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.

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 (CL = 90%)					
> 715	90	[1] CZAKON	99	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 137	95	[2] ACKERSTAFF	99D	OPAL	τ decay
>1400	68	[3] BARENBOIM	98	RVUE	Electroweak, Z-Z' mixing
> 549	68	[4] BARENBOIM	97	RVUE	μ decay
> 220	95	[5] STAHL	97	RVUE	τ decay
> 220	90	[6] ALLET	96	CNTR	β^+ decay
> 281	90	[7] KUZNETSOV	95	CNTR	Polarized neutron decay
> 282	90	[8] KUZNETSOV	94B	CNTR	Polarized neutron decay
> 439	90	[9] BHATTACH...	93	RVUE	Z-Z' mixing
> 250	90	[10] SEVERIJNS	93	CNTR	β^+ decay
		[11] IMAZATO	92	CNTR	K^+ decay
> 475	90	[12] POLAK	92B	RVUE	μ decay
> 240	90	[13] AQUINO	91	RVUE	Neutron decay
> 496	90	[13] AQUINO	91	RVUE	Neutron and muon decay
> 700		[14] COLANGELO	91	THEO	$m_{K^0_L} - m_{K^0_S}$
> 477	90	[15] POLAK	91	RVUE	μ decay
[none 540–23000]		[16] BARBIERI	89B	ASTR	SN 1987A; light ν_R
> 300	90	[17] LANGACKER	89B	RVUE	General
> 160	90	[18] BALKE	88	CNTR	$\mu \to e\nu\overline{\nu}$
> 406	90	[19] JODIDIO	86	ELEC	Any ζ
> 482	90	[19] JODIDIO	86	ELEC	$\zeta = 0$
> 800		MOHAPATRA	86	RVUE	$SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	[20] STOKER	85	ELEC	Any ζ
> 475	95	[20] STOKER	85	ELEC	$\zeta < 0.041$
		[21] BERGSMA	83	CHRM	$\nu_\mu e \to \mu\nu_e$
> 380	90	[22] CARR	83	ELEC	μ^+ decay
>1600		[23] BEALL	82	THEO	$m_{K^0_L} - m_{K^0_S}$
[> 4000]		STEIGMAN	79	COSM	Nucleosynthesis; light ν_R

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

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

[3] 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.

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

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

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

[7] 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.

[8] 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.

[9] 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.

[10] 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.

[11] 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 $|V^R_{us}|^2 = 1 - |V^R_{ud}|^2$.

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

[13] 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.

[14] 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.

[15] 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.

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

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

[18] 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.

[19] 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^+.

[20] 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.

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

[22] 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.

[23] BEALL 82 limit is obtained assuming that W_R contribution to K^0_L–K^0_S 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	[24] ACKERSTAFF	99D	OPAL	τ decay
$<$ 0.013	90	[25] CZAKON	99	RVUE	Electroweak
$<$ 0.0333		[26] BARENBOIM	97	RVUE	μ decay
$<$ 0.04	90	[27] MISHRA	92	CCFR	νN scattering
−0.0006 to 0.0028	90	[28] AQUINO	91	RVUE	
[none 0.00001–0.02]		[29] BARBIERI	89B	ASTR	SN 1987A
$<$ 0.040	90	[30] JODIDIO	86	ELEC	μ decay
−0.056 to 0.040	90	[30] JODIDIO	86	ELEC	μ decay

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

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

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

[27] 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 $\zeta^2(1-2m^2_{W_1}/m^2_{W_2}) < 0.0015$. The limit is independent of ν_R mass.

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

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

[30] First JODIDIO 86 result assumes $m_{W_R}=\infty$, second is for unconstrained m_{W_R}.

THE W' SEARCHES

Written October 1997 by K.S. Babu, C. Kolda, and J. March-Russell (IAS/Princeton).

Any electrically charged gauge boson outside of the Standard Model is generically denoted W'. A W' always couples to two different flavors of fermions, similar to the W boson. In particular, if a W' couples quarks to leptons it is a leptoquark gauge boson.

The most attractive candidate for W' is the W_R gauge boson associated with the left-right symmetric models [1]. These models seek to provide a spontaneous origin for parity violation in weak interactions. Here the gauge group is extended to

$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ with the Standard Model hypercharge identified as $Y = T_{3R} + (B–L)/2$, T_{3R} being the third component of $\mathrm{SU}(2)_R$. The fermions transform under the gauge group in a left-right symmetric fashion: $q_L(3,2,1,1/3) + q_R(3,1,2,1/3)$ for quarks and $\ell_L(1,2,1,-1) + \ell_R(1,1,2,-1)$ for leptons. Note that the model requires the introduction of right-handed neutrinos, which can facilitate the see-saw mechanism for explaining the smallness of the ordinary neutrino masses. A Higgs bidoublet $\Phi(1,2,2,0)$ is usually employed to generate quark and lepton masses and to participate in the electroweak symmetry breaking. Under left-right (or parity) symmetry, $q_L \leftrightarrow q_R$, $\ell_L \leftrightarrow \ell_R$, $W_L \leftrightarrow W_R$ and $\Phi \leftrightarrow \Phi^\dagger$.

After spontaneous symmetry breaking, the two W bosons of the model, W_L and W_R, will mix. The physical mass eigenstates are denoted as

$$W_1 = \cos\zeta\, W_L + \sin\zeta\, W_R, \qquad W_2 = -\sin\zeta\, W_L + \cos\zeta\, W_R \quad (1)$$

with W_1 identified as the observed W boson. The most general Lagrangian that describes the interactions of the $W_{1,2}$ with the quarks can be written as [2]

$$\mathcal{L} = -\frac{1}{\sqrt{2}}\overline{u}\gamma_\mu \Big[\Big(g_L \cos\zeta\, V^L P_L - g_R e^{i\omega} \sin\zeta\, V^R P_R \Big) W_1^\mu + \Big(g_L \sin\zeta\, V^L P_L + g_R e^{i\omega} \cos\zeta\, V^R P_R \Big) W_2^\mu \Big] d + h.c. \quad (2)$$

where $g_{L,R}$ are the $\mathrm{SU}(2)_{L,R}$ gauge couplings, $P_{L,R} = (1 \mp \gamma_5)/2$ and $V^{L,R}$ are the left- and right-handed CKM matrices in the quark sector. The phase ω reflects a possible complex mixing parameter in the W_L–W_R mass-squared matrix. Note that there is CP violation in the model arising from the right-handed currents even with only two generations. The Lagrangian for leptons is identical to that for quarks, with the replacements

$u \to \nu$, $d \to e$ and the identification of $V^{L,R}$ with the CKM matrices in the leptonic sector.

If parity invariance is imposed on the Lagrangian, then $g_L = g_R$. Furthermore, the Yukawa coupling matrices that arise from coupling to the Higgs bidoublet Φ will be Hermitian. If in addition the vacuum expectation values of Φ are assumed to be real, the quark and lepton mass matrices will also be Hermitian, leading to the relation $V^L = V^R$. Such models are called *manifest* left-right symmetric models and are approximately realized with a minimal Higgs sector [3]. If instead parity and CP are both imposed on the Lagrangian, then the Yukawa coupling matrices will be real symmetric and, after spontaneous CP violation, the mass matrices will be complex symmetric. In this case, which is known in the literature as *pseudo-manifest* left-right symmetry, $V^L = (V^R)^*$.

Indirect constraints: In minimal version of manifest or pseudo-manifest left-right symmetric models with $\omega = 0$ or π, there are only two free parameters, ζ and M_{W_2}, and they can be constrained from low energy processes. In the large M_{W_2} limit, stringent bounds on the angle ζ arise from three processes. (i) Nonleptonic K decays: The decays $K \to 3\pi$ and $K \to 2\pi$ are sensitive to small admixtures of right-handed currents. Assuming the validity of PCAC relations in the Standard Model it has been argued in Ref. 4 that the success in the $K \to 3\pi$ prediction will be spoiled unless $|\zeta| \leq 4 \times 10^{-3}$. (ii) $b \to s\gamma$: The amplitude for this process has an enhancement factor m_t/m_b relative to the Standard Model and thus can be used to constrain ζ yielding the limit $-0.01 \leq \zeta \leq 0.003$ [5]. (iii) Universality in weak decays: If the right-handed neutrinos are heavy, the right-handed admixture in the charged current will contribute to β decay and K decay, but not to the μ

decay. This will modify the extracted values of V^L_{ud} and V^L_{us}. Demanding that the difference not upset the three generation unitarity of the CKM matrix, a bound $|\zeta| \leq 10^{-3}$ has been derived [6].

