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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.

THE W' SEARCHES

Revised August 2005 by K.S. Babu (Oklahoma State U.) and C. Kolda (Notre Dame U.).

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 $Y = T_{3R} + (B\text{–}L)/2$, 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]

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

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, $|\zeta| \leq 0.0333$ 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 $M_{W_2} \geq 549$ 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 4 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 $M_{W_2} > 23$ TeV [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 $W_2^+ \to \ell_R^+\nu_R$ will be forbidden kinematically. Assuming that ζ is small, the dominant decay of W_2 will then 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 300 to 800 GeV [14], while CDF excludes the mass range of 225 to 566 GeV by searching for a $t\bar{b}$ final state [15].

If ν_R is lighter than W_2, the decay $W_2^+ \to e_R^+\nu_R$ is allowed; if $m_{\nu_R} < M_{W_2}/2$ then a peak in the spectrum of hard electrons can be used as a signature for W_2 production. Using this technique, DØ has a limit of $M_{W_2} > 720$ GeV if $m_{\nu_R} \ll M_{W_2}$; the bound weakens to 650 GeV for $m_{\nu_R} = M_{W_2}/2$ [16]. One can also look for the decay of the ν_R into $e_R W_R^*$, leading to an $eejj$ signature. The DØ bound here is only slightly weaker than above. Finally one can search for a stable ν_R in leptons plus missing energy. CDF finds $M_{W_2} > 786$ GeV if ν_R is much lighter than W_2, using the e and μ final states combined [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 $SU(2)_R$ singlets or doublets. If they are $SU(2)_R$ 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 a 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 a leptoquark W' comes from nonobservation of $K_L \rightarrow ee$ and μe, which require $M_{W'} \geq 1400$ and 1200 TeV respectively; 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' (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 $p\overline{p} \to W' X$ with W' decaying to the mode indicated in the comments. New decay channels (*e.g.*, $W' \to WZ$) are assumed to be suppressed. UA1 and UA2 experiments assume that the $t\overline{b}$ channel is not open.

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

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

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

[3] AFFOLDER 01I combine a new bound on $W' \to e\nu$ of 754 GeV with the bound of ABE 00 on $W' \to \mu\nu$ to obtain quoted bound.

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

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

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

[7] ABACHI 95E assume that the decay $W' \to WZ$ is suppressed and that the neutrino from W' decay is stable and has a mass significantly less $m_{W'}$.

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

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

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

[11] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(W')$ B($e\nu$) < 4.1 pb (90% CL).
[12] See Fig. 5 of ANSARI 87D for the excluded region in the $m_{W'}$–$[(g_{W'q})^2$ B($W' \rightarrow e\overline{\nu}$)] plane. Note that the quantity $(g_{W'q})^2$ B($W' \rightarrow e\overline{\nu}$) is normalized to unity for the standard W couplings.

W_R (Right-Handed W Boson) MASS LIMITS

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
> 715	90	[13] CZAKON	99	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
[> 3300]	95	[14] CYBURT	05	COSM	Nucleosynthesis; light ν_R
> 310	90	[15] THOMAS	01	CNTR	β^+ decay
> 137	95	[16] ACKERSTAFF	99D	OPAL	τ decay
>1400	68	[17] BARENBOIM	98	RVUE	Electroweak, Z-Z' mixing
> 549	68	[18] BARENBOIM	97	RVUE	μ decay
> 220	95	[19] STAHL	97	RVUE	τ decay
> 220	90	[20] ALLET	96	CNTR	β^+ decay
> 281	90	[21] KUZNETSOV	95	CNTR	Polarized neutron decay
> 282	90	[22] KUZNETSOV	94B	CNTR	Polarized neutron decay
> 439	90	[23] BHATTACH...	93	RVUE	Z-Z' mixing
> 250	90	[24] SEVERIJNS	93	CNTR	β^+ decay
		[25] IMAZATO	92	CNTR	K^+ decay
> 475	90	[26] POLAK	92B	RVUE	μ decay
> 240	90	[27] AQUINO	91	RVUE	Neutron decay
> 496	90	[27] AQUINO	91	RVUE	Neutron and muon decay
> 700		[28] COLANGELO	91	THEO	$m_{K^0_L} - m_{K^0_S}$
> 477	90	[29] POLAK	91	RVUE	μ decay
[none 540–23000]		[30] BARBIERI	89B	ASTR	SN 1987A; light ν_R
> 300	90	[31] LANGACKER	89B	RVUE	General
> 160	90	[32] BALKE	88	CNTR	$\mu \rightarrow e\nu\overline{\nu}$
> 406	90	[33] JODIDIO	86	ELEC	Any ζ
> 482	90	[33] JODIDIO	86	ELEC	$\zeta = 0$
> 800		MOHAPATRA	86	RVUE	$SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	[34] STOKER	85	ELEC	Any ζ
> 475	95	[34] STOKER	85	ELEC	$\zeta < 0.041$
		[35] BERGSMA	83	CHRM	$\nu_\mu e \rightarrow \mu\nu_e$
> 380	90	[36] CARR	83	ELEC	μ^+ decay
>1600		[37] BEALL	82	THEO	$m_{K^0_L} - m_{K^0_S}$

