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 $p\overline{p} \rightarrow W' X$ 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 $t\overline{b}$ channel is not open.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>800	95	ABAZOV	04C	D0	$W' \rightarrow q\overline{q}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
225–536	95	[1] ACOSTA	03B	CDF	$W' \rightarrow tb$
none 200–480	95	[2] AFFOLDER	02C	CDF	$W' \rightarrow WZ$
>786	95	[3] AFFOLDER	01I	CDF	$W' \rightarrow e\nu, \mu\nu$
>660	95	[4] ABE	00	CDF	$W' \rightarrow \mu\nu$
none 300–420	95	[5] ABE	97G	CDF	$W' \rightarrow q\overline{q}$
>720	95	[6] ABACHI	96C	D0	$W' \rightarrow e\nu$
>610	95	[7] ABACHI	95E	D0	$W' \rightarrow e\nu, \tau\nu$
>652	95	[8] ABE	95M	CDF	$W' \rightarrow e\nu$
>251	90	[9] ALITTI	93	UA2	$W' \rightarrow q\overline{q}$
none 260–600	95	[10] RIZZO	93	RVUE	$W' \rightarrow q\overline{q}$
>220	90	[11] ALBAJAR	89	UA1	$W' \rightarrow e\nu$
>209	90	[12] ANSARI	87D	UA2	$W' \rightarrow e\nu$

[1] The ACOSTA 03B quoted limit is for $M_{W'} \gg M_{\nu_R}$. For $M_{W'} < M_{\nu_R}$, $M_{W'}$ between 225 and 566 GeV is excluded.

[2] 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.

[3] 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.

[4] ABE 00 assume that the neutrino from W' decay is stable and has a mass significantly less than $m_{W'}$.

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

[6] For bounds on W_R with nonzero right-handed mass, see Fig. 5 from ABACHI 96C.

[7] 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 $m_{W'}$.

[8] ABE 95M assume that the decay $W' \rightarrow WZ$ is suppressed and the (right-handed) neutrino is light, noninteracting, and stable. If m_ν=60 GeV, for example, the effect on the mass limit is negligible.

[9] 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 $W_R \rightarrow t\overline{b}$ allowed. See their Fig. 4 for limits in the $m_{W'}$–B($q\overline{q}$) plane.

[10] RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed K factor.

[11] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(W')$ B($e\nu$) $<$ 4.1 pb (90% CL).

[12] See Fig. 5 of ANSARI 87D for the excluded region in the $m_{W'}$–$[(g_{W'q})^2$ B($W' \rightarrow e\overline{\nu}$)] plane. Note that the quantity $(g_{W'q})^2$ B($W' \rightarrow e\overline{\nu}$) 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 ζ 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	[13] CZAKON 99	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 310	90	[14] THOMAS 01	CNTR	β^+ decay
> 137	95	[15] ACKERSTAFF 99D	OPAL	τ decay
>1400	68	[16] BARENBOIM 98	RVUE	Electroweak, Z-Z' mixing
> 549	68	[17] BARENBOIM 97	RVUE	μ decay
> 220	95	[18] STAHL 97	RVUE	τ decay
> 220	90	[19] ALLET 96	CNTR	β^+ decay
> 281	90	[20] KUZNETSOV 95	CNTR	Polarized neutron decay
> 282	90	[21] KUZNETSOV 94B	CNTR	Polarized neutron decay
> 439	90	[22] BHATTACH... 93	RVUE	Z-Z' mixing
> 250	90	[23] SEVERIJNS 93	CNTR	β^+ decay
		[24] IMAZATO 92	CNTR	K^+ decay
> 475	90	[25] POLAK 92B	RVUE	μ decay
> 240	90	[26] AQUINO 91	RVUE	Neutron decay
> 496	90	[26] AQUINO 91	RVUE	Neutron and muon decay
> 700		[27] COLANGELO 91	THEO	$m_{K^0_L} - m_{K^0_S}$
> 477	90	[28] POLAK 91	RVUE	μ decay
[none 540–23000]		[29] BARBIERI 89B	ASTR	SN 1987A; light ν_R
> 300	90	[30] LANGACKER 89B	RVUE	General
> 160	90	[31] BALKE 88	CNTR	$\mu \rightarrow e\nu\overline{\nu}$
> 406	90	[32] JODIDIO 86	ELEC	Any ζ
> 482	90	[32] JODIDIO 86	ELEC	$\zeta = 0$
> 800		MOHAPATRA 86	RVUE	SU(2)$_L$×SU(2)$_R$×U(1)
> 400	95	[33] STOKER 85	ELEC	Any ζ
> 475	95	[33] STOKER 85	ELEC	$\zeta < 0.041$
		[34] BERGSMA 83	CHRM	$\nu_\mu e \rightarrow \mu\nu_e$
> 380	90	[35] CARR 83	ELEC	μ^+ decay
>1600		[36] BEALL 82	THEO	$m_{K^0_L} - m_{K^0_S}$
[> 4000]		STEIGMAN 79	COSM	Nucleosynthesis; light ν_R

[13] CZAKON 99 perform a simultaneous fit to charged and neutral sectors.

[14] THOMAS 01 limit is from measurement of β^+ polarization in decay of polarized ^{12}N. The listed limit assumes no mixing.

[15] ACKERSTAFF 99D limit is from τ decay parameters. Limit increase to 145 GeV for zero mixing.

[16] BARENBOIM 98 assumes minimal left-right model with Higgs of $SU(2)_R$ in $SU(2)_L$ doublet. For Higgs in $SU(2)_L$ triplet, m_{W_R} >1100 GeV. Bound calculated from effect of corresponding Z_{LR} on electroweak data through Z–Z_{LR} mixing.

[17] The quoted limit is from μ decay parameters. BARENBOIM 97 also evaluate limit from K_L-K_S mass difference.

[18] STAHL 97 limit is from fit to τ-decay parameters.

[19] ALLET 96 measured polarization-asymmetry correlation in $^{12}\mathrm{N}\beta^+$ decay. The listed limit assumes zero L-R mixing.

[20] KUZNETSOV 95 limit is from measurements of the asymmetry $\langle\vec{p}_\nu\cdot\sigma_n\rangle$ in the β decay of polarized neutrons. Zero mixing assumed. See also KUZNETSOV 94B.

[21] KUZNETSOV 94B limit is from measurements of the asymmetry $\langle\vec{p}_\nu\cdot\sigma_n\rangle$ in the β decay of polarized neutrons. Zero mixing assumed.

[22] BHATTACHARYYA 93 uses Z-Z' mixing limit from LEP '90 data, assuming a specific Higgs sector of $SU(2)_L\times SU(2)_R\times U(1)$ gauge model. The limit is for m_t=200 GeV and slightly improves for smaller m_t.

[23] SEVERIJNS 93 measured polarization-asymmetry correlation in $^{107}\mathrm{In}\,\beta^+$ decay. The listed limit assumes zero L-R mixing. Value quoted here is from SEVERIJNS 94 erratum.

[24] 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 $u\overline{s}$ with full weak strength (V^R_{us}=1), the result corresponds to m_{W_R} >653 GeV. See their Fig. 4 for m_{W_R} limits for general $|V^R_{us}|^2=1-|V^R_{ud}|^2$.

[25] POLAK 92B limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming ζ=0. Supersedes POLAK 91.

[26] 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.

[27] 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.

[28] POLAK 91 limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming ζ=0. Superseded by POLAK 92B.

[29] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

[30] LANGACKER 89B limit is for any ν_R mass (either Dirac or Majorana) and for a general class of right-handed quark mixing matrices.

[31] 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.

[32] 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 μ^+.

[33] 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.