If the ν_R are heavy, leptonic and semileptonic processes do not constrain ζ since the emission of ν_R will not be kinematically allowed. However, if the ν_R is light enough to be emitted in μ decay and β decay, stringent limits on ζ do arise. For example, $|\zeta| \leq 0.039$ can be obtained from polarized μ decay [7] in the large M_{W_2} limit of the manifest left-right model. Alternatively, in the $\zeta = 0$ limit, there is a constraint $M_{W_2} \geq 484$ GeV from direct W_2 exchange. For the constraint on the case in which M_{W_2} is not taken to be heavy, see Ref. 2. There are also cosmological and astrophysical constraints on M_{W_2} and ζ in scenarios with a light ν_R. During nucleosynthesis the process $e^+e^- \to \nu_R\overline{\nu}_R$, proceeding via W_2 exchange, will keep the ν_R in equilibrium leading to an overproduction of ^{4}He unless M_{W_2} is greater than about 1 TeV [8]. Likewise the ν_{eR} produced via $e^-_R p \to n\nu_R$ inside a supernova must not drain too much of its energy, leading to limits $M_{W_2} > 16$ TeV and $|\zeta| \leq 3 \times 10^{-5}$ [9]. Note that models with light ν_R do not have a see-saw mechanism for explaining the smallness of the neutrino masses, though other mechanisms may arise in variant models [10].

The mass of W_2 is severely constrained (independent of the value of ζ) from K_L–K_S mass-splitting. The box diagram with exchange of one W_L and one W_R has an anomalous enhancement and yields the bound $M_{W_2} \geq 1.6$ TeV [11] for the case of manifest or pseudo-manifest left-right symmetry. If the ν_R have Majorana masses, another constraint arises from neutrinoless double β decay. Combining the experimental limit from ^{76}Ge decay with arguments of vacuum stability, a limit of $M_{W_2} \geq 1.1$ TeV has been obtained [12].

Direct search limits: Limits on M_{W_2} from direct searches depend on the available decay channels of W_2. If ν_R is heavier than W_2, the decay $W_2^+ \rightarrow \ell_R^+ \nu_R$ will be forbidden kinematically. Assuming that ζ is small, the dominant decay of W_2 will be into dijets. UA2 [13] has excluded a W_2 in the mass range of 100 to 251 GeV in this channel. DØ excludes the mass range of 340 to 680 GeV [14], while CDF excludes the mass range of 300 to 420 GeV for such a W_2 [15]. If ν_R is lighter than W_2, the decay $W_2^+ \rightarrow e_R^+ \nu_R$ is allowed. The ν_R can then decay into $e_R W_R^*$, leading to an $eejj$ signature. DØ has a limit of $M_{W_2} > 720$ GeV if $m_{\nu_R} \ll M_{W_2}$; the bound weakens, for example, to 650 GeV for $m_{\nu_R} = M_{W_2}/2$ [16]. CDF finds $M_{W_2} > 652$ GeV if ν_R is stable and much lighter than W_2 [17]. All of these limits assume manifest or pseudo-manifest left-right symmetry. See [16] for some variations in the limits if the assumption of left-right symmetry is relaxed.

Alternative models: W' gauge bosons can also arise in other models. We shall briefly mention some such popular models, but for details we refer the reader to the original literature. The *alternate* left-right model [18] is based on the same gauge group as the left-right model, but arises in the following way: In E_6 unification, there is an option to identify the right-handed down quarks as $\mathrm{SU}(2)_R$ singlets or doublets. If they are $\mathrm{SU}(2)_R$ doublets, one recovers the conventional left-right model; if they are singlets it leads to the alternate left-right model. A similar ambiguity exists in the assignment of left-handed leptons; the alternate left-right model assigns them to a $(1, 2, 2, 0)$ multiplet. As a consequence, the ordinary neutrino remains exactly massless in the model. One important difference from the usual left-right model is that the limit from the K_L–K_S mass difference is no longer applicable, since the d_R do not couple to the W_R. There is also no limit from polarized μ decay, since the SU(2)$_R$ partner of e_R can receive a large Majorana mass. Other W' models include the un-unified Standard Model of Ref. 19 where there are two different SU(2) gauge groups, one each for the quarks and leptons; models with separate SU(2) gauge factors for each generation [20]; and the SU(3)$_C$ $\times$ SU(3)$_L$ $\times$ U(1) model of Ref. 21.

Leptoquark gauge bosons: The SU(3)$_C$ $\times$ U(1)$_{B-L}$ part of the gauge symmetry discussed above can be embedded into a simple SU(4)$_C$ gauge group [22]. The model then will contain leptoquark gauge boson as well, with couplings of the type $\{(\overline{e}_L\gamma_\mu d_L + \overline{\nu}_L\gamma_\mu u_L)W'^\mu + (L \rightarrow R)\}$. The best limit on such leptoquark W' comes from nonobservation of $K_L \rightarrow \mu e$, which requires $M_{W'} \geq 1400$ TeV; for the corresponding limits on less conventional leptoquark flavor structures, see Ref. 23. Thus such a W' is inaccessible to direct searches with present machines which are sensitive to vector leptoquark masses of order 300 GeV only.

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MASS LIMITS for W' (A 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*
>720	95	[31] ABACHI	96C	D0	$W' \rightarrow e\nu_e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 300–420	95	[32] ABE	97G	CDF	$W' \rightarrow q\overline{q}$
>610	95	[33] ABACHI	95E	D0	$W' \rightarrow e\nu_e$ and $W' \rightarrow \tau\nu_\tau \rightarrow e\nu\nu\overline{\nu}$
>652	95	[34] ABE	95M	CDF	$W' \rightarrow e\nu_e$
>251	90	[35] ALITTI	93	UA2	$W' \rightarrow q\overline{q}$
none 260–600	95	[36] RIZZO	93	RVUE	$W' \rightarrow q\overline{q}$
>520	95	[37] ABE	91F	CDF	$W' \rightarrow e\nu$, $\mu\nu$
none 101–158	90	[38] ALITTI	91	UA2	$W' \rightarrow q\overline{q}$
>220	90	[39] ALBAJAR	89	UA1	$W' \rightarrow e\nu$
>209	90	[40] ANSARI	87D	UA2	$W' \rightarrow e\nu$
>210	90	[41] ARNISON	86B	UA1	$W' \rightarrow e\nu$
>170	90	[42] ARNISON	83D	UA1	$W' \rightarrow e\nu$

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

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

[33] 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 $m_{W'}$.

[34] 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 neglibible.

[35] 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.

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

[37] ABE 91F assume leptonic branching ratio of 1/12 for each lepton flavor. The limit from the $e\nu$ ($\mu\nu$) mode alone is 490 (435) GeV. These limits apply to W_R if $m_{\nu_R} \lesssim 15$ GeV and ν_R does not decay in the detector. Cross section limit $\sigma \cdot \mathrm{B} <$ (1–10) pb is given for $m_{W'} = 100$–550 GeV; see Fig. 2.

[38] ALITTI 91 search is based on two-jet invariant mass spectrum, assuming $\mathrm{B}(W' \to q\overline{q}) = 67.6\%$. Limit on $\sigma \cdot \mathrm{B}$ as a function of two-jet mass is given in Fig. 7.

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

[40] See Fig. 5 of ANSARI 87D for the excluded region in the $m_{W'}$–$[(g_{W'q})^2\ \mathrm{B}(W' \to e\overline{\nu})]$ plane. Note that the quantity $(g_{W'q})^2\ \mathrm{B}(W' \to e\overline{\nu})$ is normalized to unity for the standard W couplings.

[41] ARNISON 86B find no excess at large p_T in 148 $W \to e\nu$ events. Set limit $\sigma \times \mathrm{B}(e\nu)$ <10 pb at CL = 90% at E_{cm} = 546 and 630 GeV.

[42] ARNISON 83D find among 47 $W \to e\nu$ candidates no event with excess p_T. Also set $\sigma \times \mathrm{B}(e\nu)$ <30 pb with CL = 90% at E_{cm} = 540 GeV.

THE Z' SEARCHES

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If the Standard Model is enhanced by additional gauge symmetries or embedded into a larger gauge group, there will arise new heavy gauge bosons, some of which generically are electrically neutral. Such a gauge boson is called a Z'. Consider the most general renormalizable Lagrangian describing the complete set of interactions of the neutral gauge bosons among themselves and with fermions, which is that of the Standard Model plus the following new pieces [1,2,3]:

$$\mathcal{L}_{Z'} = -\frac{1}{4}\widehat{F}'_{\mu\nu}\widehat{F}'^{\mu\nu} - \frac{\sin\chi}{2}\widehat{F}'_{\mu\nu}\widehat{F}^{\mu\nu} + \frac{1}{2}\widehat{M}^2_{Z'}\widehat{Z}'_\mu\widehat{Z}'^\mu + \delta\widehat{M}^2\,\widehat{Z}'_\mu\widehat{Z}^\mu - \frac{\widehat{g}'}{2}\sum_i \overline{\psi}_i\gamma^\mu(f^i_V - f^i_A\gamma^5)\psi_i\widehat{Z}'_\mu \qquad (1)$$

where $\widehat{F}_{\mu\nu}, \widehat{F}'_{\mu\nu}$ are the field strength tensors for the hypercharge $\widehat{B}_\mu$ gauge boson and the Z' respectively before any diagonalizations are performed, ψ_i are the matter fields with Z' vector and axial charges f^i_V and f^i_A, and $\widehat{Z}_\mu$ is the electroweak

Z boson in this basis. (See the Review on "Electroweak Model and Constraints on New Physics" for the Standard Model pieces of the Lagrangian.) The mass terms are assumed to come from spontaneous symmetry breaking via scalar expectation values. The above Lagrangian is general to all abelian and non-abelian extensions, except that $\chi = 0$ for the non-abelian case since then $\widehat{F}'_{\mu\nu}$ is not gauge invariant. Most analyses take $\chi = 0$ even for the abelian case.