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

[14] CYBURT 05 limit follows by requiring that three light ν_R's decouple when $T_{dec} > 140$ MeV. For different T_{dec}, the bound becomes $M_{W_R} > 3.3$ TeV (T_{dec} / 140 MeV)$^{3/4}$.

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

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

[17] 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.

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

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

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

[21] 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.

[22] 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.

[23] 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.

[24] 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.

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

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

[27] 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.

[28] 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.

[29] 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.

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

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

[32] 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.

[33] 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^+.

[34] 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.

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

[36] 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.

[37] 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	[38] ACKERSTAFF	99D	OPAL	τ decay
< 0.013	90	[39] CZAKON	99	RVUE	Electroweak
< 0.0333		[40] BARENBOIM	97	RVUE	μ decay
< 0.04	90	[41] MISHRA	92	CCFR	νN scattering
−0.0006 to 0.0028	90	[42] AQUINO	91	RVUE	
[none 0.00001–0.02]		[43] BARBIERI	89B	ASTR	SN 1987A
< 0.040	90	[44] JODIDIO	86	ELEC	μ decay
−0.056 to 0.040	90	[44] JODIDIO	86	ELEC	μ decay

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

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

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

[41] 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.

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

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

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

THE Z' SEARCHES

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New massive and electrically neutral gauge bosons are a common feature of physics beyond the Standard Model. They are present in most extensions of the Standard Model gauge group, including models in which the Standard Model is embedded into a unifying group. They can also arise in certain classes of theories with extra dimensions. Whatever the source, such a gauge boson is called a Z'. While current theories suggest that there may be a multitude of such states at or just below the Planck scale, there exist many models in which the Z' sits at or near the weak scale. Models with extra neutral gauge bosons often contain charged gauge bosons as well; these are discussed in the review of W' physics.

The Lagrangian describing a single Z' and its interactions with the fields of the Standard Model is [1,2,3]:

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

where c_W, s_W are the cosine and sine of the weak angle, $F_{\mu\nu}, F'_{\mu\nu}$ are the field strength tensors for the hypercharge and the Z' gauge bosons respectively, ψ_i are the matter fields with Z' vector and axial charges f^i_V and f^i_A, and Z_μ is the electroweak Z-boson. (The overall Z' coupling strength has been normalized to that of the usual Z.) The mass terms are assumed to come from spontaneous symmetry breaking via scalar expectation values; the δM^2 term is generated by Higgs bosons that are charged under both the Standard Model and the extra gauge symmetry, and can have either sign. The above Lagrangian is general to all abelian and non-abelian extensions; however, for the non-abelian case, $F'_{\mu\nu}$ is not gauge invariant and so the kinetic mixing parameter $\chi = 0$. Most analyses take $\chi = 0$, even for the abelian case, and so we do likewise here; see Ref. 3 for a discussion of observables with $\chi \neq 0$.

Strictly speaking, the Z' defined in the Lagrangian above is not a mass eigenstate since it can mix with the usual Z boson. The mixing angle is given by

$$\xi \simeq \frac{\delta M^2}{M_Z^2 - M_{Z'}^2} \ . \tag{2}$$

This mixing can alter a large number of the Z-pole observables, including the T-parameter which receives a contribution

$$\alpha T_{\rm new} = \xi^2 \left(\frac{M_{Z'}^2}{M_Z^2} - 1 \right) \tag{3}$$

to leading order in small ξ. (For $\chi \neq 0$, both S and T receive additional contributions [4,3].) However, the oblique parameters do not encode all the effects generated by $Z - Z'$ mixing; the mixing also alters the couplings of the Z itself, shifting its vector and axial couplings to $T_3^i - 2Q^i s_W^2 + \xi f_V^i$ and $T_3^i + \xi f_A^i$ respectively.

