER 98 is the combined limit of the CDF and DØ Collaborations as determined by a joint CDF/DØ working group and reported in this FNAL Technical Memo. Original data published in ABE 97X and ABBOTT 98E.

120 ABAZOV 02 search for scalar leptoquarks using  $\nu\nu jj$  events in  $\bar{p}p$  collisions at  $E_{cm}=1.8$  TeV. The bound holds for all leptoquark generations. Vector leptoquarks are likewise constrained to lie above 200 GeV.

121 ABAZOV 01D search for scalar leptoquarks using  $e\nu jj$ ,  $eejj$ , and  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The limit above assumes  $B(eq)=1$ . For  $B(eq)=0.5$  and 0, the bound becomes 204 and 79 GeV, respectively. Bounds for vector leptoquarks are also given. Supersedes ABBOTT 98E.

122 ABBIENDI 00M search for scalar/vector leptoquarks in  $e^+e^-$  collisions at  $\sqrt{s}=183$  GeV. The quoted limits are for charge  $-4/3$  isospin 0 scalar-leptoquarks with  $B(\ell q)=1$ . See their Table 8 and Figs. 6–9 for other cases.

123 AFFOLDER 00K search for scalar leptoquark using  $\nu\nu cc$  events in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The quoted limit assumes  $B(\nu c)=1$ . Bounds for vector leptoquarks are also given.

124 ABBOTT 99J search for leptoquarks using  $\mu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The quoted limit is for a scalar leptoquark with  $B(\mu q) = B(\nu q) = 0.5$ . Limits on vector leptoquarks range from 240 to 290 GeV.

125 ABBOTT 98E search for scalar leptoquarks using  $e\nu jj$ ,  $eejj$ , and  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The limit above assumes  $B(eq)=1$ . For  $B(eq)=0.5$  and 0, the bound becomes 204 and 79 GeV, respectively.

126 ABBOTT 98J search for charge  $-1/3$  third generation scalar and vector leptoquarks in  $p\bar{p}$  collisions at  $E_{cm}=1.8$  TeV. The quoted limit is for scalar leptoquark with  $B(\nu b)=1$ .

- 127 ABE 97F search for third generation scalar and vector leptoquarks in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.8$  TeV. The quoted limit is for scalar leptoquark with  $B(\tau b) = 1$ .
- 128 ABE 97X search for scalar leptoquarks using  $eejj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The limit is for  $B(eq)=1$ .
- 129 Limit is for charge  $-1/3$  isospin-0 leptoquark with  $B(\ell q) = 2/3$ .
- 130 First and second generation leptoquarks are assumed to be degenerate. The limit is slightly lower for each generation.
- 131 Limits are for charge  $-1/3$ , isospin-0 scalar leptoquarks decaying to  $\ell^- q$  or  $\nu q$  with any branching ratio. See paper for limits for other charge-isospin assignments of leptoquarks.
- 132 KIM 90 assume pair production of charge  $2/3$  scalar-leptoquark via photon exchange. The decay of the first (second) generation leptoquark is assumed to be any mixture of  $de^+$  and  $u\bar{\nu}$  ( $s\mu^+$  and  $c\bar{\nu}$ ). See paper for limits for specific branching ratios.
- 133 BARTEL 87B limit is valid when a pair of charge  $2/3$  spinless leptoquarks X is produced with point coupling, and when they decay under the constraint  $B(X \rightarrow c\bar{\nu}_\mu) + B(X \rightarrow s\mu^+) = 1$ .
- 134 BEHREND 86B assumed that a charge  $2/3$  spinless leptoquark,  $\chi$ , decays either into  $s\mu^+$  or  $c\bar{\nu}$ :  $B(\chi \rightarrow s\mu^+) + B(\chi \rightarrow c\bar{\nu}) = 1$ .

### MASS LIMITS for Leptoquarks from Single Production

These limits depend on the  $q$ - $\ell$ -leptoquark coupling  $g_{LQ}$ . It is often assumed that  $g_{LQ}^2/4\pi=1/137$ . Limits shown are for a scalar, weak isoscalar, charge  $-1/3$  leptoquark.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>290	95	135 ADLOFF	01C H1	First generation
> 73	95	136 ABREU	93J DLPH	Second generation
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>197	95	137 ABBIENDI	02B OPAL	First generation
		138 CHEKANOV	02 ZEUS	Lepton-flavor violation
>204	95	139 BREITWEG	01 ZEUS	First generation
		140 BREITWEG	00E ZEUS	First generation
>161	95	141 ABREU	99G DLPH	First generation
>200	95	142 ADLOFF	99 H1	First generation
		143 DERRICK	97 ZEUS	Lepton-flavor violation
>168	95	144 DERRICK	93 ZEUS	First generation

- 135 For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 3.
- 136 Limit from single production in Z decay. The limit is for a leptoquark coupling of electromagnetic strength and assumes  $B(\ell q) = 2/3$ . The limit is 77 GeV if first and second leptoquarks are degenerate.
- 137 For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 4 and Fig. 5.
- 138 CHEKANOV 02 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 6–7 and Tables 5–6 for detailed limits.
- 139 See their Fig. 14 for limits in the mass-coupling plane.
- 140 BREITWEG 00E search for  $F=0$  leptoquarks in  $e^+p$  collisions. For limits in mass-coupling plane, see their Fig. 11.
- 141 ABREU 99G limit obtained from process  $e\gamma \rightarrow LQ+q$ . For limits on vector and scalar states with different quantum numbers and the limits in the coupling-mass plane, see their Fig. 4 and Table 2.

- 142 For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 13 and Fig. 14. ADLOFF 99 also search for leptoquarks with lepton-flavor violating couplings. ADLOFF 99 supersedes AID 96B.
- 143 DERRICK 97 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 5–8 and Table 1 for detailed limits.
- 144 DERRICK 93 search for single leptoquark production in  $ep$  collisions with the decay  $eq$  and  $\nu q$ . The limit is for leptoquark coupling of electromagnetic strength and assumes  $B(eq) = B(\nu q) = 1/2$ . The limit for  $B(eq) = 1$  is 176 GeV. For limits on states with different quantum numbers, see their Table 3.