Going to the physical eigenbasis requires diagonalizing both the gauge kinetic and mass terms, with mass eigenstates denoted Z_1 and Z_2, where we choose Z_1 to be the observed Z boson. The interaction Lagrangian for Z_1 has the form, to leading order in the mixing angle ξ ($s_W \equiv \sin\theta_W$, etc.):

$$\mathcal{L}_{Z_1} = -\frac{e}{2 s_W c_W}\left(1 + \frac{\alpha T}{2}\right)\overline{\psi}_i \gamma^\mu \left\{ \left(g_V^i + \xi \tilde{f}_V^i\right) - \left(g_A^i + \xi \tilde{f}_A^i\right)\gamma^5 \right\} \psi_i Z_{1\mu} \tag{2}$$

where

$$\xi \simeq \frac{-\cos\chi(\delta\widehat{M}^2 + \widehat{M}_Z^2 s_W \sin\chi)}{\widehat{M}_{Z'}^2 - \widehat{M}_Z^2\cos^2\chi + \widehat{M}_Z^2 s_W^2 \sin^2\chi + 2\,\delta\widehat{M}^2\, s_W \sin\chi}\ . \tag{3}$$

We have made the identifications $g_A^i = T_3^i$, $g_V^i = T_3^i - 2Q^i s_*^2$, $\tilde{f}_{V,A}^i = (\widehat{g}' s_W c_W / e\cos\chi) f_{V,A}^i$, and s_W^2 is identified to be the $s_{M_Z}^2$ defined in the "Electroweak Model and Constraints on New Physics" review. Note that the value of the weak angle that appears in the vector coupling is shifted by the S and T oblique parameters:

$$s_*^2 = s_W^2 + \frac{1}{s_W^2 - c_W^2}\left(\frac{1}{4}\alpha S - c_W^2 s_W^2 \alpha T\right)\ . \tag{4}$$

Recall that $\rho = 1 + \alpha T$ defines the usual ρ parameter. In the presence of Z–Z' mixing, the oblique parameters receive contributions [4]:

$$\begin{aligned}
\alpha S &= 4\xi c_W^2 s_W \tan\chi \\
\alpha T &= \xi^2 \left(\frac{M_{Z_2}^2}{M_{Z_1}^2} - 1 \right) + 2\xi s_W \tan\chi \\
\alpha U &= 0
\end{aligned} \tag{5}$$

to leading order in small ξ. These contributions are in addition to those coming from top quark and Higgs boson loops in the Standard Model. (This is in contrast to the "Electroweak Model and Constraints on New Physics" Review in which oblique parameters are defined to be zero for reference values of m_t and M_H.) Note that nonzero Z–Z' contributions to S arise only in the presence of kinetic mixing.

The corresponding $Z_2\overline{\psi}\psi$ interaction Lagrangian is:

$$\mathcal{L}_{Z_2} = -\frac{e}{2 s_W c_W} \overline{\psi}_i \gamma^\mu \left\{ \left(h_V^i - g_V^i \xi \right) - \left(h_A^i - g_A^i \xi \right) \gamma^5 \right\} \psi_i Z_{2\mu} \tag{6}$$

with the following definitions:

$$\begin{aligned}
h_V^i &= \tilde{f}_V^i + \widetilde{s}(T_3^i - 2Q^i) \tan\chi \\
h_A^i &= \tilde{f}_A^i + \widetilde{s} T_3^i \tan\chi \\
\widetilde{s} &= s_W + \frac{s_W^3}{c_W^2 - s_W^2} \left(\frac{1}{4 c_W^2} \alpha S - \frac{1}{2} \alpha T \right)
\end{aligned} \tag{7}$$

where the last equation defines a weak angle appropriate for the Z_2 interactions.

If the Z' charges are generation-dependent, there exist severe constraints in the first two generations coming from precision measurements such as the K_L–K_S mass splitting and $B(\mu \to 3e)$ owing to the lack of GIM suppression in the Z' interactions; however, constraints on a Z' which couples differently only to the third generation are somewhat weaker. (It will be assumed in the Z-pole constraint section that the Z' couples identically to all three generations of matter; all other results are general.) If the new Z' interactions commute with the Standard Model gauge group, then per generation, there are only five independent $Z'\overline{\psi}\psi$ couplings; we can choose them to be $\tilde{f}_V^u$, $\tilde{f}_A^u$, $\tilde{f}_V^d$, $\tilde{f}_V^e$, and $\tilde{f}_A^e$. All other couplings can be determined in terms of these, *e.g.*, $\tilde{f}_V^\nu = (\tilde{f}_V^e + \tilde{f}_A^e)/2$.

Canonical models: One of the prime motivations for an additional Z' has come from string theory in which certain compactifications lead naturally to an E_6 gauge group, or one of its subgroups. E_6 contains two U(1) factors beyond the Standard Model, a basis for which is formed by the two groups $\mathrm{U}(1)_\chi$ and $\mathrm{U}(1)_\psi$, defined via the decompositions $E_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\psi$ and $\mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1)_\chi$; one special case often encountered is $\mathrm{U}(1)_\eta$ where $Z_\eta = \sqrt{\frac{3}{8}} Z_\chi + \sqrt{\frac{5}{8}} Z_\psi$. The charges of the SM fermions under these U(1)'s, and a discussion of their experimental signals, can be found in Ref. 5.

It is also common to express experimental bounds in terms of a toy Z' usually denoted Z_{SM}. This Z_{SM}, of arbitrary mass, couples to the SM fermions identically to the usual Z.

Almost all analyses of Z' physics have worked with one of these canonical models and have assumed zero kinetic mixing at the weak scale.

Experimental constraints: There are three primary sets of constraints on the existence of a Z' which will be considered here: precision measurements of neutral-current processes at low energies, Z-pole constraints on Z–Z' mixing, and direct search constraints from production at very high energies. In principle, one usually expects other new states to appear at the same scale as the Z', including its symmetry-breaking sector and any additional fermions necessary for anomaly cancellation. However, because these states are highly model-dependent, we will not include searches for them, or Z' decays to them, in the bounds that follow.

Low-energy constraints: After the breaking of the new gauge group and the usual electroweak breaking, the Z of the Standard Model can mix with the Z', with mixing angle ξ defined above. As already discussed, this Z–Z' mixing implies a shift in the usual oblique parameters [S, T, U defined in Eq. (5)]. Current bounds on S and T translate into stringent constraints on the mixing angle, ξ, requiring $\xi \ll 1$; similar constraints on ξ arise from the LEP Z-pole data. Thus we will only consider the small-ξ limit henceforth.

Whether or not the new gauge interactions are parity violating, stringent constraints can arise from atomic parity violation (APV) and polarized electron-nucleon scattering experiments [6]. At low energies, the effective neutral-current Lagrangian is conventionally written:

$$\mathcal{L}_{\rm NC} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left\{ C_{1q} (\overline{e}\gamma_\mu\gamma^5 e)(\overline{q}\gamma^\mu q) + C_{2q} (\overline{e}\gamma_\mu e)(\overline{q}\gamma^\mu\gamma^5 q) \right\} \quad . \tag{8}$$

APV experiments are sensitive only to C_{1u} and C_{1d} (see the "Electroweak Model and Constraints on New Physics" Review for the nuclear weak charge, Q_W, in terms of the C_{1q}) where in the presence of the Z and Z':

$$C_{1q} = 2(1+\alpha T)(g_A^e + \xi \tilde{f}_A^e)(g_V^q + \xi \tilde{f}_V^q) + 2r(h_A^e - \xi g_A^e)(h_V^q - \xi g_V^q) \tag{9}$$

where $r = (M_{Z_1}/M_{Z_2})^2$. The r-dependent terms arise from Z_2 exchange and can interfere constructively or destructively with the Z_1 contribution. In the limit $\xi = r = 0$, this reduces to the Standard Model expression. Polarized electron scattering is sensitive to both the C_{1q} and C_{2q} couplings, again as discussed in the "Electroweak Model and Constraints on New Physics" Review. The C_{2q} can be derived from the expression for C_{1q} with the complete interchange $V \leftrightarrow A$.