If the Z' charges are generation-dependent, tree-level flavor-changing neutral currents will generically arise. There exist severe constraints in the first two generations coming from precision measurements such as the $K_L - K_S$ mass splitting and $B(\mu \to 3e)$; constraints on a Z' which couples differently only to the third generation are somewhat weaker. If the Z' interactions commute with the Standard Model gauge group, then per generation, there are only five independent $Z'\bar{\psi}\psi$ couplings; one can choose them to be $f_V^u, f_A^u, f_V^d, f_V^e, f_A^e$. All other couplings can be determined in terms of these, *e.g.*, $f_V^\nu = (f_V^e + f_A^e)/2$.

Experimental Constraints: There are four 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, indirect constraints from precision electroweak measurements off the Z-pole, and direct search constraints from production at very high energies. In principle, one should expect 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. Because these states are highly model-dependent, searches for these states, or for Z' decays into them, are not included in the Listings.

Low-energy Constraints: After the gauge symmetry of the Z' and the electroweak symmetry are both broken, 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. Current bounds on T (and S) 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 [5]. At low energies, the effective neutral current Lagrangian is conventionally written:

$$\mathcal{L}_{\rm NC} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left\{ C_{1q} (\bar{e}\gamma_\mu\gamma^5 e)(\bar{q}\gamma^\mu q) + C_{2q} (\bar{e}\gamma_\mu e)(\bar{q}\gamma^\mu\gamma^5 q) \right\} . \tag{4}$$

APV experiments are sensitive only to C_{1u} and C_{1d} through the "weak charge" $Q_W = -2\,[C_{1u}(2Z+N) + C_{1d}(Z+2N)]$, where

$$C_{1q} = 2(1+\alpha T)(g_A^e + \xi f_A^e)(g_V^q + \xi f_V^q) + 2r(f_A^e f_V^q) \tag{5}$$

with $r = M_Z^2/M_{Z'}^2$. (Terms $\mathcal{O}(r\xi)$ are dropped.) The r-dependent terms arise from Z' exchange and can interfere constructively or destructively with the Z 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 Standard Model 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 $(\bar{\nu}\gamma_\mu\nu)(\bar{q}_{L,R}\gamma^\mu q_{L,R})$ with coefficients $(2\sqrt{2}G_F)\epsilon_{L,R}(q)$. (Again, see the Standard Model review.) In the presence of the Z and Z', the $\epsilon_{L,R}(q)$ are given by:

$$\begin{aligned}\epsilon_{L,R}(q) =& \frac{1+\alpha T}{2}\left\{(g_V^q \pm g_A^q)[1+\xi(f_V^\nu \pm f_A^\nu)] + \xi(f_V^q \pm f_A^q)\right\} \\ & + \frac{r}{2}(f_V^q \pm f_A^q)(f_V^\nu \pm f_A^\nu) \ . \end{aligned} \tag{6}$$

Again, the r-dependent terms arise from Z'-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. Constraints on the allowed mixing angle and Z' couplings arise by fitting all data simultaneously to the *ansatz* of $Z-Z'$ mixing. A number of such fits are included in the Listings. If the listed analysis uses data only from the Z resonance, it is marked with a comment "Z parameters" while it is commented as "Electroweak" if low-energy data is also included in the fits. Both types of fits place simultaneous limits on the Z' mass and on ξ.

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

Far below the Z' mass scale, experiments at a given $\sqrt{s}$ are only sensitive to the scaled Z' couplings $\sqrt{s} f^i_{V,A}/M_{Z'}$. However, the Z' mass and overall magnitude of the couplings can be separately extracted if measurements are made at more than one energy. As $\sqrt{s}$ approaches $M_{Z'}$ the Z' 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, for example, Ref. 6. LEP has also done similar work using data collected above the Z-peak; see, for example, Ref. 7. For indirect Z' searches at future facilities, see, for example, Refs. 8,9. At a hadron collider the possibility of measuring leptonic forward-backward asymmetries has been suggested [10] and used [11] in searches for a Z' below its threshold.