### Indirect Limits for Leptoquarks

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 1.7	95	145 CHEKANOV 02	ZEUS	Lepton-flavor violation
> 0.39	95	146 CHEUNG 01B	RVUE	First generation
> 1.4	95	147 ACCIARRI 00P	L3	$e^+e^- \rightarrow qq$
> 0.2	95	148 ADLOFF 00	H1	First generation
		149 BARATE 00i	ALEP	$e^+e^-$
		150 BARGER 00	RVUE	Cs
		151 GABRIELLI 00	RVUE	Lepton flavor violation
> 0.74	95	152 ZARNECKI 00	RVUE	$S_1$ leptoquark
		153 ABBIENDI 99	OPAL	
> 19.3	95	154 ABE 98V	CDF	$B_s \rightarrow e^\pm \mu^\mp$ , Pati-Salam type
		155 ACCIARRI 98J	L3	$e^+e^- \rightarrow q\bar{q}$
		156 ACKERSTAFF 98V	OPAL	$e^+e^- \rightarrow q\bar{q}$ , $\sim e^+e^- \rightarrow b\bar{b}$
> 0.76	95	157 DEANDREA 97	RVUE	$\tilde{R}_2$ leptoquark
		158 DERRICK 97	ZEUS	Lepton-flavor violation
		159 GROSSMAN 97	RVUE	$B \rightarrow \tau^+\tau^-$ (X)
		160 JADACH 97	RVUE	$e^+e^- \rightarrow q\bar{q}$
>1200		161 KUZNETSOV 95B	RVUE	Pati-Salam type
		162 MIZUKOSHI 95	RVUE	Third generation scalar leptoquark
> 0.3	95	163 BHATTACH... 94	RVUE	Spin-0 leptoquark coupled to $\bar{e}_R t_L$
		164 DAVIDSON 94	RVUE	
> 18		165 KUZNETSOV 94	RVUE	Pati-Salam type
> 0.43	95	166 LEURER 94	RVUE	First generation spin-1 leptoquark
> 0.44	95	166 LEURER 94B	RVUE	First generation spin-0 leptoquark
		167 MAHANTA 94	RVUE	$P$ and $T$ violation
> 1		168 SHANKER 82	RVUE	Nonchiral spin-0 leptoquark
> 125		168 SHANKER 82	RVUE	Nonchiral spin-1 leptoquark

145 CHEKANOV 02 search for lepton-flavor violation in  $ep$  collisions. See their Tables 1–4 for limits on lepton-flavor violating and four-fermion interactions induced by various leptoquarks.

146 CHEUNG 01B quoted limit is for a scalar, weak isoscalar, charge  $-1/3$  leptoquark with a coupling of electromagnetic strength. The limit is derived from bounds on contact

- interactions in a global electroweak analysis. For the limits of leptoquarks with different quantum numbers, see Table 5.
- 147 ACCIARRI 00P limit is for the weak isoscalar spin-0 leptoquark with the coupling of electromagnetic strength. For the limits of leptoquarks with different quantum numbers, see their Table 4.
- 148 ADLOFF 00 limit is for the weak isotriplet spin-0 leptoquark at strong coupling,  $\lambda=\sqrt{4\pi}$ . For the limits of leptoquarks with different quantum numbers, see their Table 2. ADLOFF 00 limits are from the  $Q^2$  spectrum measurement of  $e^+p \rightarrow e^+X$ .
- 149 BARATE 00I search for deviations in cross section and jet-charge asymmetry in  $e^+e^- \rightarrow \bar{q}q$  due to  $t$ -channel exchange of a leptoquark at  $\sqrt{s}=130$  to 183 GeV. Limits for other scalar and vector leptoquarks are also given in their Table 22.
- 150 BARGER 00 explain the deviation of atomic parity violation in cesium atoms from prediction is explained by scalar leptoquark exchange.
- 151 GABRIELLI 00 calculate various process with lepton flavor violation in leptoquark models.
- 152 ZARNECKI 00 limit is derived from data of HERA, LEP, and Tevatron and from various low-energy data including atomic parity violation. Leptoquark coupling with electromagnetic strength is assumed.
- 153 ABBIENDI 99 limits are from  $e^+e^- \rightarrow q\bar{q}$  cross section at 130–136, 161–172, 183 GeV. See their Fig. 8 and Fig. 9 for limits in mass-coupling plane.
- 154 ABE 98V quoted limit is from  $B(B_s \rightarrow e^\pm\mu^\mp) < 8.2 \times 10^{-6}$ . ABE 98V also obtain a similar limit on  $M_{LQ} > 20.4$  TeV from  $B(B_d \rightarrow e^\pm\mu^\mp) < 4.5 \times 10^{-6}$ . Both bounds assume the non-canonical association of the  $b$  quark with electrons or muons under SU(4).
- 155 ACCIARRI 98J limit is from  $e^+e^- \rightarrow q\bar{q}$  cross section at  $\sqrt{s}=130$ –172 GeV which can be affected by the  $t$ - and  $u$ -channel exchanges of leptoquarks. See their Fig. 4 and Fig. 5 for limits in the mass-coupling plane.
- 156 ACKERSTAFF 98V limits are from  $e^+e^- \rightarrow q\bar{q}$  and  $e^+e^- \rightarrow b\bar{b}$  cross sections at  $\sqrt{s}=130$ –172 GeV, which can be affected by the  $t$ - and  $u$ -channel exchanges of leptoquarks. See their Fig. 21 and Fig. 22 for limits of leptoquarks in mass-coupling plane.
- 157 DEANDREA 97 limit is for  $\tilde{R}_2$  leptoquark obtained from atomic parity violation (APV). The coupling of leptoquark is assumed to be electromagnetic strength. See Table 2 for limits of the four-fermion interactions induced by various scalar leptoquark exchange. DEANDREA 97 combines APV limit and limits from Tevatron and HERA. See Fig. 1–4 for combined limits of leptoquark in mass-coupling plane.
- 158 DERRICK 97 search for lepton-flavor violation in  $ep$  collision. See their Tables 2–5 for limits on lepton-flavor violating four-fermion interactions induced by various leptoquarks.
- 159 GROSSMAN 97 estimate the upper bounds on the branching fraction  $B \rightarrow \tau^+\tau^- (X)$  from the absence of the  $B$  decay with large missing energy. These bounds can be used to constrain leptoquark induced four-fermion interactions.
- 160 JADACH 97 limit is from  $e^+e^- \rightarrow q\bar{q}$  cross section at  $\sqrt{s}=172.3$  GeV which can be affected by the  $t$ - and  $u$ -channel exchanges of leptoquarks. See their Fig. 1 for limits on vector leptoquarks in mass-coupling plane.
- 161 KUZNETSOV 95B use  $\pi, K, B, \tau$  decays and  $\mu e$  conversion and give a list of bounds on the leptoquark mass and the fermion mixing matrix in the Pati-Salam model. The quoted limit is from  $K_L \rightarrow \mu e$  decay assuming zero mixing.
- 162 MIZUKOSHI 95 calculate the one-loop radiative correction to the  $Z$ -physics parameters in various scalar leptoquark models. See their Fig. 4 for the exclusion plot of third generation leptoquark models in mass-coupling plane.
- 163 BHATTACHARYYA 94 limit is from one-loop radiative correction to the leptonic decay width of the  $Z$ .  $m_H=250$  GeV,  $\alpha_s(m_Z)=0.12$ ,  $m_t=180$  GeV, and the electroweak strength of leptoquark coupling are assumed. For leptoquark coupled to  $\bar{e}_L t_R, \bar{\mu} t$ , and  $\bar{\tau} t$ , see Fig. 2 in BHATTACHARYYA 94B erratum and Fig. 3.
- 164 DAVIDSON 94 gives an extensive list of the bounds on leptoquark-induced four-fermion interactions from  $\pi, K, D, B, \mu, \tau$  decays and meson mixings, etc. See Table 15 of DAVIDSON 94 for detail.