Stringent limits also arise from neutrino-hadron scattering. One usually expresses experimental results in terms of the effective 4-fermion operators $(\overline{\nu}\gamma_\mu\nu)(\overline{q}_{L,R}\gamma^\mu q_{L,R})$ with coefficients $(2\sqrt{2}G_F)\epsilon_{L,R}(q)$. (Again, see the "Electroweak Model and Constraints on New Physics" Review.) In the presence of the Z and Z', the $\epsilon_{L,R}(q)$ are given by:

$$\begin{aligned}\epsilon_{L,R}(q) =& \frac{1+\alpha T}{2}\left\{(g_V^q \pm g_A^q)[1+\xi(\tilde{f}_V^\nu \pm \tilde{f}_A^\nu)] + \xi(\tilde{f}_V^q \pm \tilde{f}_A^q)\right\} \\ &+ \frac{r}{2}\left\{(h_V^q \pm h_A^q)(h_V^\nu \pm h_A^\nu) - \xi(g_V^q \pm g_A^q)(h_V^\nu \pm h_A^\nu)\right. \\ &\left. - \xi(h_V^q \pm h_A^q)\right\} \quad . \qquad (10)\end{aligned}$$

Again, the r-dependent terms arise from Z_2-exchange.

***Z*-pole constraints:** Electroweak measurements made at LEP and SLC while sitting on the Z resonance are generally sensitive to Z' physics only through the mixing with the Z unless the Z and Z' are very nearly degenerate, a possibility we ignore. Constraints on the allowed mixing angle and Z couplings arise by fitting all data simultaneously to the *ansatz* of Z–Z' mixing. For any observable, $\mathcal{O}$, the shift in that observable, $\Delta\mathcal{O}$, can be expressed (following the procedure of Ref. 7) as:

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} = \mathcal{A}_{\mathcal{O}}^S\,\alpha S + \mathcal{A}_{\mathcal{O}}^T\,\alpha T + \xi\sum_i \mathcal{B}_{\mathcal{O}}^{(i)}\tilde{f}^i \qquad (11)$$

where i runs over the 5 independent $Z'\overline{\psi}\psi$ couplings listed earlier (assuming a Z' couplings commute with the generation and gauge symmetries of the Standard Model; this is the only place where we enforce such a restriction). The coefficients $\mathcal{A}^{S,T}_{\mathcal{O}}$ and $\mathcal{B}^{(i)}_{\mathcal{O}}$, which are functions only of the Standard Model parameters, are given in Table 1. The first 5 observables are directly measured at LEP and SLC, while $\overline{A}_e$, $\overline{A}_b$ and $\overline{A}_c$ are measured via the asymmetries $\overline{A}^{(0,f)}_{FB} = \frac{3}{4}\overline{A}_e\overline{A}_f$ and $A^0_{LR} = \overline{A}_e$ as defined in the "Electroweak Model and Constraints on New Physics" Review. As an example, the shift in $\overline{A}_e$ due to Z' physics is given by

$$\frac{\Delta\overline{A}_e}{\overline{A}_e} = -24.9\,\alpha S + 17.7\,\alpha T - 26.7\,\xi\,\tilde{f}^e_V + 2.0\,\xi\,\tilde{f}^e_A \ . \qquad (12)$$

Table 1: Expansion coefficients for shifts in Z-pole observables normalized to the Standard Model value of the observable [7,3].

$\mathcal{O}$	$\mathcal{A}^S_{\mathcal{O}}$	$\mathcal{A}^T_{\mathcal{O}}$	$\mathcal{B}^{Vu}_{\mathcal{O}}$	$\mathcal{B}^{Au}_{\mathcal{O}}$	$\mathcal{B}^{Vd}_{\mathcal{O}}$	$\mathcal{B}^{Ve}_{\mathcal{O}}$	$\mathcal{B}^{Ae}_{\mathcal{O}}$
Γ_Z	-0.49	1.35	-0.89	-0.40	0.37	0.37	0
R_ℓ	-0.39	0.28	-1.3	-0.56	0.52	0.30	4.0
σ_h	0.046	-0.033	0.50	0.22	-0.21	-1.0	-4.0
R_b	0.085	-0.061	-1.4	-2.1	0.29	0	0
R_c	-0.16	0.12	2.7	4.1	-0.59	0	0
$\overline{A}_e$	-24.9	17.7	0	0	0	-26.7	2.0
$\overline{A}_b$	-0.32	0.23	0.71	0.71	-1.73	0	0
$\overline{A}_c$	-2.42	1.72	3.89	-1.49	0	0	0
M^2_W	-0.93	1.43	0	0	0	0	0

High-energy indirect constraints: At $\sqrt{s} < M_{Z_2}$, but off the Z_1 pole, strong constraints on new Z' physics arise from measurements of deviations of asymmetries and leptonic and hadronic cross sections from their Standard Model predictions. These processes are sensitive not only to Z–Z' mixing but also to direct Z_2 exchange primarily through γ–Z_2 and Z_1–Z_2 interference; therefore information on the Z_2 couplings and mass can be extracted that is not accessible via Z–Z' mixing alone.

Far below the Z_2 mass scale, experiment is only sensitive to the scaled Z_2 couplings $(\sqrt{s}/M_{Z_2}) \cdot h^i_{V,A}$ so the Z_2 mass and overall magnitude of the couplings cannot both be extracted. However as $\sqrt{s}$ approaches M_{Z_2} the Z_2 exchange can no longer be approximated by a contact interaction and the mass and couplings can be simultaneously extracted.

Z' studies done before LEP relied heavily on this approach; see, *e.g.*, Ref. 8. LEP has also done similar work using data collected above the Z peak; see, *e.g.*, Ref. 9. For indirect Z' searches at future facilities, see, *e.g.* Refs. 10 and 11.

Direct-search constraints: Finally, high-energy experiments have searched for on-shell Z' (here Z_2) production and decay. Searches can be classified by the initial state off of which the Z' is produced, and the final state into which the Z' decays; we will not include here exotic decays of a Z'. Experiments to date have been sensitive to Z' production via their coupling to quarks ($p\overline{p}$ colliders), to electrons (e^+e^-) or to both (ep).

For a heavy Z' ($M_{Z_2} \gg M_{Z_1}$), the best limits come from $p\overline{p}$ machines via Drell-Yan production and subsequent decay to charged leptons. For $M_{Z_2} > 600\,\mathrm{GeV}$, CDF [12] quotes limits on $\sigma(p\overline{p} \to Z_2 X) \cdot B(Z_2 \to \ell^+\ell^-) < 0.04\,\mathrm{pb}$ at 95% C.L. for $\ell = e + \mu$ combined; DØ [13] quotes $\sigma \cdot B < 0.025\,\mathrm{pb}$ for $\ell = e$.

For $M_{Z_2} < 600\,\mathrm{GeV}$, the mass dependence is complicated and one should refer to the original literature. For studies of the search capabilities of future facilities, see *e.g.* Ref. 10.

If the Z' has suppressed, or no, couplings to leptons (*i.e.*, it is leptophobic) then experimental sensitivities are much weaker. In particular, searches for a Z' via hadronic decays at DØ [14] are able to rule out a Z' with quark couplings identical to those of the Z only in the mass range $365\,\mathrm{GeV} < M_{Z_2} < 615\,\mathrm{GeV}$; CDF [15] cannot exclude even this range. Additionally, UA2 [16] finds $\sigma \cdot B(Z' \to jj) < 11.7\,\mathrm{pb}$ at 90% C.L. for $M_{Z'} > 200\,\mathrm{GeV}$ and more complicated bounds in the range $130\,\mathrm{GeV} < M_{Z'} < 200\,\mathrm{GeV}$.

For a light Z' ($M_{Z'} < M_Z$) direct searches in e^+e^- colliders have ruled out any Z' unless it has extremely weak couplings to leptons. For a combined analysis of the various pre-LEP experiments see Ref. 8.

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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*
>898 (CL = 95%)					
>898	95	[43] BARATE	00I	ALEP	e^+e^-
>690	95	[44] 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. • • •

>809	95	[45] ERLER	99	RVUE	Electroweak
>490	95	ABACHI	96D	D0	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
>505	95	[46] ABE	95	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
>398	95	[47] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>237	90	[48] ALITTI	93	UA2	$p\overline{p}$; $Z'_{SM} \rightarrow q\overline{q}$
none 260–600	95	[49] RIZZO	93	RVUE	$p\overline{p}$; $Z'_{SM} \rightarrow q\overline{q}$
>426	90	[50] ABE	90F	VNS	e^+e^-

[43] 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.