[34] BERGSMA 83 set limit m_{W_2}/m_{W_1} >1.9 at CL = 90%.

[35] CARR 83 is TRIUMF experiment with a highly polarized μ^+ 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.

[36] 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 ζ

Lighter mass eigenstate $W_1 = W_L \cos\zeta - W_R \sin\zeta$. Light ν_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	[37] ACKERSTAFF	99D	OPAL	τ decay
$<$ 0.013	90	[38] CZAKON	99	RVUE	Electroweak
$<$ 0.0333		[39] BARENBOIM	97	RVUE	μ decay
$<$ 0.04	90	[40] MISHRA	92	CCFR	νN scattering
-0.0006 to 0.0028	90	[41] AQUINO	91	RVUE	
[none 0.00001–0.02]		[42] BARBIERI	89B	ASTR	SN 1987A
$<$ 0.040	90	[43] JODIDIO	86	ELEC	μ decay
-0.056 to 0.040	90	[43] JODIDIO	86	ELEC	μ decay

[37] ACKERSTAFF 99D limit is from τ decay parameters.

[38] CZAKON 99 perform a simultaneous fit to charged and neutral sectors.

[39] The quoted limit is from μ decay parameters. BARENBOIM 97 also evaluate limit from K_L-K_S mass difference.

[40] MISHRA 92 limit is from the absence of extra large-x, large-y $\overline{\nu}_\mu N \rightarrow \overline{\nu}_\mu X$ events at Tevatron, assuming left-handed ν and right-handed $\overline{\nu}$ 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 ν_R mass.

[41] AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right asymmetry is assumed.

[42] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV.

[43] 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*
$>$1018	95	[44] ABBIENDI	04G	OPAL	e^+e^-
>1500	95	[45] CHEUNG	01B	RVUE	Electroweak
> 690	95	[46] ABE	97S	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$, $\mu^+\mu^-$

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

none 400–640	95	ABAZOV 04C	D0	$p\overline{p}$: $Z'_{SM} \to q\overline{q}$
$>$ 670	95	[47] ABAZOV 01B	D0	$p\overline{p}$, $Z'_{SM} \to e^+e^-$
$>$ 710	95	[48] ABREU 00S	DLPH	e^+e^-
$>$ 898	95	[49] BARATE 00I	ALEP	e^+e^-
$>$ 809	95	[50] ERLER 99	RVUE	Electroweak
$>$ 490	95	ABACHI 96D	D0	$p\overline{p}$; $Z'_{SM} \to e^+e^-$
$>$ 398	95	[51] VILAIN 94B	CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
$>$ 237	90	[52] ALITTI 93	UA2	$p\overline{p}$; $Z'_{SM} \to q\overline{q}$
none 260–600	95	[53] RIZZO 93	RVUE	$p\overline{p}$; $Z'_{SM} \to q\overline{q}$
$>$ 426	90	[54] ABE 90F	VNS	e^+e^-

[44] ABBIENDI 04G give 95%CL limit on $Z-Z'$ mixing $-0.00422 < \theta < 0.00091$. $\sqrt{s} = 91$ to 207 GeV.

[45] CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.

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

[47] ABAZOV 01B search for resonances in $p\overline{p} \to e^+e^-$ at $\sqrt{s}$=1.8 TeV. They find $\sigma \cdot B(Z' \to ee) < 0.06$ pb for $M_{Z'} > 500$ GeV.

[48] ABREU 00S uses LEP data at $\sqrt{s}$=90 to 189 GeV.

[49] BARATE 00I search for deviations in cross section and asymmetries in $e^+e^- \to$ fermions at $\sqrt{s}$=90 to 183 GeV. Assume θ=0. Bounds in the mass-mixing plane are shown in their Figure 18.

[50] ERLER 99 give 90%CL limit on the Z-Z' mixing $-0.0041 < \theta < 0.0003$. ρ_0=1 is assumed.

[51] VILAIN 94B assume $m_t = 150$ GeV.

[52] ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes $B(Z' \to q\overline{q})$=0.7. See their Fig. 5 for limits in the $m_{Z'}$–$B(q\overline{q})$ plane.

[53] RIZZO 93 analyses CDF limit on possible two-jet resonances.

[54] 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*
>518	95	[55] ABBIENDI 04G	OPAL	e^+e^-
>860	95	[56] CHEUNG 01B	RVUE	Electroweak
>630	95	[57] ABE 97S	CDF	$p\overline{p}$; $Z'_{LR} \to e^+e^-$, $\mu^+\mu^-$

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

>380	95	[58] ABREU	00S	DLPH	e^+e^-
>436	95	[59] BARATE	00I	ALEP	e^+e^-
>550	95	[60] CHAY	00	RVUE	Electroweak
		[61] ERLER	00	RVUE	Cs
		[62] CASALBUONI	99	RVUE	Cs
(> 1205)	90	[63] CZAKON	99	RVUE	Electroweak
>564	95	[64] ERLER	99	RVUE	Electroweak
(> 1673)	95	[65] ERLER	99	RVUE	Electroweak
(> 1700)	68	[66] BARENBOIM	98	RVUE	Electroweak
>244	95	[67] CONRAD	98	RVUE	$\nu_\mu N$ scattering
>253	95	[68] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
none 200–600	95	[69] RIZZO	93	RVUE	$p\overline{p}$; $Z_{LR} \rightarrow q\overline{q}$
[> 2000]		WALKER	91	COSM	Nucleosynthesis; light ν_R
none 200–500		[70] GRIFOLS	90	ASTR	SN 1987A; light ν_R
none 350–2400		[71] BARBIERI	89B	ASTR	SN 1987A; light ν_R

[55] ABBIENDI 04G give 95%CL limit on $Z-Z'$ mixing $-0.00098 < \theta < 0.00190$. See their Fig. 20 for the limit contour in the mass-mixing plane. $\sqrt{s} = 91$ to 207 GeV.

[56] CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.

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

[58] 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.

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

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

[61] ERLER 00 discuss the possibility that a discrepancy between the observed and predicted values of Q_W(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_χ.

[62] CASALBUONI 99 discuss the discrepancy between the observed and predicted values of Q_W(Cs). It is shown that the data are better described in a class of models including the Z_{LR} model.

[63] CZAKON 99 perform a simultaneous fit to charged and neutral sectors. Assumes manifest left-right symmetric model. Finds $|\theta| < 0.0042$.

[64] ERLER 99 give 90%CL limit on the Z-Z' mixing $-0.0009 < \theta < 0.0017$.

[65] ERLER 99 assumes 2 Higgs doublets, transforming as 10 of SO(10), embedded in E_6.

[66] 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.

[67] CONRAD 98 limit is from measurements at CCFR, assuming no Z-Z' mixing.

[68] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[69] RIZZO 93 analyses CDF limit on possible two-jet resonances.

[70] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim 1$ MeV. A specific Higgs sector is assumed. See also GRIFOLS 90D, RIZZO 91.

[71] BARBIERI 89B limit holds for $m_{\nu_R} \leq 10$ MeV. Bounds depend on assumed supernova core temperature.