- 165 KUZNETSOV 94 gives mixing independent bound of the Pati-Salam leptoquark from the cosmological limit on  $\pi^0 \rightarrow \bar{\nu}\nu$ .
- 166 LEURER 94, LEURER 94B limits are obtained from atomic parity violation and apply to any chiral leptoquark which couples to the first generation with electromagnetic strength. For a nonchiral leptoquark, universality in  $\pi_{\ell 2}$  decay provides a much more stringent bound.
- 167 MAHANTA 94 gives bounds of  $P$ - and  $T$ -violating scalar-leptoquark couplings from atomic and molecular experiments.
- 168 From  $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$  ratio. SHANKER 82 assumes the leptoquark induced four-fermion coupling  $4g^2/M^2 (\bar{\nu}_{eL} u_R) (\bar{d}_L e_R)$  with  $g=0.004$  for spin-0 leptoquark and  $g^2/M^2 (\bar{\nu}_{eL} \gamma_\mu u_L) (\bar{d}_R \gamma^\mu e_R)$  with  $g \simeq 0.6$  for spin-1 leptoquark.

### MASS LIMITS for Diquarks

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
none 290–420	95	169 ABE	97G CDF	$E_6$ diquark
none 15–31.7	95	170 ABREU	94O DLPH	SUSY $E_6$ diquark
169 ABE 97G search for new particle decaying to dijets.				
170 ABREU 94O limit is from $e^+ e^- \rightarrow \bar{c} \bar{s} c s$ . Range extends up to 43 GeV if diquarks are degenerate in mass.				

### MASS LIMITS for $g_A$ (axigluon)

Axigluons are massive color-octet gauge bosons in chiral color models and have axial-vector coupling to quarks with the same coupling strength as gluons.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>365	95	171 DONCHESKI	98 RVUE	$\Gamma(Z \rightarrow \text{hadron})$
none 200–980	95	172 ABE	97G CDF	$p\bar{p} \rightarrow g_A X, X \rightarrow 2 \text{ jets}$
none 200–870	95	173 ABE	95N CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow q\bar{q}$
none 240–640	95	174 ABE	93G CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2\text{jets}$
> 50	95	175 CUYPERS	91 RVUE	$\sigma(e^+ e^- \rightarrow \text{hadrons})$
none 120–210	95	176 ABE	90H CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2\text{jets}$
> 29		177 ROBINETT	89 THEO	Partial-wave unitarity
none 150–310	95	178 ALBAJAR	88B UA1	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2\text{jets}$
> 20		BERGSTROM	88 RVUE	$p\bar{p} \rightarrow \Upsilon X$ via $g_A g$
> 9		179 CUYPERS	88 RVUE	$\Upsilon$ decay
> 25		180 DONCHESKI	88B RVUE	$\Upsilon$ decay
171 DONCHESKI 98 compare $\alpha_s$ derived from low-energy data and that from $\Gamma(Z \rightarrow \text{hadrons})/\Gamma(Z \rightarrow \text{leptons})$ .				
172 ABE 97G search for new particle decaying to dijets.				
173 ABE 95N assume axigluons decaying to quarks in the Standard Model only.				
174 ABE 93G assume $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 10$ .				
175 CUYPERS 91 compare $\alpha_s$ measured in $\Upsilon$ decay and that from $R$ at PEP/PETRA energies.				
176 ABE 90H assumes $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 5$ ( $\Gamma(g_A) = 0.09m_{g_A}$ ). For $N = 10$ , the excluded region is reduced to 120–150 GeV.				

- 177 ROBINETT 89 result demands partial-wave unitarity of  $J = 0$   $t\bar{t} \rightarrow t\bar{t}$  scattering amplitude and derives a limit  $m_{g_A} > 0.5 m_t$ . Assumes  $m_t > 56$  GeV.
- 178 ALBAJAR 88B result is from the nonobservation of a peak in two-jet invariant mass distribution.  $\Gamma(g_A) < 0.4 m_{g_A}$  assumed. See also BAGGER 88.
- 179 CUYPERS 88 requires  $\Gamma(\Upsilon \rightarrow g g_A) < \Gamma(\Upsilon \rightarrow g g g)$ . A similar result is obtained by DONCHESKI 88.
- 180 DONCHESKI 88B requires  $\Gamma(\Upsilon \rightarrow g q\bar{q})/\Gamma(\Upsilon \rightarrow g g g) < 0.25$ , where the former decay proceeds via axigluon exchange. A more conservative estimate of  $< 0.5$  leads to  $m_{g_A} > 21$  GeV.