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

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

[46] ABE 97S find $\sigma(Z')\times$B(e^+e^-)< 350 fb for $m_{Z'} >$ 350 GeV at $\sqrt{s}$= 1.8 TeV.

[47] VILAIN 94B assume m_t = 150 GeV.

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

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

[50] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$. They fix m_W = 80.49 ± 0.43 ± 0.24 GeV and m_Z = 91.13 ± 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*
>564 (CL = 95%)					
>564	95	[51] ERLER	99	RVUE	Electroweak
>630	95	[52] ABE	97S	CDF	$p\overline{p}$; $Z'_{LR} \rightarrow e^+e^-$, $\mu^+\mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>436	95	[53] BARATE	00I	ALEP	e^+e^-
>550	95	[54] CHAY	00	RVUE	Electroweak
		[55] ERLER	00	RVUE	Cs
>230	95	[56] ABREU	99A	DLPH	e^+e^-
		[57] CASALBUONI	99	RVUE	Cs
(> 1205)	90	[58] CZAKON	99	RVUE	Electroweak
(> 1673)	95	[59] ERLER	99	RVUE	Electroweak
(> 1700)	68	[60] BARENBOIM	98	RVUE	Electroweak

>244	95	[61] CONRAD	98	RVUE	$\nu_\mu N$ scattering
>190	95	[62] BARATE	97B	ALEP	$e^+e^- \rightarrow \mu^+\mu^-$ and hadronic cross section
>445	95	[63] ABE	95	CDF	$p\overline{p}$; $Z'_{LR} \rightarrow e^+e^-$
>253	95	[64] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>130	95	[65] ADRIANI	93D	L3	Z parameters
(> 1500)	90	[66] ALTARELLI	93B	RVUE	Z parameters
none 200–600	95	[67] RIZZO	93	RVUE	$p\overline{p}$; $Z_{LR} \rightarrow q\overline{q}$
$[> 2000]$		WALKER	91	COSM	Nucleosynthesis; light ν_R
none 200–500		[68] GRIFOLS	90	ASTR	SN 1987A; light ν_R
none 350–2400		[69] BARBIERI	89B	ASTR	SN 1987A; light ν_R

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

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

[53] 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.

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

[55] 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.

[56] ABREU 99A give 95%CL limit on the Z-Z' mixing $|\theta| < 0.0031$. For the limit contour in the mass-mixing plane, see their Fig. 16. Data taken at $\sqrt{s}$= 130–172 GeV.

[57] 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.

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

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

[60] 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.

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

[62] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.0017 < \theta < 0.0035$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+150}_{-\ 90}$ GeV. Data taken at $\sqrt{s}$=20–136 GeV.

[63] ABE 97S find $\sigma(Z')\times$B$(e^+e^-)<$ 350 fb for $m_{Z'} > 350$ GeV at $\sqrt{s}$= 1.8 TeV. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

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

[65] ADRIANI 93D give limits on the Z-Z' mixing $-0.002 < \theta < 0.015$ assuming $m_{Z'} > 310$ GeV.

[66] ALTARELLI 93B limit is from LEP data available in summer '93 and is for $m_t = 110$ GeV. $m_H = 100$ GeV and $\alpha_s = 0.118$ assumed. The limit improves for larger m_t (see their Fig. 5). The 90%CL limit on the Z-Z' mixing angle is in Table 4.

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

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

[69] 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) $\rightarrow$ 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*
>545 (CL = 95%)					
>545	95	[70] ERLER	99	RVUE	Electroweak
>595	95	[71] 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. • • •					
>533	95	[72] BARATE	00I	ALEP	e^+e^-
		[73] ERLER	00	RVUE	Cs
		[74] ROSNER	00	RVUE	Cs
>250	95	[75] ABREU	99A	DLPH	e^+e^-
(> 1368)	95	[76] ERLER	99	RVUE	Electroweak
>470	95	[77] CHO	98	RVUE	
>451	95	[78] CHO	98B	RVUE	Electroweak
>215	95	[79] CONRAD	98	RVUE	$\nu_\mu N$ scattering
>190	95	[80] ARIMA	97	VNS	Bhabha scattering
>236	95	[81] BARATE	97B	ALEP	$e^+e^- \rightarrow \mu^+\mu^-$ and hadronic cross section
>425	95	[82] ABE	95	CDF	$p\overline{p}$; $Z'_\chi \rightarrow e^+e^-$
>147	95	[83] ABREU	95M	DLPH	Z parameters and $e^+e^- \rightarrow \mu^+\mu^-$
>262	95	[84] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>117	95	[85] ADRIANI	93D	L3	Z parameters
(>900)	90	[86] ALTARELLI	93B	RVUE	Z parameters
[>1470]		[87] FARAGGI	91	COSM	Nucleosynthesis; light ν_R
>231	90	[88] ABE	90F	VNS	e^+e^-
[> 1140]		[89] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 2100]		[90] GRIFOLS	90	ASTR	SN 1987A; light ν_R

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

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

[72] 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.

[73] 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.

[74] ROSNER 00 discusses the possiblitiy 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.

[75] ABREU 99A give 95%CL limit on the Z-Z' mixing $|\theta| < 0.0033$. For the limit contour in the mass-mixing plane, see their Fig. 16. Data taken at $\sqrt{s}$= 130–172 GeV.

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

[77] CHO 98 limit is from constraints on four-Fermi contact interactions obtained from low-energy electroweak experiments, and assumes no Z-Z' mixing.

[78] CHO 98B use various electroweak data to constrain Z' models assuming m_H=100 GeV. ρ=1 is not assumed. See their Eq. (4.8) for their fit in mass-mixing plane, and Table 10 for limits assuming E_6-motivated Higgs sector.

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

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

[81] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.0016 < \theta < 0.0036$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+150}_{-\ 90}$ GeV. Data was taken at $\sqrt{s}$= 20–136 GeV.

[82] ABE 95 limit is obtained assuming that Z' decays to known fermions only. See their Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[83] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

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

[85] ADRIANI 93D give limits on the Z-Z' mixing $-0.004 < \theta < 0.015$ assuming the ABE 92B mass limit.

[86] ALTARELLI 93B limit is from LEP data available in summer '93 and is for m_t = 110 GeV. m_H = 100 GeV and α_s = 0.118 assumed. The limit improves for larger m_t (see their Fig. 5). The 90%CL limit on the Z-Z' mixing angle is in their Fig. 2.

[87] 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.

[88] 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.

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

[90] 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*
>294 (CL = 95%)					
>294	95	[91] BARATE	00I	ALEP	e^+e^-
>590	95	[92] 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. • • •					
>280	95	[93] ABREU	99A	DLPH	e^+e^-
>146	95	[94] ERLER	99	RVUE	Electroweak
>140	95	[95] CHO	98	RVUE	
>136	95	[96] CHO	98B	RVUE	Electroweak

$>$ 54	95	[97] CONRAD	98	RVUE	$\nu_\mu N$ scattering
$>$160	95	[98] BARATE	97B	ALEP	$e^+e^- \to \mu^+\mu^-$ and hadronic cross section
$>$415	95	[99] ABE	95	CDF	$p\overline{p}$; $Z'_\psi \to e^+e^-$
$>$105	95	[100] ABREU	95M	DLPH	Z parameters and $e^+e^- \to \mu^+\mu^-$
$>$135	95	[101] VILAIN	94B	CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
$>$118	95	[102] ADRIANI	93D	L3	Z parameters
$>$105	90	[103] ABE	90F	VNS	e^+e^-
[$>$ 160]		[104] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[$>$ 2000]		[105] GRIFOLS	90D	ASTR	SN 1987A; light ν_R

[91] 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.

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

[93] ABREU 99A give 95%CL limit on the Z-Z' mixing $|\theta| <$ 0.0021. For the limit contour in the mass-mixing plane, see their Fig. 16. Data taken at $\sqrt{s}$= 130–172 GeV.

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

[95] CHO 98 limit is from constraints on four-Fermi contact interactions obtained from low-energy electroweak experiments and assumes no Z-Z' mixing.

[96] CHO 98B use various electroweak data to constrain Z' models. See their Eq. (4.9) for their fit in mass-mixing plane.

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

[98] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.0020 < \theta < 0.0038$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+150}_{-\ 90}$ GeV. Data taken at $\sqrt{s}$= 20–136 GeV.

[99] See ABE 95 Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[100] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

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

[102] ADRIANI 93D give limits on the Z-Z' mixing $-0.003 < \theta < 0.020$ assuming the ABE 92B mass limit.

[103] 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.