Limits for Z_χ

Z_χ is the extra neutral boson in SO(10) → SU(5) × $U(1)_\chi$. $g_\chi = e/\cos\theta_W$ 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*
> 781	95	[72] ABBIENDI 04G	OPAL	e^+e^-
> 595	95	[73] ABE 97S	CDF	$p\overline{p}$; $Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
>2100		[74] BARGER 03B	COSM	Nucleosynthesis; light ν_R
> 680	95	[75] CHEUNG 01B	RVUE	Electroweak
> 440	95	[76] ABREU 00S	DLPH	e^+e^-
> 533	95	[77] BARATE 00I	ALEP	e^+e^-
> 554	95	[78] CHO 00	RVUE	Electroweak
		[79] ERLER 00	RVUE	Cs
		[80] ROSNER 00	RVUE	Cs
> 545	95	[81] ERLER 99	RVUE	Electroweak
(> 1368)	95	[82] ERLER 99	RVUE	Electroweak
> 215	95	[83] CONRAD 98	RVUE	$\nu_\mu N$ scattering
> 190	95	[84] ARIMA 97	VNS	Bhabha scattering
> 262	95	[85] VILAIN 94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
[>1470]		[86] FARAGGI 91	COSM	Nucleosynthesis; light ν_R
> 231	90	[87] ABE 90F	VNS	e^+e^-
[> 1140]		[88] GONZALEZ-G..90D	COSM	Nucleosynthesis; light ν_R
[> 2100]		[89] GRIFOLS 90	ASTR	SN 1987A; light ν_R

[72] ABBIENDI 04G give 95%CL limit on $Z-Z'$ mixing $-0.00099 < \theta < 0.00194$. See their Fig. 20 for the limit contour in the mass-mixing plane. $\sqrt{s}$ = 91 to 207 GeV.

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

[74] BARGER 03B limit is from the nucleosynthesis bound on the effective number of light neutrino $\delta N_\nu < 1$. The quark-hadron transition temperature T_c=150 MeV is assumed. The limit with T_c=400 MeV is >4300 GeV.

[75] CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.

[76] 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.

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

[78] 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.

[79] ERLER 00 discuss the possibility that a discrepancy between the observed and predicted values of Q_W(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_χ.

[80] ROSNER 00 discusses the possibility that a discrepancy between the observed and predicted values of Q_W(Cs) is due to the exchange of Z'. The data are better described in a certain class of the Z' models including Z_χ.

[81] ERLER 99 give 90%CL limit on the Z-Z' mixing $-0.0020 < \theta < 0.0015$.

[82] ERLER 99 assumes 2 Higgs doublets, transforming as 10 of SO(10), embedded in E_6.

[83] CONRAD 98 limit is from measurements at CCFR, assuming no Z-Z' mixing.

[84] Z-Z' mixing is assumed to be zero. $\sqrt{s}$= 57.77 GeV.

[85] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[86] 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.

[87] 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.

[88] Assumes the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) and that ν_R is light ($\lesssim$ 1 MeV).

[89] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also GRIFOLS 90D, RIZZO 91.

Limits for Z_ψ

Z_ψ 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*
>366	95	[90] ABBIENDI	04G	OPAL	e^+e^-
>590	95	[91] ABE	97S	CDF	$p\overline{p}$; $Z'_\psi \rightarrow e^+e^-$, $\mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>600		[92] BARGER	03B	COSM	Nucleosynthesis; light ν_R
>350	95	[93] ABREU	00S	DLPH	e^+e^-
>294	95	[94] BARATE	00I	ALEP	e^+e^-
>137	95	[95] CHO	00	RVUE	Electroweak
>146	95	[96] ERLER	99	RVUE	Electroweak
> 54	95	[97] CONRAD	98	RVUE	$\nu_\mu N$ scattering
>135	95	[98] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>105	90	[99] ABE	90F	VNS	e^+e^-
[> 160]		[100] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 2000]		[101] GRIFOLS	90D	ASTR	SN 1987A; light ν_R

[90] ABBIENDI 04G give 95%CL limit on $Z - Z'$ mixing $-0.00129 < \theta < 0.00258$. See their Fig. 20 for the limit contour in the mass-mixing plane. $\sqrt{s}$ = 91 to 207 GeV.

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

[92] BARGER 03B limit is from the nucleosynthesis bound on the effective number of light neutrino δN_ν <1. The quark-hadron transition temperature T_c=150 MeV is assumed. The limit with T_c=400 MeV is >1100 GeV.

[93] 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.

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

[95] 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.

[96] ERLER 99 give 90%CL limit on the Z-Z' mixing $-0.0013 < \theta < 0.0024$.

[97] CONRAD 98 limit is from measurements at CCFR, assuming no Z-Z' mixing.

[98] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[99] 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.

[100] Assumes the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) and that ν_R is light ($\lesssim$ 1 MeV).

[101] GRIFOLS 90D limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also RIZZO 91.

Limits for Z_η

Z_η 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*
$>$ 515	95	[102] ABBIENDI 04G	OPAL	e^+e^-
$>$ 619	95	[103] CHO 00	RVUE	Electroweak
$>$ 620	95	[104] ABE 97S	CDF	$p\overline{p}$; $Z'_\eta \rightarrow e^+e^-, \mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>$1600		[105] BARGER 03B	COSM	Nucleosynthesis; light ν_R
$>$ 310	95	[106] ABREU 00S	DLPH	e^+e^-
$>$ 329	95	[107] BARATE 00I	ALEP	e^+e^-
$>$ 365	95	[108] ERLER 99	RVUE	Electroweak
$>$ 87	95	[109] CONRAD 98	RVUE	$\nu_\mu N$ scattering
$>$ 100	95	[110] VILAIN 94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
$>$ 125	90	[111] ABE 90F	VNS	e^+e^-
[$>$ 820]		[112] GONZALEZ-G..90D	COSM	Nucleosynthesis; light ν_R
[$>$ 3300]		[113] GRIFOLS 90	ASTR	SN 1987A; light ν_R
[$>$ 1040]		[112] LOPEZ 90	COSM	Nucleosynthesis; light ν_R

[102] ABBIENDI 04G give 95%CL limit on $Z-Z'$ mixing $-0.00447 < \theta < 0.00331$. See their Fig. 20 for the limit contour in the mass-mixing plane. $\sqrt{s}$ = 91 to 207 GeV.

[103] 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.

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

[105] BARGER 03B limit is from the nucleosynthesis bound on the effective number of light neutrino $\delta N_\nu < 1$. The quark-hadron transition temperature T_c=150 MeV is assumed. The limit with T_c=400 MeV is $>$3300 GeV.

[106] 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.

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

[108] ERLER 99 give 90%CL limit on the Z-Z' mixing $-0.0062 < \theta < 0.0011$.

[109] CONRAD 98 limit is from measurements at CCFR, assuming no Z-Z' mixing.

[110] VILAIN 94B assume m_t = 150 GeV and θ=0. See Fig. 2 for limit contours in the mass-mixing plane.

[111] 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.

[112] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains Z' masses if ν_R is light ($\lesssim$ 1 MeV).

[113] GRIFOLS 90 limit holds for $m_{\nu_R} \lesssim$ 1 MeV. See also GRIFOLS 90D, RIZZO 91.

Limits for other Z'

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[114] ABAZOV 04A	D0	$Z' \rightarrow t\overline{t}$
	[115] BARGER 03B	COSM	Nucleosynthesis; light ν_R
	[116] CHO 00	RVUE	E_6-motivated
	[117] CHO 98	RVUE	E_6-motivated
	[118] ABE 97G	CDF	$Z' \rightarrow \overline{q}q$

[114] Search for narrow resonance decaying to $t\overline{t}$. See their Fig.2 for limit on σB.

[115] BARGER 03B use the nucleosynthesis bound on the effective number of light neutrino δN_ν. See their Figs. 4–5 for limits in general E_6 motivated models.

[116] 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.

[117] CHO 98 study constraints on four-Fermi contact interactions obtained from low-energy electroweak experiments, assuming no Z-Z' mixing.

[118] 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. See also the section on "Extra Dimensions" in the "Searches" Listings in this *Review*.