## $X^0$ (Heavy Boson) Searches in Z Decays

Searches for radiative transition of Z to a lighter spin-0 state  $X^0$  decaying to hadrons, a lepton pair, a photon pair, or invisible particles as shown in the comments. The limits are for the product of branching ratios.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
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• • • We do not use the following data for averages, fits, limits, etc. • • •

- |                        |    |              |          |  |
|------------------------|----|--------------|----------|--|
|                        |    | 181 BARATE   | 98U ALEP | $X^0 \rightarrow \ell\bar{\ell}, q\bar{q}, gg, \gamma\gamma, \nu\bar{\nu}$ |
|                        |    | 182 ACCIARRI | 97Q L3   | $X^0 \rightarrow$ invisible particle(s)                                    |
|                        |    | 183 ACTON    | 93E OPAL | $X^0 \rightarrow \gamma\gamma$   |
|                        |    | 184 ABREU    | 92D DLPH | $X^0 \rightarrow$ hadrons  |
|                        |    | 185 ADRIANI  | 92F L3   | $X^0 \rightarrow$ hadrons  |
|                        |    | 186 ACTON    | 91 OPAL  | $X^0 \rightarrow$ anything   |
| $< 1.1 \times 10^{-4}$ | 95 | 187 ACTON    | 91B OPAL | $X^0 \rightarrow e^+e^-$   |
| $< 9 \times 10^{-5}$   | 95 | 187 ACTON    | 91B OPAL | $X^0 \rightarrow \mu^+\mu^-$   |
| $< 1.1 \times 10^{-4}$ | 95 | 187 ACTON    | 91B OPAL | $X^0 \rightarrow \tau^+\tau^-$   |
| $< 2.8 \times 10^{-4}$ | 95 | 188 ADEVA    | 91D L3   | $X^0 \rightarrow e^+e^-$   |
| $< 2.3 \times 10^{-4}$ | 95 | 188 ADEVA    | 91D L3   | $X^0 \rightarrow \mu^+\mu^-$   |
| $< 4.7 \times 10^{-4}$ | 95 | 189 ADEVA    | 91D L3   | $X^0 \rightarrow$ hadrons  |
| $< 8 \times 10^{-4}$   | 95 | 190 AKRAWY   | 90J OPAL | $X^0 \rightarrow$ hadrons  |
- 181 BARATE 98U obtain limits on  $B(Z \rightarrow \gamma X^0)B(X^0 \rightarrow \ell\bar{\ell}, q\bar{q}, gg, \gamma\gamma, \nu\bar{\nu})$ . See their Fig. 17.
- 182 See Fig. 4 of ACCIARRI 97Q for the upper limit on  $B(Z \rightarrow \gamma X^0; E_\gamma > E_{\min})$  as a function of  $E_{\min}$ .
- 183 ACTON 93E give  $\sigma(e^+e^- \rightarrow X^0\gamma) \cdot B(X^0 \rightarrow \gamma\gamma) < 0.4$  pb (95%CL) for  $m_{X^0} = 60 \pm 2.5$  GeV. If the process occurs via s-channel  $\gamma$  exchange, the limit translates to  $\Gamma(X^0) \cdot B(X^0 \rightarrow \gamma\gamma)^2 < 20$  MeV for  $m_{X^0} = 60 \pm 1$  GeV.
- 184 ABREU 92D give  $\sigma_Z \cdot B(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) < (3-10)$  pb for  $m_{X^0} = 10-78$  GeV. A very similar limit is obtained for spin-1  $X^0$ .
- 185 ADRIANI 92F search for isolated  $\gamma$  in hadronic Z decays. The limit  $\sigma_Z \cdot B(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) < (2-10)$  pb (95%CL) is given for  $m_{X^0} = 25-85$  GeV.
- 186 ACTON 91 searches for  $Z \rightarrow Z^* X^0$ ,  $Z^* \rightarrow e^+e^-, \mu^+\mu^-,$  or  $\nu\bar{\nu}$ . Excludes any new scalar  $X^0$  with  $m_{X^0} < 9.5$  GeV/c if it has the same coupling to  $Z Z^*$  as the MSM Higgs boson.
- 187 ACTON 91B limits are for  $m_{X^0} = 60-85$  GeV.
- 188 ADEVA 91D limits are for  $m_{X^0} = 30-89$  GeV.
- 189 ADEVA 91D limits are for  $m_{X^0} = 30-86$  GeV.



<sup>190</sup> AKRAWY 90J give  $\Gamma(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) < 1.9 \text{ MeV}$  (95%CL) for  $m_{X^0} = 32\text{--}80 \text{ GeV}$ . We divide by  $\Gamma(Z) = 2.5 \text{ GeV}$  to get product of branching ratios. For nonresonant transitions, the limit is  $B(Z \rightarrow \gamma q\bar{q}) < 8.2 \text{ MeV}$  assuming three-body phase space distribution.

### MASS LIMITS for a Heavy Neutral Boson Coupling to $e^+ e^-$

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
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• • • We do not use the following data for averages, fits, limits, etc. • • •

none 55–61		<sup>191</sup> ODAKA	89 VNS	$\Gamma(X^0 \rightarrow e^+ e^-) \cdot B(X^0 \rightarrow \text{hadrons}) \gtrsim 0.2 \text{ MeV}$
>45	95	<sup>192</sup> DERRICK	86 HRS	$\Gamma(X^0 \rightarrow e^+ e^-) = 6 \text{ MeV}$
>46.6	95	<sup>193</sup> ADEVA	85 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 10 \text{ keV}$
>48	95	<sup>193</sup> ADEVA	85 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 4 \text{ MeV}$
		<sup>194</sup> BERGER	85B PLUT	
none 39.8–45.5		<sup>195</sup> ADEVA	84 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 10 \text{ keV}$
>47.8	95	<sup>195</sup> ADEVA	84 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 4 \text{ MeV}$
none 39.8–45.2		<sup>195</sup> BEHREND	84C CELL	
>47	95	<sup>195</sup> BEHREND	84C CELL	$\Gamma(X^0 \rightarrow e^+ e^-) = 4 \text{ MeV}$

<sup>191</sup> ODAKA 89 looked for a narrow or wide scalar resonance in  $e^+ e^- \rightarrow \text{hadrons}$  at  $E_{\text{cm}} = 55.0\text{--}60.8 \text{ GeV}$ .