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

[105] 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
>365 (CL = 95%)					
>365	95	[106] ERLER	99	RVUE	Electroweak
>620	95	[107] 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. • • •					
>329	95	[108] BARATE	00I	ALEP	e^+e^-
>200	95	[109] ABREU	99A	DLPH	e^+e^-
>340	95	[110] CHO	98	RVUE	
>317	95	[111] CHO	98B	RVUE	Electroweak
> 87	95	[112] CONRAD	98	RVUE	$\nu_\mu N$ scattering
>173	95	[113] BARATE	97B	ALEP	$e^+e^- \rightarrow \mu^+\mu^-$ and hadronic cross section
>440	95	[114] ABE	95	CDF	$p\overline{p}$; $Z'_{\eta} \rightarrow e^+e^-$
>109	95	[115] ABREU	95M	DLPH	Z parameters and $e^+e^- \rightarrow \mu^+\mu^-$
>100	95	[116] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
>100	95	[117] ADRIANI	93D	L3	Z parameters
(>500)	90	[118] ALTARELLI	93B	RVUE	Z parameters
>125	90	[119] ABE	90F	VNS	e^+e^-
[> 820]		[120] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 3300]		[121] GRIFOLS	90	ASTR	SN 1987A; light ν_R
[> 1040]		[120] LOPEZ	90	COSM	Nucleosynthesis; light ν_R

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

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

[108] 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.

[109] ABREU 99A give 95%CL limit on the Z-Z' mixing $|\theta| < 0.0046$. For the limit contour in the mass-mixing plane, see their Fig. 16. Data taken at $\sqrt{s}$= 130–172 GeV.

[110] CHO 98 limit is from constraints on four-Fermi contact interactions obtained from low-energy electroweak experiments, and assumes no Z-Z' mixing.

[111] CHO 98B use various electroweak data to constrain Z' models assuming m_H=100 GeV. ρ=1 is not assumed. See their Eq. (4.8) for their fit in mass-mixing plane, and Table 10 for limits assuming E_6-motivated Higgs sector.

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

[113] BARATE 97B gives 95% CL limits on Z-Z' mixing $-0.021 < \theta < 0.012$. The bounds are computed with $\alpha_s = 0.120 \pm 0.003$, $m_t = 175 \pm 6$ GeV, and $M_H = 150^{+150}_{-\ 90}$ GeV. Data was taken at $\sqrt{s}$= 20–136 GeV.

[114] See ABE 95 Fig. 3 for the mass bound of Z' decaying to all allowed fermions and supersymmetric fermions.

[115] ABREU 95M limit is for α_s=0.123, m_t=150 GeV, and m_H=300 GeV. For the limit contour in the mass-mixing plane, see their Fig. 13.

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

[117] ADRIANI 93D give limits on the Z-Z' mixing $-0.029 < \theta < 0.010$ assuming the ABE 92B mass limit.

[118] ALTARELLI 93B limit is from LEP data available in summer '93 and is for $m_t = 110$ GeV. $m_H = 100$ GeV and $\alpha_s = 0.118$ assumed. The 90%CL limit on the Z-Z' mixing angle is in Fig. 2.

[119] 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.

[120] 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).

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

Limits for other Z'

$Z_\beta = Z_\chi \cos\beta + Z_\psi \sin\beta$

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[122] CHO	98	RVUE	E_6-motivated
	[123] CHO	98B	RVUE	E_6-motivated

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

[123] CHO 98B use various electroweak data to constrain Z' models.

LEPTOQUARK QUANTUM NUMBERS

Written December 1997 by M. Tanabashi (Tohoku U.).

Leptoquarks are particles carrying both baryon number (B) and lepton number (L). They are expected to exist in various extensions of the Standard Model (SM). The possible quantum numbers of leptoquark states can be restricted by assuming that their direct interactions with the ordinary SM fermions are dimensionless and invariant under the SM gauge group. Table 1 shows the list of all possible quantum numbers with this assumption [1]. The columns of $\mathrm{SU}(3)_C$, $\mathrm{SU}(2)_W$, and $\mathrm{U}(1)_Y$ in Table 1 indicate the QCD representation, the weak isospin representation, and the weak hypercharge, respectively. Naming conventions of leptoquark states are taken from Ref. 1. The spin of a leptoquark state is taken to be 1 (vector leptoquark) or 0 (scalar leptoquark).

Table 1: Possible leptoquarks and their quantum numbers.

Leptoquarks	Spin	$3B+L$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_W$	$\mathrm{U}(1)_Y$
S_1	0	-2	$\bar{3}$	1	1/3
$\tilde{S}_1$	0	-2	$\bar{3}$	1	4/3
S_3	0	-2	$\bar{3}$	3	1/3
V_2	1	-2	$\bar{3}$	2	5/6
$\tilde{V}_2$	1	-2	$\bar{3}$	2	$-1/6$
R_2	0	0	3	2	7/6
$\tilde{R}_2$	0	0	3	2	1/6
U_1	1	0	3	1	2/3
$\tilde{U}_1$	1	0	3	1	5/3
U_3	1	0	3	3	2/3

If we do not require leptoquark states to couple directly with SM fermions, different assignments of quantum numbers become possible.

The Pati-Salam model [2] is an example predicting the existence of a leptoquark state. In this model a vector leptoquark appears at the scale where the Pati-Salam SU(4) "color" gauge group breaks into the familiar QCD $\mathrm{SU}(3)_C$ group (or $\mathrm{SU}(3)_C \times \mathrm{U}(1)_{B-L}$). The Pati-Salam leptoquark is a weak isosinglet and its hypercharge is 2/3 (U_1 leptoquark in Table 1). The coupling strength of the Pati-Salam leptoquark is given by the QCD coupling at the Pati-Salam symmetry breaking scale.

Bounds on leptoquark states are obtained both directly and indirectly. Direct limits are from their production cross sections at colliders, while indirect limits are calculated from the bounds on the leptoquark induced four-fermion interactions which are obtained from low energy experiments.

The pair production cross sections of leptoquarks are evaluated from their interactions with gauge bosons. The gauge couplings of a scalar leptoquark are determined uniquely according to its quantum numbers in Table 1. The magnetic-dipole-type and the electric-quadrupole-type interactions of a vector leptoquark are, however, not determined even if we fix its gauge quantum numbers as listed in the table [3]. We need extra assumptions about these interactions to evaluate the pair production cross section for a vector leptoquark.

If a leptoquark couples to fermions of more than a single generation in the mass eigenbasis of the SM fermions, it can induce four-fermion interactions causing flavor-changing-neutral-currents and lepton-family-number violations. Non-chiral leptoquarks, which couple simultaneously to both left- and right-handed quarks, cause four-fermion interactions affecting the $(\pi \to e\nu)/(\pi \to \mu\nu)$ ratio [4]. Indirect limits provide stringent constraints on these leptoquarks. Since the Pati-Salam leptoquark has non-chiral coupling with both e and μ, indirect limits from the bounds on $K_L \to \mu e$ lead to severe bounds on the Pati-Salam leptoquark mass. For detailed bounds obtained in this way, see the Boson Particle Listings for "Indirect Limits for Leptoquarks" and its references.

It is therefore often assumed that a leptoquark state couples only to a single generation in a chiral interaction, where indirect limits become much weaker. This assumption gives strong constraints on concrete models of leptoquarks, however. Leptoquark states which couple only to left- or right-handed quarks are called chiral leptoquarks. Leptoquark states which couple only to the first (second, third) generation are referred as the first (second, third) generation leptoquarks in this section.

Reference

1. W. Buchmüller, R. Rückl, and D. Wyler, Phys. Lett. **B191**, 442 (1987).
2. J.C. Pati and A. Salam, Phys. Rev. **D10**, 275 (1974).
3. J. Blümlein, E. Boos, and A. Kryukov, Z. Phys. **C76**, 137 (1997).
4. O. Shanker, Nucl. Phys. **B204**, 375 (1982).

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*
>202 (CL = 95%)						
>200	95		[124] ABBOTT	00C	D0	Second generation
>225	95		[125] ABBOTT	98E	D0	First generation
> 94	95		[126] ABBOTT	98J	D0	Third generation
>202	95		[127] ABE	98S	CDF	Second generation
> 99	95		[128] ABE	97F	CDF	Third generation
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>160	95		[129] ABBOTT	99J	D0	Second generation
>213	95		[130] ABE	97X	CDF	First generation
> 45.5	95		[131,132] ABREU	93J	DLPH	First + second generation
> 44.4	95		[133] ADRIANI	93M	L3	First generation
> 44.5	95		[133] ADRIANI	93M	L3	Second generation
> 45	95		[133] DECAMP	92	ALEP	Third generation
none 8.9–22.6	95		[134] KIM	90	AMY	First generation
none 10.2–23.2	95		[134] KIM	90	AMY	Second generation
none 5–20.8	95		[135] BARTEL	87B	JADE	
none 7–20.5	95	2	[136] BEHREND	86B	CELL	

[124] ABBOTT 00C search for scalar leptoquarks using $\mu\mu jj$, $\mu\nu jj$, and $\nu\nu jj$ events in $p\overline{p}$ collisions at $E_{\rm cm}$=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.