VALUE (TeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>$ 4.7		[119] MUECK 02	RVUE	Electroweak
$>$ 3.3	95	[120] CORNET 00	RVUE	$e\nu qq'$
$>$5000		[121] DELGADO 00	RVUE	ϵ_K
$>$ 2.6	95	[122] DELGADO 00	RVUE	Electroweak
$>$ 3.3	95	[123] RIZZO 00	RVUE	Electroweak
$>$ 2.9	95	[124] MARCIANO 99	RVUE	Electroweak
$>$ 2.5	95	[125] MASIP 99	RVUE	Electroweak
$>$ 1.6	90	[126] NATH 99	RVUE	Electroweak
$>$ 3.4	95	[127] STRUMIA 99	RVUE	Electroweak

[119] MUECK 02 limit is 2σ and is from global electroweak fit ignoring correlations among observables. Higgs is assumed to be confined on the brane and its mass is fixed. For scenarios of bulk Higgs, of brane-SU(2)$_L$, bulk-U(1)$_Y$, and of bulk-SU(2)$_L$, brane-U(1)$_Y$, the corresponding limits are $>$ 4.6 TeV, $>$ 4.3 TeV and $>$ 3.0 TeV, respectively.

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

[121] 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 Δm_K.

[122] 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(Cs). Quoted bound assumes all Higgs bosons confined to brane; placing one Higgs doublet in the bulk lowers bound to 2.3 TeV.

[123] 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.

[124] Bound is derived from global electroweak analysis but considering only presence of the KK W bosons.

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

[126] Bounds from effect of KK states on G_F, α, 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.

[127] 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		[128] ABBOTT 00C	D0	Second generation
>148	95		[129] AFFOLDER 00K	CDF	Third generation
>202	95		[130] ABE 98S	CDF	Second generation
>242	95		[131] GROSS-PILCH...98		First generation
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 99	95		[132] ABBIENDI 03R	OPAL	First generation
>100	95		[132] ABBIENDI 03R	OPAL	Second generation
> 98	95		[132] ABBIENDI 03R	OPAL	Third generation
> 98	95		[133] ABAZOV 02	D0	All generatrions
>225	95		[134] ABAZOV 01D	D0	First generation
> 85.8	95		[135] ABBIENDI 00M	OPAL	Superseded by ABBIENDI 03R
> 85.5	95		[135] ABBIENDI 00M	OPAL	Superseded by ABBIENDI 03R
> 82.7	95		[135] ABBIENDI 00M	OPAL	Superseded by ABBIENDI 03R
>123	95		[136] AFFOLDER 00K	CDF	Second generation
>160	95		[137] ABBOTT 99J	D0	Second generation
>225	95		[138] ABBOTT 98E	D0	First generation
> 94	95		[139] ABBOTT 98J	D0	Third generation
> 99	95		[140] ABE 97F	CDF	Third generation
>213	95		[141] ABE 97X	CDF	First generation
> 45.5	95		[142,143] ABREU 93J	DLPH	First + second generation
> 44.4	95		[144] ADRIANI 93M	L3	First generation
> 44.5	95		[144] ADRIANI 93M	L3	Second generation
> 45	95		[144] DECAMP 92	ALEP	Third generation
none 8.9–22.6	95		[145] KIM 90	AMY	First generation
none 10.2–23.2	95		[145] KIM 90	AMY	Second generation
none 5–20.8	95		[146] BARTEL 87B	JADE	
none 7–20.5	95	2	[147] BEHREND 86B	CELL	

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

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

[130] ABE 98S search for scalar leptoquarks using $\mu\mu jj$ events in $p\overline{p}$ collisions at $E_{\rm cm}$= 1.8 TeV. The limit is for B(μq)= 1. For B(μq)=B(νq)=0.5, the limit is > 160 GeV.

[131] 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.

[132] ABBIENDI 03R search for scalar/vector leptoquarks in e^+e^- collisions at $\sqrt{s}$ = 189–209 GeV. The quoted limis are for charge $-4/3$ isospin 0 scalar-leptoquark with B(ℓq) = 1. See their table 12 for other cases.

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

[134] ABAZOV 01D search for scalar leptoquarks using $e\nu jj$, $eejj$, and $\nu\nu jj$ events in $p\overline{p}$ collisions at $E_{\rm cm}$=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.

[135] 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(ℓq)=1. See their Table 8 and Figs. 6–9 for other cases.

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

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

[138] ABBOTT 98E search for scalar leptoquarks using $e\nu jj$, $eejj$, and $\nu\nu jj$ events in $p\overline{p}$ collisions at $E_{\rm cm}$=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.

[139] ABBOTT 98J search for charge $-1/3$ third generation scalar and vector leptoquarks in $p\overline{p}$ collisions at $E_{\rm cm}$= 1.8 TeV. The quoted limit is for scalar leptoquark with B(νb)=1.

[140] ABE 97F search for third generation scalar and vector leptoquarks in $p\overline{p}$ collisions at $E_{\rm cm}$ = 1.8 TeV. The quoted limit is for scalar leptoquark with B(τb) = 1.

[141] ABE 97X search for scalar leptoquarks using $eejj$ events in $p\overline{p}$ collisions at $E_{\rm cm}$=1.8 TeV. The limit is for B(eq)=1.

[142] Limit is for charge $-1/3$ isospin-0 leptoquark with B(ℓq) = 2/3.

[143] First and second generation leptoquarks are assumed to be degenerate. The limit is slightly lower for each generation.

[144] Limits are for charge $-1/3$, isospin-0 scalar leptoquarks decaying to $\ell^- q$ or νq with any branching ratio. See paper for limits for other charge-isospin assignments of leptoquarks.

[145] 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 $u\overline{\nu}$ ($s\mu^+$ and $c\overline{\nu}$). See paper for limits for specific branching ratios.

[146] 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 $\rightarrow$ $c\overline{\nu}_\mu$) + B(X $\rightarrow$ $s\mu^+$) = 1.

[147] BEHREND 86B assumed that a charge 2/3 spinless leptoquark, χ, decays either into $s\mu^+$ or $c\overline{\nu}$: B($\chi \rightarrow s\mu^+$) + B($\chi \rightarrow c\overline{\nu}$) = 1.

MASS LIMITS for Leptoquarks from Single Production

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*

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

>298	95	[148] CHEKANOV	03B	ZEUS	First generation
>197	95	[149] ABBIENDI	02B	OPAL	First generation
		[150] CHEKANOV	02	ZEUS	Lepton-flavor violation
>290	95	[151] ADLOFF	01C	H1	First generation
>204	95	[152] BREITWEG	01	ZEUS	First generation
		[153] BREITWEG	00E	ZEUS	First generation
>161	95	[154] ABREU	99G	DLPH	First generation
>200	95	[155] ADLOFF	99	H1	First generation
		[156] DERRICK	97	ZEUS	Lepton-flavor violation
> 73	95	[157] ABREU	93J	DLPH	Second generation
>168	95	[158] DERRICK	93	ZEUS	First generation

[148] CHEKANOV 03B limit is for a scalar, weak isoscalar, charge $-1/3$ leptoquark coupled with e_R. See their Figs. 11–12 and Table 5 for limits on states with different quantum numbers.

[149] For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 4 and Fig. 5.

[150] CHEKANOV 02 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 6–7 and Tables 5–6 for detailed limits.

[151] For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 3.

[152] See their Fig. 14 for limits in the mass-coupling plane.

[153] BREITWEG 00E search for F=0 leptoquarks in $e^+ p$ collisions. For limits in mass-coupling plane, see their Fig. 11.

[154] 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.

[155] 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.

[156] DERRICK 97 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 5–8 and Table 1 for detailed limits.

[157] Limit from single production in Z decay. The limit is for a leptoquark coupling of electromagnetic strength and assumes B(ℓq) = 2/3. The limit is 77 GeV if first and second leptoquarks are degenerate.