Direct Search Constraints: Finally, high-energy experiments have searched for on-shell Z' 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; exotic decays of a Z' are not included in the listings. Experiments to date have been sensitive to Z' production via their coupling to quarks ($p\bar{p}$ colliders), to electrons (e^+e^-), or to both (ep).

For a heavy Z' ($M_{Z'} \gg M_Z$), the best limits come from $p\bar{p}$ machines via Drell-Yan production and subsequent decay to charged leptons. For $M_{Z'} > 600\,\mathrm{GeV}$, CDF [12] quotes limits on $\sigma(p\bar{p} \to Z'X) \cdot B(Z' \to \ell^+\ell^-) < 0.04\,\mathrm{pb}$ at 95% C.L. for $\ell = e+\mu$ combined; DØ [13] quotes $\sigma \cdot B < 0.06\,\mathrm{pb}$ for $\ell = e$ and $M_{Z'} > 500\,\mathrm{GeV}$. For smaller masses, the bounds can be found in the original literature. For studies of the search capabilities of future facilities, see, for example, Ref. 8.

If the Z' has suppressed, or no, couplings to leptons (*i.e.*, it is leptophobic), then experimental sensitivities are much weaker. Searches for a Z' via hadronic decays at CDF [14] are unable to rule out a Z' with quark couplings identical to those of the Z in any mass region. UA2 [15] does find $\sigma \cdot B(Z' \to jj) < 11.7\,\mathrm{pb}$ at 90% C.L. for $M_{Z'} > 200\,\mathrm{GeV}$, with more complicated bounds in the range $130\,\mathrm{GeV} < M_{Z'} < 200\,\mathrm{GeV}$. CDF and D0 [16] have also searched for a narrow, leptophobic Z' predicted by some topcolor models as a peak in the $\bar{t}t$ spectrum.

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. 6.

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 $Q_\eta = \sqrt{\frac{3}{8}}Q_\chi - \sqrt{\frac{5}{8}}Q_\psi$. The charges of the SM fermions under these U(1)'s can be found in Table 1, and a discussion of their experimental signatures can be found in Ref. 17. A separate listing appears for each of the canonical models, with direct and indirect constraints combined.

Table 1: Charges of Standard Model fermions in canonical Z' models.

	Y	T_{3R}	$B-L$	$\sqrt{24}Q_\chi$	$\sqrt{\frac{72}{5}}Q_\psi$	Q_η
ν_L, e_L	$-\frac{1}{2}$	0	-1	$+3$	$+1$	$+\frac{1}{6}$
ν_R	0	$+\frac{1}{2}$	-1	$+5$	-1	$+\frac{5}{6}$
e_R	-1	$-\frac{1}{2}$	-1	$+1$	-1	$+\frac{1}{3}$
u_L, d_L	$+\frac{1}{6}$	0	$+\frac{1}{3}$	-1	$+1$	$-\frac{1}{3}$
u_R	$+\frac{2}{3}$	$+\frac{1}{2}$	$+\frac{1}{3}$	$+1$	-1	$+\frac{1}{3}$
d_R	$-\frac{1}{3}$	$-\frac{1}{2}$	$+\frac{1}{3}$	-3	-1	$-\frac{1}{6}$

It is also common to express experimental bounds in terms of a toy Z', usually denoted $Z'_{\rm SM}$. This $Z'_{\rm SM}$, 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.

Extra Dimensions: A new motivation for Z' searches comes from recent work on extensions of the Standard Model into extra dimensions. (See the "Review of Extra Dimensions" for many details not included here.) In some classes of these models, the gauge bosons of the Standard Model can inhabit these new directions [18]. When compactified down to the usual (3+1) dimensions, the extra degrees of freedom that were present in the higher-dimensional theory (associated with propagation in the extra dimensions) appear as a tower of massive gauge bosons, called Kaluza-Klein (KK) states. The simplest case is the compactification of a $(4+d)$-dimensional space on a d-torus (T^d) of uniform radius R in all d directions. Then a tower of massive gauge bosons are present with masses

$$M_{V_{\vec{n}}}^2 = M_{V_{\vec{0}}}^2 + \frac{\vec{n}\cdot\vec{n}}{R^2}\,, \tag{7}$$

where V represents any of the gauge fields of the Standard Model and $\vec{n}$ is a d-vector whose components are semi-positive integers; the vector $\vec{n} = (0, 0, \ldots 0)$ corresponds to the "zero-mode" gauge boson, which is nothing more than the usual gauge boson of the Standard Model, with mass $M_{V_{\vec{0}}} = M_V$. Compactifications on either non-factorizable or asymmetric manifolds can significantly alter the KK mass formula, but a tower of states will nonetheless persist. All bounds cited in the Listings assume the maximally symmetric spectrum given above for simplicity.