[125] 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.

[126] 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.

[127] 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.

[128] 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.

[129] 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.

[130] ABBOTT 97B, 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.

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

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

[133] 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.

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

[135] 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.

[136] 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
>200 (CL = 95%)					
>200	95	[137] ADLOFF	99	H1	First generation
> 73	95	[138] ABREU	93J	DLPH	Second generation
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>161	95	[139] ABREU	99G	DLPH	First generation
		[140] DERRICK	97	ZEUS	Lepton-flavor violation
>237	95	[141] AID	96B	H1	First generation
> 65	95	[138] ABREU	93J	DLPH	First generation
>168	95	[142] DERRICK	93	ZEUS	First generation

[137] 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.

[138] 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.

[139] 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.

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

[141] AID 96B also search for leptoquarks with lepton-flavor violating couplings. For limits on states with different quantum numbers and the limits in the coupling-mass plane, see their Fig. 2, Fig. 3, and Table 2.

[142] 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. • • •					
> 0.2	95	[143] BARATE	00I	ALEP	e^+e^-
		[144] ABBIENDI	99	OPAL	
> 19.3	95	[145] ABE	98V	CDF	$B_s \rightarrow e^{\pm}\mu^{\mp}$, Pati-Salam type
		[146] ACCIARRI	98J	L3	$e^+e^- \rightarrow q\overline{q}$
		[147] ACKERSTAFF	98V	OPAL	$e^+e^- \rightarrow q\overline{q}$, $e^+e^- \rightarrow b\overline{b}$
> 0.76	95	[148] DEANDREA	97	RVUE	$\widetilde{R}_2$ leptoquark
		[149] DERRICK	97	ZEUS	Lepton-flavor violation
		[150] GROSSMAN	97	RVUE	$B \rightarrow \tau^+\tau^-$(X)
		[151] JADACH	97	RVUE	$e^+e^- \rightarrow q\overline{q}$
> 0.31	95	[152] AID	95	H1	First generation
>1200		[153] KUZNETSOV	95B	RVUE	Pati-Salam type
		[154] MIZUKOSHI	95	RVUE	Third generation scalar leptoquark
> 0.3	95	[155] BHATTACH...	94	RVUE	Spin-0 leptoquark coupled to $\overline{e}_R t_L$
		[156] DAVIDSON	94	RVUE	
> 18		[157] KUZNETSOV	94	RVUE	Pati-Salam type
> 0.43	95	[158] LEURER	94	RVUE	First generation spin-1 leptoquark
> 0.44	95	[158] LEURER	94B	RVUE	First generation spin-0 leptoquark
		[159] MAHANTA	94	RVUE	*P* and *T* violation
> 350		[160] DESHPANDE	83	RVUE	Sup. by KUZNETSOV 95B
> 1		[161] SHANKER	82	RVUE	Nonchiral spin-0 leptoquark
> 125		[161] SHANKER	82	RVUE	Nonchiral spin-1 leptoquark

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

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

[145] ABE 98V quoted limit is from B($B_s \rightarrow e^{\pm}\mu^{\mp}$)< 8.2×10^{-6}. ABE 98V also obtain a similar limit on $M_{LQ} >$ 20.4 TeV from B($B_d \rightarrow e^{\pm}\mu^{\mp}$)< 4.5×10^{-6}. Both bounds assume the non-canonical association of the *b* quark with electrons or muons under SU(4).

[146] 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.

[147] 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.

[148] 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.

[149] DERRICK 97 search for lepton-flavor violation in $e p$ collision. See their Tables 2–5 for limits on lepton-flavor violating four-fermion interactions induced by various leptoquarks.

[150] 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.

[151] 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.

[152] AID 95 limit is for the weak isotriplet spin-1 leptoquark with the electromagnetic coupling strength. For the limits of leptoquarks with different quantum number, see their Table 2. AID 95 limits are from the measurements of the Q^2 spectrum measurement of $e p \rightarrow e X$.

[153] 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. See also KUZNETSOV 94, DESHPANDE 83, and DIMOPOULOS 81.

[154] 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.

[155] 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.

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

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

[158] 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. See also SHANKER 82.

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

[160] DESHPANDE 83 used upper limit on $K^0_L \rightarrow \mu e$ decay with renormalization-group equations to estimate coupling at the heavy boson mass. See also DIMOPOULOS 81.

[161] 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	[162] ABE	97G	CDF	E_6 diquark
none 15–31.7	95	[163] ABREU	94O	DLPH	SUSY E_6 diquark

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

[163] ABREU 94O limit is from $e^+ e^- \rightarrow \overline{c}\,\overline{s}\,c\,s$. 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	[164] DONCHESKI	98	RVUE	$\Gamma(Z \to$ hadron)
none 200–980	95	[165] ABE	97G	CDF	$p\overline{p} \to g_A X$, $X \to 2$ jets
none 200–870	95	[166] ABE	95N	CDF	$p\overline{p} \to g_A X$, $g_A \to q\overline{q}$
none 240–640	95	[167] ABE	93G	CDF	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
> 50	95	[168] CUYPERS	91	RVUE	$\sigma(e^+e^- \to$ hadrons)
none 120–210	95	[169] ABE	90H	CDF	$p\overline{p} \to g_A X$, $g_A \to$ 2jets
> 29		[170] ROBINETT	89	THEO	Partial-wave unitarity
none 150–310	95	[171] 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		[172] CUYPERS	88	RVUE	Υ decay
> 25		[173] DONCHESKI	88B	RVUE	Υ decay

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

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

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

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

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

[169] 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.

[170] 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.

[171] 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.

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

[173] DONCHESKI 88B requires $\Gamma(\Upsilon \to g q\overline{q})/\Gamma(\Upsilon \to ggg) < 0.25$, 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. • • •					
		[174] BARATE	98U	ALEP	$X^0 \to \ell\overline{\ell}, q\overline{q}, gg, \gamma\gamma, \nu\overline{\nu}$
		[175] ACCIARRI	97Q	L3	$X^0 \to$ invisible particle(s)
		[176] ACTON	93E	OPAL	$X^0 \to \gamma\gamma$
		[177] ABREU	92D	DLPH	$X^0 \to$ hadrons
		[178] ADRIANI	92F	L3	$X^0 \to$ hadrons
		[179] ACTON	91	OPAL	$X^0 \to$ anything
$<1.1 \times 10^{-4}$	95	[180] ACTON	91B	OPAL	$X^0 \to e^+e^-$
$<9 \times 10^{-5}$	95	[180] ACTON	91B	OPAL	$X^0 \to \mu^+\mu^-$
$<1.1 \times 10^{-4}$	95	[180] ACTON	91B	OPAL	$X^0 \to \tau^+\tau^-$
$<2.8 \times 10^{-4}$	95	[181] ADEVA	91D	L3	$X^0 \to e^+e^-$
$<2.3 \times 10^{-4}$	95	[181] ADEVA	91D	L3	$X^0 \to \mu^+\mu^-$
$<4.7 \times 10^{-4}$	95	[182] ADEVA	91D	L3	$X^0 \to$ hadrons
$<8 \times 10^{-4}$	95	[183] AKRAWY	90J	OPAL	$X^0 \to$ hadrons

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

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

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

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

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

[179] 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.

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

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

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

[183] AKRAWY 90J give $\Gamma(Z \to \gamma X^0)\cdot$B($X^0 \to$ 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 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		[184] ODAKA	89	VNS	$\Gamma(X^0 \to e^+e^-) \cdot B(X^0 \to \text{hadrons}) \gtrsim 0.2$ MeV
>45	95	[185] DERRICK	86	HRS	$\Gamma(X^0 \to e^+e^-)$=6 MeV
>46.6	95	[186] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
>48	95	[186] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
		[187] BERGER	85B	PLUT	
none 39.8–45.5		[188] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
>47.8	95	[188] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
none 39.8–45.2		[188] BEHREND	84C	CELL	
>47	95	[188] BEHREND	84C	CELL	$\Gamma(X^0 \to e^+e^-)$=4 MeV

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

[185] DERRICK 86 found no deviation from the Standard Model Bhabha scattering at E_{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.

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

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

[188] ADEVA 84 and BEHREND 84C have E_{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 $m_X > E_{cm}$. 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 $\Gamma(X^0 \to e^+e^-) \cdot B(X^0 \to f)$, 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	[189] ABE	93C	VNS	$\Gamma(ee)$
<(0.4–10)	95	[190] ABE	93C	VNS	$f = \gamma\gamma$
<(0.3–5)	95	[191,192] ABE	93D	TOPZ	$f = \gamma\gamma$
<(2–12)	95	[191,192] ABE	93D	TOPZ	f = hadrons
<(4–200)	95	[192,193] ABE	93D	TOPZ	$f = ee$
<(0.1–6)	95	[192,193] ABE	93D	TOPZ	$f = \mu\mu$
<(0.5–8)	90	[194] STERNER	93	AMY	$f = \gamma\gamma$

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

[190] 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.