<sup>192</sup> DERRICK 86 found no deviation from the Standard Model Bhabha scattering at  $E_{\text{cm}} = 29 \text{ GeV}$  and set limits on the possible scalar boson  $e^+ e^-$  coupling. See their figure 4 for excluded region in the  $\Gamma(X^0 \rightarrow e^+ e^-) - m_{X^0}$  plane. Electronic chiral invariance requires a parity doublet of  $X^0$ , in which case the limit applies for  $\Gamma(X^0 \rightarrow e^+ e^-) = 3 \text{ MeV}$ .

<sup>193</sup> ADEVA 85 first limit is from  $2\gamma, \mu^+ \mu^-, \text{hadrons}$  assuming  $X^0$  is a scalar. Second limit is from  $e^+ e^-$  channel.  $E_{\text{cm}} = 40\text{--}47 \text{ GeV}$ . Supersedes ADEVA 84.

<sup>194</sup> BERGER 85B looked for effect of spin-0 boson exchange in  $e^+ e^- \rightarrow e^+ e^-$  and  $\mu^+ \mu^-$  at  $E_{\text{cm}} = 34.7 \text{ GeV}$ . See Fig. 5 for excluded region in the  $m_{X^0} - \Gamma(X^0)$  plane.

<sup>195</sup> ADEVA 84 and BEHREND 84C have  $E_{\text{cm}} = 39.8\text{--}45.5 \text{ GeV}$ . MARK-J searched  $X^0$  in  $e^+ e^- \rightarrow \text{hadrons}, 2\gamma, \mu^+ \mu^-, e^+ e^-$  and CELLO in the same channels plus  $\tau$  pair. No narrow or broad  $X^0$  is found in the energy range. They also searched for the effect of  $X^0$  with  $m_{X^0} > E_{\text{cm}}$ . The second limits are from Bhabha data and for spin-0 singlet. The same limits apply for  $\Gamma(X^0 \rightarrow e^+ e^-) = 2 \text{ MeV}$  if  $X^0$  is a spin-0 doublet. The second limit of BEHREND 84C was read off from their figure 2. The original papers also list limits in other channels.

### Search for $X^0$ Resonance in $e^+ e^-$ Collisions

The limit is for  $\Gamma(X^0 \rightarrow e^+ e^-) \cdot B(X^0 \rightarrow f)$ , where  $f$  is the specified final state.

Spin 0 is assumed for  $X^0$ .

VALUE (keV)	CL%	DOCUMENT ID	TECN	COMMENT
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• • • We do not use the following data for averages, fits, limits, etc. • • •

$< 10^3$	95	<sup>196</sup> ABE	93C VNS	$\Gamma(ee)$
$< (0.4\text{--}10)$	95	<sup>197</sup> ABE	93C VNS	$f = \gamma\gamma$
$< (0.3\text{--}5)$	95	<sup>198,199</sup> ABE	93D TOPZ	$f = \gamma\gamma$
$< (2\text{--}12)$	95	<sup>198,199</sup> ABE	93D TOPZ	$f = \text{hadrons}$

<(4–200)	95 199,200	ABE	93D TOPZ	$f = e e$
<(0.1–6)	95 199,200	ABE	93D TOPZ	$f = \mu \mu$
<(0.5–8)	90 201	STERNER	93 AMY	$f = \gamma \gamma$

196 Limit is for  $\Gamma(X^0 \rightarrow e^+ e^-)$   $m_{X^0} = 56\text{--}63.5$  GeV for  $\Gamma(X^0) = 0.5$  GeV.

197 Limit is for  $m_{X^0} = 56\text{--}61.5$  GeV and is valid for  $\Gamma(X^0) \ll 100$  MeV. See their Fig. 5 for limits for  $\Gamma = 1, 2$  GeV.

198 Limit is for  $m_{X^0} = 57.2\text{--}60$  GeV.

199 Limit is valid for  $\Gamma(X^0) \ll 100$  MeV. See paper for limits for  $\Gamma = 1$  GeV and those for  $J = 2$  resonances.

200 Limit is for  $m_{X^0} = 56.6\text{--}60$  GeV.

201 STERNER 93 limit is for  $m_{X^0} = 57\text{--}59.6$  GeV and is valid for  $\Gamma(X^0) < 100$  MeV. See their Fig. 2 for limits for  $\Gamma = 1, 3$  GeV.

### Search for $X^0$ Resonance in $e p$ Collisions

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • We do not use the following data for averages, fits, limits, etc. • • •

202 CHEKANOV 02B ZEUS  $X \rightarrow jj$

202 CHEKANOV 02B search for photoproduction of  $X$  decaying into dijets in  $e p$  collisions. See their Fig. 5 for the limit on the photoproduction cross section.

### Search for $X^0$ Resonance in Two-Photon Process

The limit is for  $\Gamma(X^0) \cdot B(X^0 \rightarrow \gamma \gamma)^2$ . Spin 0 is assumed for  $X^0$ .

<u>VALUE (MeV)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • We do not use the following data for averages, fits, limits, etc. • • •

<2.6 95 203 ACTON 93E OPAL  $m_{X^0} = 60 \pm 1$  GeV

<2.9 95 BUSKULIC 93F ALEP  $m_{X^0} \sim 60$  GeV

203 ACTON 93E limit for a  $J = 2$  resonance is 0.8 MeV.

### Search for $X^0$ Resonance in $e^+ e^- \rightarrow X^0 \gamma$

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • We do not use the following data for averages, fits, limits, etc. • • •

204 ABREU 00Z DLPH  $X^0$  decaying invisibly

205 ADAM 96C DLPH  $X^0$  decaying invisibly

204 ABREU 00Z is from the single photon cross section at  $\sqrt{s} = 183, 189$  GeV. The production cross section upper limit is less than 0.3 pb for  $X^0$  mass between 40 and 160 GeV. See their Fig. 4 for the limit in mass-cross section plane.

205 ADAM 96C is from the single photon production cross at  $\sqrt{s} = 130, 136$  GeV. The upper bound is less than 3 pb for  $X^0$  masses between 60 and 130 GeV. See their Fig. 5 for the exact bound on the cross section  $\sigma(e^+ e^- \rightarrow \gamma X^0)$ .