[158] DERRICK 93 search for single leptoquark production in $e p$ collisions with the decay $e q$ and νq. The limit is for leptoquark coupling of electromagnetic strength and assumes B($e q$) = B(νq) = 1/2. The limit for B($e q$) = 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	96	[159] ADLOFF	03	H1	First generation
		[160] CHEKANOV	02	ZEUS	Lepton-flavor violation
> 1.7	95	[161] CHEUNG	01B	RVUE	First generation
> 0.39	95	[162] ACCIARRI	00P	L3	$e^+ e^- \rightarrow q q$
> 1.5	95	[163] ADLOFF	00	H1	First generation
> 0.2	95	[164] BARATE	00I	ALEP	$e^+ e^-$
		[165] BARGER	00	RVUE	Cs
		[166] GABRIELLI	00	RVUE	Lepton flavor violation
> 0.74	95	[167] ZARNECKI	00	RVUE	S_1 leptoquark
		[168] ABBIENDI	99	OPAL	

$>$ 19.3	95	[169] ABE	98V	CDF	$B_s \to e^{\pm}\mu^{\mp}$, Pati-Salam type
		[170] ACCIARRI	98J	L3	$e^+e^- \to q\overline{q}$
		[171] ACKERSTAFF	98V	OPAL	$e^+e^- \to q\overline{q}$, $e^+e^- \to b\overline{b}$
$>$ 0.76	95	[172] DEANDREA	97	RVUE	$\widetilde{R}_2$ leptoquark
		[173] DERRICK	97	ZEUS	Lepton-flavor violation
		[174] GROSSMAN	97	RVUE	$B \to \tau^+\tau^-$ (X)
		[175] JADACH	97	RVUE	$e^+e^- \to q\overline{q}$
$>$1200		[176] KUZNETSOV	95B	RVUE	Pati-Salam type
		[177] MIZUKOSHI	95	RVUE	Third generation scalar leptoquark
$>$ 0.3	95	[178] BHATTACH...	94	RVUE	Spin-0 leptoquark coupled to $\overline{e}_R t_L$
		[179] DAVIDSON	94	RVUE	
$>$ 18		[180] KUZNETSOV	94	RVUE	Pati-Salam type
$>$ 0.43	95	[181] LEURER	94	RVUE	First generation spin-1 leptoquark
$>$ 0.44	95	[181] LEURER	94B	RVUE	First generation spin-0 leptoquark
		[182] MAHANTA	94	RVUE	P and T violation
$>$ 1		[183] SHANKER	82	RVUE	Nonchiral spin-0 leptoquark
$>$ 125		[183] SHANKER	82	RVUE	Nonchiral spin-1 leptoquark

[159] ADLOFF 03 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 3. Limits are derived from bounds on $e^{\pm}q$ contact interactions.

[160] 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.

[161] 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.

[162] 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.

[163] 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 $e^+p \to e^+$X.

[164] BARATE 00I search for deviations in cross section and jet-charge asymmetry in $e^+e^- \to \overline{q}q$ 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.

[165] BARGER 00 explain the deviation of atomic parity violation in cesium atoms from prediction is explained by scalar leptoquark exchange.

[166] GABRIELLI 00 calculate various process with lepton flavor violation in leptoquark models.

[167] 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.

[168] ABBIENDI 99 limits are from $e^+e^- \to q\overline{q}$ cross section at 130–136, 161–172, 183 GeV. See their Fig. 8 and Fig. 9 for limits in mass-coupling plane.

[169] ABE 98V quoted limit is from B($B_s \to e^{\pm}\mu^{\mp}$)$< 8.2 \times 10^{-6}$. ABE 98V also obtain a similar limit on $M_{LQ} > 20.4$ TeV from B($B_d \to e^{\pm}\mu^{\mp}$)$< 4.5 \times 10^{-6}$. Both

bounds assume the non-canonical association of the b quark with electrons or muons under SU(4).

[170] ACCIARRI 98J limit is from $e^+e^- \rightarrow q\overline{q}$ 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.

[171] ACKERSTAFF 98V limits are from $e^+e^- \rightarrow q\overline{q}$ and $e^+e^- \rightarrow b\overline{b}$ 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.

[172] DEANDREA 97 limit is for $\widetilde{R}_2$ 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.

[173] 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.

[174] 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.

[175] JADACH 97 limit is from $e^+e^- \rightarrow q\overline{q}$ 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.

[176] KUZNETSOV 95B use π, K, B, τ decays and μe 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.

[177] 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.

[178] 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 $\overline{e}_L\, t_R$, $\overline{\mu}\, t$, and $\overline{\tau}\, t$, see Fig. 2 in BHATTACHARYYA 94B erratum and Fig. 3.

[179] DAVIDSON 94 gives an extensive list of the bounds on leptoquark-induced four-fermion interactions from π, K, D, B, μ, τ decays and meson mixings, *etc.* See Table 15 of DAVIDSON 94 for detail.

[180] KUZNETSOV 94 gives mixing independent bound of the Pati-Salam leptoquark from the cosmological limit on $\pi^0 \rightarrow \overline{\nu}\nu$.

[181] 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.

[182] MAHANTA 94 gives bounds of P- and T-violating scalar-leptoquark couplings from atomic and molecular experiments.

[183] From $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$ ratio. SHANKER 82 assumes the leptoquark induced four-fermion coupling $4g^2/M^2$ $(\overline{\nu}_{eL}\, u_R)$ $(\overline{d}_L\, e_R)$with g=0.004 for spin-0 leptoquark and g^2/M^2 $(\overline{\nu}_{eL}\, \gamma_\mu u_L)$ $(\overline{d}_R\, \gamma^\mu e_R)$ 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	[184] ABE 97G	CDF	E_6 diquark
none 15–31.7	95	[185] ABREU 94O	DLPH	SUSY E_6 diquark

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

[185] ABREU 94O limit is from $e^+e^- \to \overline{c}\,\overline{s}\,c\,s$. 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	[186] DONCHESKI 98	RVUE	$\Gamma(Z \to$ hadron)
none 200–980	95	[187] ABE 97G	CDF	$p\overline{p} \to g_A X$, $X \to$ 2 jets
none 200–870	95	[188] ABE 95N	CDF	$p\overline{p} \to g_A X$, $g_A \to q\overline{q}$
none 240–640	95	[189] ABE 93G	CDF	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
$>$ 50	95	[190] CUYPERS 91	RVUE	$\sigma(e^+e^- \to$ hadrons)
none 120–210	95	[191] ABE 90H	CDF	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
$>$ 29		[192] ROBINETT 89	THEO	Partial-wave unitarity
none 150–310	95	[193] ALBAJAR 88B	UA1	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
$>$ 20		BERGSTROM 88	RVUE	$p\overline{p} \to \Upsilon X$ via $g_A g$
$>$ 9		[194] CUYPERS 88	RVUE	Υ decay
$>$ 25		[195] DONCHESKI 88B	RVUE	Υ decay

[186] DONCHESKI 98 compare α_s derived from low-energy data and that from $\Gamma(Z \to \text{hadrons})/\Gamma(Z \to \text{leptons})$.

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

[188] ABE 95N assume axigluons decaying to quarks in the Standard Model only.

[189] ABE 93G assume $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 10$.

[190] CUYPERS 91 compare α_s measured in Υ decay and that from R at PEP/PETRA energies.

[191] ABE 90H assumes $\Gamma(g_A) = N\alpha_s m_{g_A}/6$ with $N = 5\,(\Gamma(g_A) = 0.09 m_{g_A})$. For $N = 10$, the excluded region is reduced to 120–150 GeV.

[192] ROBINETT 89 result demands partial-wave unitarity of $J = 0$ $t\overline{t} \to t\overline{t}$ scattering amplitude and derives a limit $m_{g_A} > 0.5\ m_t$. Assumes $m_t > 56$ GeV.