The KK mass formula, coupled with the absence of any observational evidence for W' or Z' states below the weak scale, implies that the extra dimensions in which gauge bosons can propagate must have inverse radii greater than at least a few hundred GeV. If any extra dimensions are larger than this, gravity alone may propagate in them.

Though the gauge principle guarantees that the usual Standard Model gauge fields couple with universal strength (or gauge coupling) to all charged matter, the coupling of KK bosons to ordinary matter is highly model-dependent. In the simplest case, all Standard Model fields are localized at the same point in the d-dimensional subspace; in the parlance of the field, they all live on the same 3-brane. Then the couplings of KK bosons are identical to those of the usual gauge fields, but enhanced: $g_{KK} = \sqrt{2}\,g$. However, in many models, particularly those which naturally suppress proton decay [19], it is common to find ordinary fermions living on different, parallel branes in the extra dimensions. In such cases, different fermions experience very different coupling strengths for the KK states; the effective coupling varies fermion by fermion, and also KK mode by KK mode. In the particular case that fermions of different generations with identical quantum numbers are placed on different branes, large flavor-changing neutral currents can occur unless the mass scale of the KK states is very heavy: $R^{-1} \gtrsim 1000\,\mathrm{TeV}$ [20]. In the Listings, all bounds assume that Standard Model fermions live on a single 3-brane. (The case of the Higgs field is again complicated; see the footnotes on the individual listings.)

In some sense, searches for KK bosons are no different than searches for any other Z' or W'; in fact, bounds on the artificially defined Z'_{SM} are almost precisely bounds on the first KK mode of the Z^0, modulo the $\sqrt{2}$ enhancement in the coupling strength. To date, no experiment has examined direct production of KK Z^0 bosons, but an approximate bound of 820 GeV [21] can be inferred from the CDF bound on Z'_{SM} [12].

Indirect bounds have a very different behavior for KK gauge bosons than for canonical Z' bosons; a number of indirect bounds are given in the Listings. Indirect bounds arise from virtual boson exchange and require a summation over the entire tower of KK states. For $d > 1$, this summation diverges, a remnant of the non-renormalizability of the underlying $(4+d)$-dimensional field theory. In a fully consistent theory, such as a string theory, the summation would be regularized and finite.

However, this procedure cannot be uniquely defined within the confines of our present knowledge, and so most authors choose to terminate the sum with an explicit cut-off, Λ_{KK}, set equal to the "Planck scale" of the D-dimensional theory, M_D [22]. Reasonable arguments exist that this cut-off could be very different and could vary by process, and so these bounds should be regarded merely as indicative [23].

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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
> 825	95	[45] ABULENCIA	05A	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$, $\mu^+\mu^-$
$>$1018	95	[46] ABBIENDI	04G	OPAL	e^+e^-
>1500	95	[47] CHEUNG	01B	RVUE	Electroweak
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>$ 399	95	[48] ACOSTA	05R	CDF	$\overline{p}p$: $Z'_{SM} \rightarrow \tau^+\tau^-$
none 400–640	95	ABAZOV	04C	D0	$p\overline{p}$: $Z'_{SM} \rightarrow q\overline{q}$
$>$ 670	95	[49] ABAZOV	01B	D0	$p\overline{p}$, $Z'_{SM} \rightarrow e^+e^-$
$>$ 710	95	[50] ABREU	00S	DLPH	e^+e^-
$>$ 898	95	[51] BARATE	00I	ALEP	e^+e^-
$>$ 809	95	[52] ERLER	99	RVUE	Electroweak
$>$ 690	95	[53] ABE	97S	CDF	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$, $\mu^+\mu^-$
$>$ 490	95	ABACHI	96D	D0	$p\overline{p}$; $Z'_{SM} \rightarrow e^+e^-$
$>$ 398	95	[54] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
$>$ 237	90	[55] ALITTI	93	UA2	$p\overline{p}$; $Z'_{SM} \rightarrow q\overline{q}$
none 260–600	95	[56] RIZZO	93	RVUE	$p\overline{p}$; $Z'_{SM} \rightarrow q\overline{q}$
$>$ 426	90	[57] ABE	90F	VNS	e^+e^-

[45] ABULENCIA 05A search for resonances decaying to electron or muon pairs in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

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

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

[48] ACOSTA 05R search for resonances decaying to tau lepton pairs in $\overline{p}p$ collisions at $\sqrt{s} = 1.96$ TeV.