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

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

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

[194] 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 $\Gamma = 1,3$ GeV.

Search for X^0 Resonance in Two-Photon Process

The limit is for $\Gamma(X^0) \cdot \mathrm{B}(X^0 \to \gamma\gamma)^2$. 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	[195] ACTON	93E	OPAL	$m_{X^0}=60 \pm 1$ GeV
<2.9	95	BUSKULIC	93F	ALEP	$m_{X^0} \sim 60$ GeV

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

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

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[196] ADAM	96C	DLPH	X^0 decaying invisibly

[196] 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 $\sigma(e^+e^- \to \gamma X^0)$.

Search for X^0 Resonance in $Z \to f\overline{f}X^0$

The limit is for $\mathrm{B}(Z \to f\overline{f}X^0) \cdot \mathrm{B}(X^0 \to F)$ where f is a fermion and F is the specified final state. 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. • • •					
		[197] ABREU	96T	DLPH	f=e,μ,τ; F=$\gamma\gamma$
$<3.7 \times 10^{-6}$	95	[198] ABREU	96T	DLPH	f=ν; F=$\gamma\gamma$
		[199] ABREU	96T	DLPH	f=q; F=$\gamma\gamma$
$<6.8 \times 10^{-6}$	95	[198] ACTON	93E	OPAL	f=e,μ,τ; F=$\gamma\gamma$
$<5.5 \times 10^{-6}$	95	[198] ACTON	93E	OPAL	f=q; F=$\gamma\gamma$
$<3.1 \times 10^{-6}$	95	[198] ACTON	93E	OPAL	f=ν; F=$\gamma\gamma$
$<6.5 \times 10^{-6}$	95	[198] ACTON	93E	OPAL	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
$<7.1 \times 10^{-6}$	95	[198] BUSKULIC	93F	ALEP	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
		[200] ADRIANI	92F	L3	f=q; F=$\gamma\gamma$

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

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

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

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

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

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

[201] 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 $X^0 \rightarrow b\overline{b}$ 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}.

Search for Resonance X, Y in $e^+e^- \rightarrow XY$

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[202] ABREU	99H	DLPH	$X \rightarrow$ 2 jets, $Y \rightarrow$ 2 jets
	[203] ACKERSTAFF	98X	OPAL	$X \rightarrow$ 2 jets, $Y \rightarrow$ 2 jets
	[204] ACKERSTAFF	98Y	OPAL	$X \rightarrow \gamma\gamma$, $Y \rightarrow f\overline{f}$
	[205] ALEXANDER	97B	OPAL	$X \rightarrow$ 2 jets, $Y \rightarrow$ 2 jets
	[206] BUSKULIC,D	96	ALEP	$X \rightarrow$ 2 jets, $Y \rightarrow$ 2 jets

[202] ABREU 99H refutes the hypothesis that the excess reported in BUSKULIC,D 96 is a sign of new physics at over 99%CL.

[203] ACKERSTAFF 98X search for $e^+e^- \rightarrow XY \rightarrow$ 4jets at $\sqrt{s}$= 130–184 GeV. The upper limits on $\sigma(e^+e^- \rightarrow XY)$, which are well below the excess reported by BUSKULIC,D 96, are shown in their Fig. 5.

[204] ACKERSTAFF 98Y search for $e^+e^- \rightarrow XY$, with $X \rightarrow \gamma\gamma$, $Y \rightarrow f\overline{f}$ where $f\overline{f}$ may be $q\overline{q}$, $\ell\overline{\ell}$, or $\nu\overline{\nu}$ at $\sqrt{s}$= 183 GeV. The upper limits on $\sigma(e^+e^- \rightarrow XY)\times$B($X \rightarrow \gamma\gamma$) are shown in their Fig. 4.

[205] ALEXANDER 97B search for the associated production of two massive particles decaying into quarks in e^+e^- collisions at $\sqrt{s}$=130–136 GeV. The 95%CL upper limits on $\sigma(e^+e^- \rightarrow XY)$ range from 2.7 to 4.5 pb for 95<m_X+m_Y < 120 GeV.

[206] BUSKULIC,D 96 observed an excess of four-jet production cross section in e^+e^- collisions at $\sqrt{s}$=130–136 GeV and find an enhancement in the sum of two dijet masses around 105 GeV.

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. • • •					
$<1.5\times10^{-5}$	90	[207] BALEST	95	CLE2	$\Upsilon(1S) \rightarrow X^0\gamma$, m_{X^0} < 5 GeV
$< 3\times10^{-5}$–6×10^{-3}	90	[208] BALEST	95	CLE2	$\Upsilon(1S) \rightarrow X^0\overline{X}^0\gamma$, m_{X^0} < 3.9 GeV
$<5.6\times10^{-5}$	90	[209] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \rightarrow X^0\gamma$, m_{X^0} < 7.2 GeV
		[210] ALBRECHT	89	ARG	

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

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

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

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

REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

ABBOTT	00C	PRL 84 2088	B. Abbott *et al.*	(D0 Collab.)
BARATE	00I	EPJ C12 183	R. Barate *et al.*	(ALEPH Collab.)
CHAY	00	PR D61 035002	J. Chay, K.Y. Lee, S. Nam	
ERLER	00	PRL 84 212	J. Erler, P. Langacker	
ROSNER	00	PR D61 016006	J.L. Rosner	
ABBIENDI	99	EPJ C6 1	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	99J	PRL 83 2896	B. Abbott *et al.*	(D0 Collab.)
ABREU	99A	EPJ C11 383	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99G	PL B446 62	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	99H	PL B448 311	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.)
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	
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.)
ACKERSTAFF	98X	PL B429 399	K. Ackerstaff *et al.*	(OPAL Collab.)
ACKERSTAFF	98Y	PL B437 218	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	
CHO	98B	NP B531 65	G. Cho, K. Hagiwara, Y. Umeda	
CONRAD	98	RMP 70 1341	J.M. Conrad, M.H. Shaevitz, T. Bolton	
DONCHESKI	98	PR D58 097702	M.A. Doncheski, R.W. Robinett	
ABBOTT	97B	PRL 79 4321	B. Abbott *et al.*	(D0 Collab.)
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.)
ALEXANDER	97B	ZPHY C73 201	G. Alexander *et al.*	(OPAL Collab.)
ARIMA	97	PR D55 19	T. Arima *et al.*	(VENUS Collab.)
BARATE	97B	PL B399 329	R. Barate *et al.*	(ALEPH 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)
BUSKULIC,D	96	ZPHY C71 179	D. Buskulic *et al.*	(ALEPH Collab.)
ABACHI	95E	PL B358 405	S. Abachi *et al.*	(D0 Collab.)
ABE	95	PR D51 R949	F. Abe *et al.*	(CDF Collab.)
ABE	95M	PRL 74 2900	F. Abe *et al.*	(CDF Collab.)
ABE	95N	PRL 74 3538	F. Abe *et al.*	(CDF Collab.)
ABREU	95M	ZPHY C65 603	P. Abreu *et al.*	(DELPHI Collab.)
AID	95	PL B353 578	S. Aid *et al.*	(H1 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	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 *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	I.A. Kuznetsov *et al.*	(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 *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	93D	PL B306 187	O. Adriani *et al.*	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani *et al.*	(L3 Collab.)
ALITTI	93	NP B400 3	J. Alitti *et al.*	(UA2 Collab.)
ALTARELLI	93B	PL B318 139	G. Altarelli *et al.*	(CERN, FIRZ, GEVA+)
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.)
ABE	92B	PRL 68 1463	F. Abe *et al.*	(CDF 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)
ABE	91F	PRL 67 2609	F. Abe *et al.*	(CDF Collab.)
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.)
ALITTI	91	ZPHY C49 17	J. Alitti *et al.*	(UA2 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.)
ARNISON	86B	EPL 1 327	G.T.J. Arnison *et al.*	(UA1 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.)
ARNISON	83D	PL 129B 273	G.T.J. Arnison *et al.*	(UA1 Collab.)
BERGSMA	83	PL 122B 465	F. Bergsma *et al.*	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr *et al.*	(LBL, NWES, TRIU)
DESHPANDE	83	PR D27 1193	N.G. Deshpande, R.J. Johnson	(OREG)
BEALL	82	PRL 48 848	G. Beall, M. Bander, A. Soni	(UCI, UCLA)
SHANKER	82	NP B204 375	O. Shanker	(TRIU)
DIMOPOUL...	81	NP B182 77	S. Dimopoulos, S. Raby, G.L. Kane	(STAN, MICH)
STEIGMAN	79	PRL 43 239	G. Steigman, K.A. Olive, D.N. Schramm	(BART+)