[193] 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.

[194] CUYPERS 88 requires $\Gamma(\Upsilon \to g g_A) < \Gamma(\Upsilon \to g g g)$. A similar result is obtained by DONCHESKI 88.

[195] DONCHESKI 88B requires $\Gamma(\Upsilon \to g q\overline{q})/\Gamma(\Upsilon \to g g g) < 0.25$, 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*
• • • We do not use the following data for averages, fits, limits, etc. • • •				

		[196] BARATE 98U	ALEP	$X^0 \to \ell\overline{\ell}, q\overline{q}, gg, \gamma\gamma, \nu\overline{\nu}$
		[197] ACCIARRI 97Q	L3	$X^0 \to$ invisible particle(s)
		[198] ACTON 93E	OPAL	$X^0 \to \gamma\gamma$
		[199] ABREU 92D	DLPH	$X^0 \to$ hadrons
		[200] ADRIANI 92F	L3	$X^0 \to$ hadrons
		[201] ACTON 91	OPAL	$X^0 \to$ anything
$<1.1 \times 10^{-4}$	95	[202] ACTON 91B	OPAL	$X^0 \to e^+e^-$
$<9 \times 10^{-5}$	95	[202] ACTON 91B	OPAL	$X^0 \to \mu^+\mu^-$
$<1.1 \times 10^{-4}$	95	[202] ACTON 91B	OPAL	$X^0 \to \tau^+\tau^-$
$<2.8 \times 10^{-4}$	95	[203] ADEVA 91D	L3	$X^0 \to e^+e^-$
$<2.3 \times 10^{-4}$	95	[203] ADEVA 91D	L3	$X^0 \to \mu^+\mu^-$
$<4.7 \times 10^{-4}$	95	[204] ADEVA 91D	L3	$X^0 \to$ hadrons
$<8 \times 10^{-4}$	95	[205] AKRAWY 90J	OPAL	$X^0 \to$ hadrons

[196] BARATE 98U obtain limits on $\mathrm{B}(Z \to \gamma X^0)\mathrm{B}(X^0 \to \ell\overline{\ell}, q\overline{q}, gg, \gamma\gamma, \nu\overline{\nu})$. See their Fig. 17.

[197] See Fig. 4 of ACCIARRI 97Q for the upper limit on $\mathrm{B}(Z \to \gamma X^0;\ E_\gamma > E_{\mathrm{min}})$ as a function of E_{min}.

[198] ACTON 93E give $\sigma(e^+e^- \to X^0\gamma)\cdot\mathrm{B}(X^0 \to \gamma\gamma) < 0.4$ pb (95%CL) for $m_{X^0} = 60 \pm 2.5$ GeV. If the process occurs via *s*-channel γ exchange, the limit translates to $\Gamma(X^0)\cdot\mathrm{B}(X^0 \to \gamma\gamma)^2 < 20$ MeV for $m_{X^0} = 60 \pm 1$ GeV.

[199] ABREU 92D give $\sigma_Z \cdot \mathrm{B}(Z \to \gamma X^0) \cdot \mathrm{B}(X^0 \to \text{hadrons}) <$(3–10) pb for $m_{X^0} =$ 10–78 GeV. A very similar limit is obtained for spin-1 X^0.

[200] ADRIANI 92F search for isolated γ in hadronic Z decays. The limit $\sigma_Z \cdot \mathrm{B}(Z \to \gamma X^0) \cdot \mathrm{B}(X^0 \to \text{hadrons}) <$(2–10) pb (95%CL) is given for $m_{X^0} =$ 25–85 GeV.

[201] ACTON 91 searches for $Z \to Z^* X^0$, $Z^* \to e^+e^-$, $\mu^+\mu^-$, or $\nu\overline{\nu}$. Excludes any new scalar X^0 with $m_{X^0} < 9.5$ GeV/c if it has the same coupling to ZZ^* as the MSM Higgs boson.

[202] ACTON 91B limits are for $m_{X^0} =$ 60–85 GeV.

[203] ADEVA 91D limits are for $m_{X^0} =$ 30–89 GeV.

[204] ADEVA 91D limits are for $m_{X^0} =$ 30–86 GeV.

[205] AKRAWY 90J give $\Gamma(Z \to \gamma X^0)\cdot\mathrm{B}(X^0 \to \text{hadrons}) < 1.9$ MeV (95%CL) for $m_{X^0} =$ 32–80 GeV. We divide by $\Gamma(Z) = 2.5$ GeV to get product of branching ratios. For nonresonant transitions, the limit is $\mathrm{B}(Z \to \gamma q\overline{q}) < 8.2$ 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*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 55–61		[206] ODAKA 89	VNS	$\Gamma(X^0 \to e^+e^-) \cdot\mathrm{B}(X^0 \to \text{hadrons}) \gtrsim 0.2$ MeV
>45	95	[207] DERRICK 86	HRS	$\Gamma(X^0 \to e^+e^-)$=6 MeV
>46.6	95	[208] ADEVA 85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
>48	95	[208] ADEVA 85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
		[209] BERGER 85B	PLUT	

none 39.8–45.5		[210] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
$>$47.8	95	[210] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
none 39.8–45.2		[210] BEHREND	84C	CELL	
$>$47	95	[210] BEHREND	84C	CELL	$\Gamma(X^0 \to e^+e^-)$=4 MeV

[206] ODAKA 89 looked for a narrow or wide scalar resonance in $e^+e^- \to$ hadrons at $E_{\rm cm}$ = 55.0–60.8 GeV.

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

[208] ADEVA 85 first limit is from 2γ, $\mu^+\mu^-$, hadrons assuming X^0 is a scalar. Second limit is from e^+e^- channel. $E_{\rm cm}$ = 40–47 GeV. Supersedes ADEVA 84.

[209] BERGER 85B looked for effect of spin-0 boson exchange in $e^+e^- \to e^+e^-$ and $\mu^+\mu^-$ at $E_{\rm cm}$ = 34.7 GeV. See Fig. 5 for excluded region in the $m_{X^0} - \Gamma(X^0)$ plane.

[210] ADEVA 84 and BEHREND 84C have $E_{\rm cm}$ = 39.8–45.5 GeV. MARK-J searched X^0 in $e^+e^- \to$ hadrons, 2γ, $\mu^+\mu^-$, e^+e^- and CELLO in the same channels plus τ pair. No narrow or broad X^0 is found in the energy range. They also searched for the effect of X^0 with $m_X > E_{\rm cm}$. The second limits are from Bhabha data and for spin-0 singlet. The same limits apply for $\Gamma(X^0 \to e^+e^-)$ = 2 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 $\Gamma(X^0 \to e^+e^-) \cdot {\rm B}(X^0 \to f)$, where f is the specified final state. Spin 0 is assumed for X^0.

VALUE (keV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<10^3$	95	[211] ABE	93C	VNS	$\Gamma(ee)$
$<$(0.4–10)	95	[212] ABE	93C	VNS	$f = \gamma\gamma$
$<$(0.3–5)	95	[213,214] ABE	93D	TOPZ	$f = \gamma\gamma$
$<$(2–12)	95	[213,214] ABE	93D	TOPZ	f = hadrons
$<$(4–200)	95	[214,215] ABE	93D	TOPZ	$f = ee$
$<$(0.1–6)	95	[214,215] ABE	93D	TOPZ	$f = \mu\mu$
$<$(0.5–8)	90	[216] STERNER	93	AMY	$f = \gamma\gamma$

[211] Limit is for $\Gamma(X^0 \to e^+e^-)$ m_{X^0} = 56–63.5 GeV for $\Gamma(X^0)$ = 0.5 GeV.