### Search for $X^0$ Resonance in $Z \rightarrow f\bar{f}X^0$

The limit is for  $B(Z \rightarrow f\bar{f}X^0) \cdot B(X^0 \rightarrow F)$  where  $f$  is a fermion and  $F$  is the specified final state. Spin 0 is assumed for  $X^0$ .

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		206 ABREU	96T DLPH	$f=e,\mu,\tau; F=\gamma\gamma$
$<3.7 \times 10^{-6}$	95	207 ABREU	96T DLPH	$f=\nu; F=\gamma\gamma$
		208 ABREU	96T DLPH	$f=q; F=\gamma\gamma$
$<6.8 \times 10^{-6}$	95	207 ACTON	93E OPAL	$f=e,\mu,\tau; F=\gamma\gamma$
$<5.5 \times 10^{-6}$	95	207 ACTON	93E OPAL	$f=q; F=\gamma\gamma$
$<3.1 \times 10^{-6}$	95	207 ACTON	93E OPAL	$f=\nu; F=\gamma\gamma$
$<6.5 \times 10^{-6}$	95	207 ACTON	93E OPAL	$f=e,\mu; F=\ell\bar{\ell}, q\bar{q}, \nu\bar{\nu}$
$<7.1 \times 10^{-6}$	95	207 BUSKULIC	93F ALEP	$f=e,\mu; F=\ell\bar{\ell}, q\bar{q}, \nu\bar{\nu}$
		209 ADRIANI	92F L3	$f=q; F=\gamma\gamma$

206 ABREU 96T obtain limit as a function of  $m_{X^0}$ . See their Fig. 6.

207 Limit is for  $m_{X^0}$  around 60 GeV.

208 ABREU 96T obtain limit as a function of  $m_{X^0}$ . See their Fig. 15.

209 ADRIANI 92F give  $\sigma_Z \cdot B(Z \rightarrow q\bar{q}X^0) \cdot B(X^0 \rightarrow \gamma\gamma) < (0.75-1.5)$  pb (95%CL) for  $m_{X^0} = 10-70$  GeV. The limit is 1 pb at 60 GeV.

### Search for $X^0$ Resonance in $p\bar{p} \rightarrow WX^0$

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
	210 ABE	97W CDF	$X^0 \rightarrow b\bar{b}$

210 ABE 97W search for  $X^0$  production associated with  $W$  in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The 95%CL upper limit on the production cross section times the branching ratio for  $X^0 \rightarrow b\bar{b}$  ranges from 14 to 19 pb for  $X^0$  mass between 70 and 120 GeV. See their Fig. 3 for upper limits of the production cross section as a function of  $m_{X^0}$ .

### Heavy Particle Production in Quarkonium Decays

Limits are for branching ratios to modes shown.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$<1.5 \times 10^{-5}$	90	211 BALEST	95 CLE2	$\Upsilon(1S) \rightarrow X^0\gamma,$ $m_{X^0} < 5$ GeV
$<3 \times 10^{-5}-6 \times 10^{-3}$	90	212 BALEST	95 CLE2	$\Upsilon(1S) \rightarrow X^0\bar{X}^0\gamma,$ $m_{X^0} < 3.9$ GeV
$<5.6 \times 10^{-5}$	90	213 ANTREASYAN 90C	CBAL	$\Upsilon(1S) \rightarrow X^0\gamma,$ $m_{X^0} < 7.2$ GeV
		214 ALBRECHT	89 ARG	

211 BALEST 95 two-body limit is for pseudoscalar  $X^0$ . The limit becomes  $< 10^{-4}$  for  $m_{X^0} < 7.7$  GeV.

212 BALEST 95 three-body limit is for phase-space photon energy distribution and angular distribution same as for  $\Upsilon \rightarrow gg\gamma$ .

213 ANTREASYAN 90C assume that  $X^0$  does not decay in the detector.

214 ALBRECHT 89 give limits for  $B(\Upsilon(1S), \Upsilon(2S) \rightarrow X^0\gamma) \cdot B(X^0 \rightarrow \pi^+\pi^-, K^+K^-, p\bar{p})$  for  $m_{X^0} < 3.5$  GeV.

## REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

ABAZOV	02	PRL 88 191801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABBIENDI	02B	PL B526 233	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
AFFOLDER	02C	PRL 88 071806	T. Affolder <i>et al.</i>	(CDF Collab.)
CHEKANOV	02	PR D65 092004	S. Chekanov <i>et al.</i>	(ZEUS Collab.)
CHEKANOV	02B	PL B531 9	S. Chekanov <i>et al.</i>	(ZEUS Collab.)
ABAZOV	01B	PRL 87 061802	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	01D	PR D64 092004	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ADLOFF	01C	PL B523 234	C. Adloff <i>et al.</i>	(H1 Collab.)
AFFOLDER	01I	PRL 87 231803	T. Affolder <i>et al.</i>	(CDF Collab.)
BREITWEG	01	PR D63 052002	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
CHEUNG	01B	PL B517 167	K. Cheung	
THOMAS	01	NP A694 559	E. Thomas <i>et al.</i>	
ABBIENDI	00M	EPJ C13 15	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	00C	PRL 84 2088	B. Abbott <i>et al.</i>	(D0 Collab.)
ABE	00	PRL 84 5716	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	00S	PL B485 45	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACCIARRI	00P	PL B489 81	M. Acciarri <i>et al.</i>	(L3 Collab.)
ADLOFF	00	PL B479 358	C. Adloff <i>et al.</i>	(H1 Collab.)
AFFOLDER	00K	PRL 85 2056	T. Affolder <i>et al.</i>	(CDF Collab.)
BARATE	00I	EPJ C12 183	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARGER	00	PL B480 149	V. Barger, K. Cheung	
BREITWEG	00E	EPJ C16 253	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
CHAY	00	PR D61 035002	J. Chay, K.Y. Lee, S. Nam	
CHO	00	MPL A15 311	G. Cho	
CORNET	00	PR D61 037701	F. Cornet, M. Relano, J. Rico	
DELGADO	00	JHEP 0001 030	A. Delgado, A. Pomarol, M. Quiros	
ERLER	00	PRL 84 212	J. Erler, P. Langacker	
GABRIELLI	00	PR D62 055009	E. Gabrielli	
RIZZO	00	PR D61 016007	T.G. Rizzo, J.D. Wells	
ROSNER	00	PR D61 016006	J.L. Rosner	
ZARNECKI	00	EPJ C17 695	A. Zarnecki	
ABBIENDI	99	EPJ C6 1	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	99J	PRL 83 2896	B. Abbott <i>et al.</i>	(D0 Collab.)
ABREU	99G	PL B446 62	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACKERSTAFF	99D	EPJ C8 3	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
ADLOFF	99	EPJ C11 447	C. Adloff <i>et al.</i>	(H1 Collab.)
Also	00C	EPJ C14 553 errata	C. Adloff <i>et al.</i>	(H1 Collab.)
CASALBUONI	99	PL B460 135	R. Casalbuoni <i>et al.</i>	
CZAKON	99	PL B458 355	M. Czakon, J. Gluza, M. Zralek	
ERLER	99	PL B456 68	J. Erler, P. Langacker	
MARCIANO	99	PR D60 093006	W. Marciano	
MASIP	99	PR D60 096005	M. Masip, A. Pomarol	
NATH	99	PR D60 116004	P. Nath, M. Yamaguchi	
STRUMIA	99	PL B466 107	A. Strumia	
ABBOTT	98E	PRL 80 2051	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	98J	PRL 81 38	B. Abbott <i>et al.</i>	(D0 Collab.)
ABE	98S	PRL 81 4806	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	98V	PRL 81 5742	F. Abe <i>et al.</i>	(CDF Collab.)
ACCIARRI	98J	PL B433 163	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACKERSTAFF	98V	EPJ C2 441	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
BARATE	98U	EPJ C4 571	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARENBOIM	98	EPJ C1 369	G. Barenboim	
CHO	98	EPJ C5 155	G. Cho, K. Hagiwara, S. Matsumoto	
CONRAD	98	RMP 70 1341	J.M. Conrad, M.H. Shaevitz, T. Bolton	
DONCHESKI	98	PR D58 097702	M.A. Doncheski, R.W. Robinett	
GROSS-PILCHER	98	hep-ex/9810015	C. Grosso-Pilcher, G. Landsberg, M. Paterno	
ABE	97F	PRL 78 2906	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97G	PR D55 R5263	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97S	PRL 79 2192	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97W	PRL 79 3819	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97X	PRL 79 4327	F. Abe <i>et al.</i>	(CDF Collab.)
ACCIARRI	97Q	PL B412 201	M. Acciarri <i>et al.</i>	(L3 Collab.)
ARIMA	97	PR D55 19	T. Arima <i>et al.</i>	(VENUS Collab.)
BARENBOIM	97	PR D55 4213	G. Barenboim <i>et al.</i>	(VALE, IFIC)
DEANDREA	97	PL B409 277	A. Deandrea	(MARS)
DERRICK	97	ZPHY C73 613	M. Derrick <i>et al.</i>	(ZEUS Collab.)
GROSSMAN	97	PR D55 2768	Y. Grossman, Z. Ligeti, E. Nardi	(REHO, CIT)
JADACH	97	PL B408 281	S. Jadach, B.F.L. Ward, Z. Was	(CERN, INPK+)

STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ABACHI	96C	PRL 76 3271	S. Abachi <i>et al.</i>	(D0 Collab.)
ABACHI	96D	PL B385 471	S. Abachi <i>et al.</i>	(D0 Collab.)
ABREU	96T	ZPHY C72 179	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ADAM	96C	PL B380 471	W. Adam <i>et al.</i>	(DELPHI Collab.)
AID	96B	PL B369 173	S. Aid <i>et al.</i>	(H1 Collab.)
ALLET	96	PL B383 139	M. Allet <i>et al.</i>	(VILL, LEUV, LOUV, WISC)
ABACHI	95E	PL B358 405	S. Abachi <i>et al.</i>	(D0 Collab.)
ABE	95M	PRL 74 2900	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	95N	PRL 74 3538	F. Abe <i>et al.</i>	(CDF Collab.)
BALEST	95	PR D51 2053	R. Balest <i>et al.</i>	(CLEO Collab.)
KUZNETSOV	95	PRL 75 794	I.A. Kuznetsov <i>et al.</i>	(PNPI, KIAE, HARV+)
KUZNETSOV	95B	PAN 58 2113	A.V. Kuznetsov, N.V. Mikheev	(YARO)
		Translated from YAF 58 2228.		
MIZUKOSHI	95	NP B443 20	J.K. Mizukoshi, O.J.P. Eboli, M.C. Gonzalez-Garcia	
ABREU	94O	ZPHY C64 183	P. Abreu <i>et al.</i>	(DELPHI Collab.)
BHATTACH...	94	PL B336 100	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
Also	94B	PL B338 522 (erratum)	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
BHATTACH...	94B	PL B338 522 (erratum)	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
DAVIDSON	94	ZPHY C61 613	S. Davidson, D. Bailey, B.A. Campbell	(CFPA+)
KUZNETSOV	94	PL B329 295	A.V. Kuznetsov, N.V. Mikheev	(YARO)
KUZNETSOV	94B	JETPL 60 315	I.A. Kuznetsov <i>et al.</i>	(PNPI, KIAE, HARV+)
		Translated from ZETFP 60 311.		
LEURER	94	PR D50 536	M. Leurer	(REHO)
LEURER	94B	PR D49 333	M. Leurer	(REHO)
Also	93	PRL 71 1324	M. Leurer	(REHO)
MAHANTA	94	PL B337 128	U. Mahanta	(MEHTA)
SEVERIJNS	94	PRL 73 611 (erratum)	N. Severijns <i>et al.</i>	(LOUV, WISC, LEUV+)
VILAIN	94B	PL B332 465	P. Vilain <i>et al.</i>	(CHARM II Collab.)
ABE	93C	PL B302 119	K. Abe <i>et al.</i>	(VENUS Collab.)
ABE	93D	PL B304 373	T. Abe <i>et al.</i>	(TOPAZ Collab.)
ABE	93G	PRL 71 2542	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	93J	PL B316 620	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACTON	93E	PL B311 391	P.D. Acton <i>et al.</i>	(OPAL Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani <i>et al.</i>	(L3 Collab.)
ALITTI	93	NP B400 3	J. Alitti <i>et al.</i>	(UA2 Collab.)
BHATTACH...	93	PR D47 R3693	G. Bhattacharyya <i>et al.</i>	(CALC, JADA, ICTP+)
BUSKULIC	93F	PL B308 425	D. Buskulic <i>et al.</i>	(ALEPH Collab.)
DERRICK	93	PL B306 173	M. Derrick <i>et al.</i>	(ZEUS Collab.)
RIZZO	93	PR D48 4470	T.G. Rizzo	(ANL)
SEVERIJNS	93	PRL 70 4047	N. Severijns <i>et al.</i>	(LOUV, WISC, LEUV+)
Also	94	PRL 73 611 (erratum)	N. Severijns <i>et al.</i>	(LOUV, WISC, LEUV+)
STERNER	93	PL B303 385	K.L. Sterner <i>et al.</i>	(AMY Collab.)
ABREU	92D	ZPHY C53 555	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ADRIANI	92F	PL B292 472	O. Adriani <i>et al.</i>	(L3 Collab.)
DECAMP	92	PRPL 216 253	D. Decamp <i>et al.</i>	(ALEPH Collab.)
IMAZATO	92	PRL 69 877	J. Imazato <i>et al.</i>	(KEK, INUS, TOKY+)
MISHRA	92	PRL 68 3499	S.R. Mishra <i>et al.</i>	(COLU, CHIC, FNAL+)
POLAK	92B	PR D46 3871	J. Polak, M. Zralek	(SILES)
ACTON	91	PL B268 122	D.P. Acton <i>et al.</i>	(OPAL Collab.)
ACTON	91B	PL B273 338	D.P. Acton <i>et al.</i>	(OPAL Collab.)
ADEVA	91D	PL B262 155	B. Adeva <i>et al.</i>	(L3 Collab.)
AQUINO	91	PL B261 280	M. Aquino, A. Fernandez, A. Garcia	(CINV, PUEB)
COLANGELO	91	PL B253 154	P. Colangelo, G. Nardulli	(BARI)
CUYPERS	91	PL B259 173	F. Cuypers, A.F. Falk, P.H. Frampton	(DURH, HARV+)
FARAGGI	91	MPL A6 61	A.E. Faraggi, D.V. Nanopoulos	(TAMU)
POLAK	91	NP B363 385	J. Polak, M. Zralek	(SILES)
RIZZO	91	PR D44 202	T.G. Rizzo	(WISC, ISU)
WALKER	91	APJ 376 51	T.P. Walker <i>et al.</i>	(HSCA, OSU, CHIC+)
ABE	90F	PL B246 297	K. Abe <i>et al.</i>	(VENUS Collab.)
ABE	90H	PR D41 1722	F. Abe <i>et al.</i>	(CDF Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy <i>et al.</i>	(OPAL Collab.)
ANTREASYAN	90C	PL B251 204	D. Antreasyan <i>et al.</i>	(Crystal Ball Collab.)
GONZALEZ-G...	90D	PL B240 163	M.C. Gonzalez-Garcia, J.W.F. Valle	(VALE)
GRIFOLS	90	NP B331 244	J.A. Grifols, E. Masso	(BARC)
GRIFOLS	90D	PR D42 3293	J.A. Grifols, E. Masso, T.G. Rizzo	(BARC, CERN+)
KIM	90	PL B240 243	G.N. Kim <i>et al.</i>	(AMY Collab.)
LOPEZ	90	PL B241 392	J.L. Lopez, D.V. Nanopoulos	(TAMU)
ALBAJAR	89	ZPHY C44 15	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALBRECHT	89	ZPHY C42 349	H. Albrecht <i>et al.</i>	(ARGUS Collab.)
BARBIERI	89B	PR D39 1229	R. Barbieri, R.N. Mohapatra	(PISA, UMD)

LANGACKER	89B	PR D40 1569	P. Langacker, S. Uma Sankar	(PENN)
ODAKA	89	JPSJ 58 3037	S. Odaka <i>et al.</i>	(VENUS Collab.)
ROBINETT	89	PR D39 834	R.W. Robinett	(PSU)
ALBAJAR	88B	PL B209 127	C. Albajar <i>et al.</i>	(UA1 Collab.)
BAGGER	88	PR D37 1188	J. Bagger, C. Schmidt, S. King	(HARV, BOST)
BALKE	88	PR D37 587	B. Balke <i>et al.</i>	(LBL, UCB, COLO, NWES+)
BERGSTROM	88	PL B212 386	L. Bergstrom	(STOH)
CUYPERS	88	PRL 60 1237	F. Cuypers, P.H. Frampton	(UNCCH)
DONCHESKI	88	PL B206 137	M.A. Doncheski, H. Grotch, R. Robinett	(PSU)
DONCHESKI	88B	PR D38 412	M.A. Doncheski, H. Grotch, R.W. Robinett	(PSU)
ANSARI	87D	PL B195 613	R. Ansari <i>et al.</i>	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	W. Bartel <i>et al.</i>	(JADE Collab.)
BEHREND	86B	PL B178 452	H.J. Behrend <i>et al.</i>	(CELLO Collab.)
DERRICK	86	PL 166B 463	M. Derrick <i>et al.</i>	(HRS Collab.)
Also	86B	PR D34 3286	M. Derrick <i>et al.</i>	(HRS Collab.)
JODIDIO	86	PR D34 1967	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909	R.N. Mohapatra	(UMD)
ADEVA	85	PL 152B 439	B. Adeva <i>et al.</i>	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	C. Berger <i>et al.</i>	(PLUTO Collab.)
STOKER	85	PRL 54 1887	D.P. Stoker <i>et al.</i>	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	B. Adeva <i>et al.</i>	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	H.J. Behrend <i>et al.</i>	(CELLO Collab.)
BERGSMA	83	PL 122B 465	F. Bergsma <i>et al.</i>	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr <i>et al.</i>	(LBL, NWES, TRIU)
BEALL	82	PRL 48 848	G. Beall, M. Bander, A. Soni	(UCI, UCLA)
SHANKER	82	NP B204 375	O. Shanker	(TRIU)
STEIGMAN	79	PRL 43 239	G. Steigman, K.A. Olive, D.N. Schramm	(BART+)