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

[213] Limit is for m_{X^0} = 57.2–60 GeV.

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

[215] Limit is for m_{X^0} = 56.6–60 GeV.

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

Search for X^0 Resonance in ep Collisions

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[217] CHEKANOV	02B	ZEUS	$X \to jj$

[217] 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.

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.6	95	[218] ACTON	93E	OPAL	$m_{X^0}=60 \pm 1$ GeV
<2.9	95	BUSKULIC	93F	ALEP	$m_{X^0} \sim 60$ GeV

[218] ACTON 93E limit for a $J = 2$ resonance is 0.8 MeV.

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

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[219] ABBIENDI	03D	OPAL	$X^0 \rightarrow \gamma\gamma$
	[220] ABREU	00Z	DLPH	X^0 decaying invisibly
	[221] ADAM	96C	DLPH	X^0 decaying invisibly

[219] ABBIENDI 03D measure the $e^+ e^- \rightarrow \gamma\gamma\gamma$ cross section at $\sqrt{s}$=181–209 GeV. The upper bound on the production cross section, $\sigma(e^+ e^- \rightarrow X^0\gamma)$ times the branching ratio for $X^0 \rightarrow \gamma\gamma$, is less than 0.03 pb at 95%CL for X^0 masses between 20 and 180 GeV. See their Fig. 9b for the limits in the mass-cross section plane.

[220] 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.

[221] 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 $Z \rightarrow f\overline{f}X^0$

The limit is for $B(Z \rightarrow f\overline{f}X^0) \cdot B(X^0 \rightarrow F)$ 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. • • •					
		[222] ABREU	96T	DLPH	f=e,μ,τ; F=$\gamma\gamma$
$<3.7 \times 10^{-6}$	95	[223] ABREU	96T	DLPH	f=ν; F=$\gamma\gamma$
		[224] ABREU	96T	DLPH	f=q; F=$\gamma\gamma$
$<6.8 \times 10^{-6}$	95	[223] ACTON	93E	OPAL	f=e,μ,τ; F=$\gamma\gamma$
$<5.5 \times 10^{-6}$	95	[223] ACTON	93E	OPAL	f=q; F=$\gamma\gamma$
$<3.1 \times 10^{-6}$	95	[223] ACTON	93E	OPAL	f=ν; F=$\gamma\gamma$
$<6.5 \times 10^{-6}$	95	[223] ACTON	93E	OPAL	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
$<7.1 \times 10^{-6}$	95	[223] BUSKULIC	93F	ALEP	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
		[225] ADRIANI	92F	L3	f=q; F=$\gamma\gamma$

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

[223] Limit is for m_{X^0} around 60 GeV.

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

[225] ADRIANI 92F give $\sigma_Z \cdot \mathrm{B}(Z \to q\overline{q}X^0) \cdot \mathrm{B}(X^0 \to \gamma\gamma) < (0.75\text{–}1.5)$ pb (95%CL) for $m_{X^0} = 10\text{–}70$ GeV. The limit is 1 pb at 60 GeV.

Search for X^0 Resonance in $p\overline{p} \to WX^0$

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[226] ABE	97W	CDF	$X^0 \to b\overline{b}$

[226] ABE 97W search for X^0 production associated with W in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The 95%CL upper limit on the production cross section times the branching ratio for $X^0 \to b\overline{b}$ 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	[227] BALEST	95	CLE2	$\Upsilon(1S) \to X^0\gamma$, $m_{X^0} < 5$ GeV
$< 3 \times 10^{-5}\text{–}6 \times 10^{-3}$	90	[228] BALEST	95	CLE2	$\Upsilon(1S) \to X^0\overline{X}^0\gamma$, $m_{X^0} < 3.9$ GeV
$<5.6 \times 10^{-5}$	90	[229] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \to X^0\gamma$, $m_{X^0} < 7.2$ GeV
		[230] ALBRECHT	89	ARG	

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

[228] BALEST 95 three-body limit is for phase-space photon energy distribution and angular distribution same as for $\Upsilon \to gg\gamma$.

[229] ANTREASYAN 90C assume that X^0 does not decay in the detector.

[230] ALBRECHT 89 give limits for $\mathrm{B}(\Upsilon(1S), \Upsilon(2S) \to X^0\gamma) \cdot \mathrm{B}(X^0 \to \pi^+\pi^-, K^+K^-, p\overline{p})$ for $m_{X^0} < 3.5$ GeV.

REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

ABAZOV	04A	PRL 92 221801	V.M. Abazov *et al.*	(D0 Collab.)
ABAZOV	04C	PR D69 111101R	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	04G	EPJ C33 173	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	03D	EPJ C26 331	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	03R	EPJ C31 281	G. Abbiendi *et al.*	(OPAL)
ACOSTA	03B	PRL 90 081802	D. Acosta *et al.*	(CDF Collab.)
ADLOFF	03	PL B568 35	C. Adloff *et al.*	(H1 Collab.)
BARGER	03B	PR D67 075009	V. Barger, P. Langacker, H. Lee	
CHEKANOV	03B	PR D68 052004	S. Chekanov *et al.*	(ZEUS Collab.)
ABAZOV	02	PRL 88 191801	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	02B	PL B526 233	G. Abbiendi *et al.*	(OPAL Collab.)
AFFOLDER	02C	PRL 88 071806	T. Affolder *et al.*	(CDF Collab.)
CHEKANOV	02	PR D65 092004	S. Chekanov *et al.*	(ZEUS Collab.)
CHEKANOV	02B	PL B531 9	S. Chekanov *et al.*	(ZEUS Collab.)
MUECK	02	PR D65 085037	A. Mueck, A. Pilaftsis, R. Rueckl	

ABAZOV	01B	PRL 87 061802	V.M. Abazov *et al.*	(D0 Collab.)
ABAZOV	01D	PR D64 092004	V.M. Abazov *et al.*	(D0 Collab.)
ADLOFF	01C	PL B523 234	C. Adloff *et al.*	(H1 Collab.)
AFFOLDER	01I	PRL 87 231803	T. Affolder *et al.*	(CDF Collab.)
BREITWEG	01	PR D63 052002	J. Breitweg *et al.*	(ZEUS Collab.)
CHEUNG	01B	PL B517 167	K. Cheung	
THOMAS	01	NP A694 559	E. Thomas *et al.*	
ABBIENDI	00M	EPJ C13 15	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	00C	PRL 84 2088	B. Abbott *et al.*	(D0 Collab.)
ABE	00	PRL 84 5716	F. Abe *et al.*	(CDF Collab.)
ABREU	00S	PL B485 45	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	00P	PL B489 81	M. Acciarri *et al.*	(L3 Collab.)
ADLOFF	00	PL B479 358	C. Adloff *et al.*	(H1 Collab.)
AFFOLDER	00K	PRL 85 2056	T. Affolder *et al.*	(CDF Collab.)
BARATE	00I	EPJ C12 183	R. Barate *et al.*	(ALEPH Collab.)
BARGER	00	PL B480 149	V. Barger, K. Cheung	
BREITWEG	00E	EPJ C16 253	J. Breitweg *et al.*	(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 *et al.*	(OPAL Collab.)
ABBOTT	99J	PRL 83 2896	B. Abbott *et al.*	(D0 Collab.)
ABREU	99G	PL B446 62	P. Abreu *et al.*	(DELPHI Collab.)
ACKERSTAFF	99D	EPJ C8 3	K. Ackerstaff *et al.*	(OPAL Collab.)
ADLOFF	99	EPJ C11 447	C. Adloff *et al.*	(H1 Collab.)
Also	00C	EPJ C14 553 errata	C. Adloff *et al.*	(H1 Collab.)
CASALBUONI	99	PL B460 135	R. Casalbuoni *et al.*	
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 *et al.*	(D0 Collab.)
ABBOTT	98J	PRL 81 38	B. Abbott *et al.*	(D0 Collab.)
ABE	98S	PRL 81 4806	F. Abe *et al.*	(CDF Collab.)
ABE	98V	PRL 81 5742	F. Abe *et al.*	(CDF Collab.)
ACCIARRI	98J	PL B433 163	M. Acciarri *et al.*	(L3 Collab.)
ACKERSTAFF	98V	EPJ C2 441	K. Ackerstaff *et al.*	(OPAL Collab.)
BARATE	98U	EPJ C4 571	R. Barate *et al.*	(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-PILCH...	98	hep-ex/9810015	C. Grosso-Pilcher, G. Landsberg, M. Paterno	
ABE	97F	PRL 78 2906	F. Abe *et al.*	(CDF Collab.)
ABE	97G	PR D55 R5263	F. Abe *et al.*	(CDF Collab.)
ABE	97S	PRL 79 2192	F. Abe *et al.*	(CDF Collab.)
ABE	97W	PRL 79 3819	F. Abe *et al.*	(CDF Collab.)
ABE	97X	PRL 79 4327	F. Abe *et al.*	(CDF Collab.)
ACCIARRI	97Q	PL B412 201	M. Acciarri *et al.*	(L3 Collab.)
ARIMA	97	PR D55 19	T. Arima *et al.*	(VENUS Collab.)
BARENBOIM	97	PR D55 4213	G. Barenboim *et al.*	(VALE, IFIC)
DEANDREA	97	PL B409 277	A. Deandrea	(MARS)
DERRICK	97	ZPHY C73 613	M. Derrick *et al.*	(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 *et al.*	(D0 Collab.)
ABACHI	96D	PL B385 471	S. Abachi *et al.*	(D0 Collab.)
ABREU	96T	ZPHY C72 179	P. Abreu *et al.*	(DELPHI Collab.)
ADAM	96C	PL B380 471	W. Adam *et al.*	(DELPHI Collab.)
AID	96B	PL B369 173	S. Aid *et al.*	(H1 Collab.)
ALLET	96	PL B383 139	M. Allet *et al.*	(VILL, LEUV, LOUV, WISC)

ABACHI	95E	PL B358 405	S. Abachi *et al.*	(D0 Collab.)
ABE	95M	PRL 74 2900	F. Abe *et al.*	(CDF Collab.)
ABE	95N	PRL 74 3538	F. Abe *et al.*	(CDF Collab.)
BALEST	95	PR D51 2053	R. Balest *et al.*	(CLEO Collab.)
KUZNETSOV	95	PRL 75 794	I.A. Kuznetsov *et al.*	(PNPI, KIAE, HARV+)
KUZNETSOV	95B	PAN 58 2113 Translated from YAF 58 2228.	A.V. Kuznetsov, N.V. Mikheev	(YARO)
MIZUKOSHI	95	NP B443 20	J.K. Mizukoshi, O.J.P. Eboli, M.C. Gonzalez-Garcia	
ABREU	94O	ZPHY C64 183	P. Abreu *et al.*	(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 Translated from ZETFP 60 311.	I.A. Kuznetsov *et al.*	(PNPI, KIAE, HARV+)
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 *et al.*	(LOUV, WISC, LEUV+)
VILAIN	94B	PL B332 465	P. Vilain *et al.*	(CHARM II Collab.)
ABE	93C	PL B302 119	K. Abe *et al.*	(VENUS Collab.)
ABE	93D	PL B304 373	T. Abe *et al.*	(TOPAZ Collab.)
ABE	93G	PRL 71 2542	F. Abe *et al.*	(CDF Collab.)
ABREU	93J	PL B316 620	P. Abreu *et al.*	(DELPHI Collab.)
ACTON	93E	PL B311 391	P.D. Acton *et al.*	(OPAL Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani *et al.*	(L3 Collab.)
ALITTI	93	NP B400 3	J. Alitti *et al.*	(UA2 Collab.)
BHATTACH...	93	PR D47 R3693	G. Bhattacharyya *et al.*	(CALC, JADA, ICTP+)
BUSKULIC	93F	PL B308 425	D. Buskulic *et al.*	(ALEPH Collab.)
DERRICK	93	PL B306 173	M. Derrick *et al.*	(ZEUS Collab.)
RIZZO	93	PR D48 4470	T.G. Rizzo	(ANL)
SEVERIJNS	93	PRL 70 4047	N. Severijns *et al.*	(LOUV, WISC, LEUV+)
Also	94	PRL 73 611 (erratum)	N. Severijns *et al.*	(LOUV, WISC, LEUV+)
STERNER	93	PL B303 385	K.L. Sterner *et al.*	(AMY Collab.)
ABREU	92D	ZPHY C53 555	P. Abreu *et al.*	(DELPHI Collab.)
ADRIANI	92F	PL B292 472	O. Adriani *et al.*	(L3 Collab.)
DECAMP	92	PRPL 216 253	D. Decamp *et al.*	(ALEPH Collab.)
IMAZATO	92	PRL 69 877	J. Imazato *et al.*	(KEK, INUS, TOKY+)
MISHRA	92	PRL 68 3499	S.R. Mishra *et al.*	(COLU, CHIC, FNAL+)
POLAK	92B	PR D46 3871	J. Polak, M. Zralek	(SILES)
ACTON	91	PL B268 122	D.P. Acton *et al.*	(OPAL Collab.)
ACTON	91B	PL B273 338	D.P. Acton *et al.*	(OPAL Collab.)
ADEVA	91D	PL B262 155	B. Adeva *et al.*	(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 *et al.*	(HSCA, OSU, CHIC+)
ABE	90F	PL B246 297	K. Abe *et al.*	(VENUS Collab.)
ABE	90H	PR D41 1722	F. Abe *et al.*	(CDF Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy *et al.*	(OPAL Collab.)
ANTREASYAN	90C	PL B251 204	D. Antreasyan *et al.*	(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 *et al.*	(AMY Collab.)
LOPEZ	90	PL B241 392	J.L. Lopez, D.V. Nanopoulos	(TAMU)
ALBAJAR	89	ZPHY C44 15	C. Albajar *et al.*	(UA1 Collab.)
ALBRECHT	89	ZPHY C42 349	H. Albrecht *et al.*	(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 *et al.*	(VENUS Collab.)
ROBINETT	89	PR D39 834	R.W. Robinett	(PSU)
ALBAJAR	88B	PL B209 127	C. Albajar *et al.*	(UA1 Collab.)
BAGGER	88	PR D37 1188	J. Bagger, C. Schmidt, S. King	(HARV, BOST)
BALKE	88	PR D37 587	B. Balke *et al.*	(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 *et al.*	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	W. Bartel *et al.*	(JADE Collab.)
BEHREND	86B	PL B178 452	H.J. Behrend *et al.*	(CELLO Collab.)
DERRICK	86	PL 166B 463	M. Derrick *et al.*	(HRS Collab.)
Also	86B	PR D34 3286	M. Derrick *et al.*	(HRS Collab.)
JODIDIO	86	PR D34 1967	A. Jodidio *et al.*	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	A. Jodidio *et al.*	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909	R.N. Mohapatra	(UMD)
ADEVA	85	PL 152B 439	B. Adeva *et al.*	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	C. Berger *et al.*	(PLUTO Collab.)
STOKER	85	PRL 54 1887	D.P. Stoker *et al.*	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	B. Adeva *et al.*	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	H.J. Behrend *et al.*	(CELLO Collab.)
BERGSMA	83	PL 122B 465	F. Bergsma *et al.*	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr *et al.*	(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+)