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

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

[51] 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.

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

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

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

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

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

[57] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$. They fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

Limits for Z_{LR}

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>518	95	[58] ABBIENDI	04G	OPAL	$e^+ e^-$
>860	95	[59] CHEUNG	01B	RVUE	Electroweak
>630	95	[60] ABE	97S	CDF	$p\overline{p}$; $Z'_{LR} \to e^+ e^-$, $\mu^+ \mu^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>380	95	[61] ABREU	00S	DLPH	$e^+ e^-$
>436	95	[62] BARATE	00I	ALEP	$e^+ e^-$
>550	95	[63] CHAY	00	RVUE	Electroweak
		[64] ERLER	00	RVUE	Cs
		[65] CASALBUONI	99	RVUE	Cs
(> 1205)	90	[66] CZAKON	99	RVUE	Electroweak
>564	95	[67] ERLER	99	RVUE	Electroweak
(> 1673)	95	[68] ERLER	99	RVUE	Electroweak
(> 1700)	68	[69] BARENBOIM	98	RVUE	Electroweak
>244	95	[70] CONRAD	98	RVUE	$\nu_\mu N$ scattering
>253	95	[71] VILAIN	94B	CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
none 200–600	95	[72] RIZZO	93	RVUE	$p\overline{p}$; $Z_{LR} \to q\overline{q}$
[> 2000]		WALKER	91	COSM	Nucleosynthesis; light ν_R
none 200–500		[73] GRIFOLS	90	ASTR	SN 1987A; light ν_R
none 350–2400		[74] BARBIERI	89B	ASTR	SN 1987A; light ν_R

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

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

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

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

[62] 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.

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

[64] 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.

[65] 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.

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

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

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

[69] 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.

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

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

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

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

[74] 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
> 690	95	[75] ABULENCIA	05A	CDF	$p\overline{p}$; $Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
> 781	95	[76] ABBIENDI	04G	OPAL	e^+e^-
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>2100		[77] BARGER	03B	COSM	Nucleosynthesis; light ν_R
> 680	95	[78] CHEUNG	01B	RVUE	Electroweak
> 440	95	[79] ABREU	00S	DLPH	e^+e^-
> 533	95	[80] BARATE	00I	ALEP	e^+e^-
> 554	95	[81] CHO	00	RVUE	Electroweak
		[82] ERLER	00	RVUE	Cs
		[83] ROSNER	00	RVUE	Cs
> 545	95	[84] ERLER	99	RVUE	Electroweak
(> 1368)	95	[85] ERLER	99	RVUE	Electroweak
> 215	95	[86] CONRAD	98	RVUE	$\nu_\mu N$ scattering
> 595	95	[87] ABE	97S	CDF	$p\overline{p}$; $Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
> 190	95	[88] ARIMA	97	VNS	Bhabha scattering
> 262	95	[89] VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$
[>1470]		[90] FARAGGI	91	COSM	Nucleosynthesis; light ν_R
> 231	90	[91] ABE	90F	VNS	e^+e^-
[> 1140]		[92] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 2100]		[93] GRIFOLS	90	ASTR	SN 1987A; light ν_R

[75] ABULENCIA 05A search for resonances decaying to electron or muon pairs in $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV.

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

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

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

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

[80] 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.

[81] CHO 00 use various electroweak data to constrain Z' models assuming m_H=100 GeV. See Fig. 3 for limits in the mass-mixing plane.

[82] 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.

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

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

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

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

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

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

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

[90] FARAGGI 91 limit assumes the nucleosynthesis bound on the effective number of neutrinos ΔN_ν < 0.5 and is valid for m_{ν_R} < 1 MeV.

[91] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$. ABE 90F fix m_W = 80.49 ± 0.43 ± 0.24 GeV and m_Z = 91.13 ± 0.03 GeV.

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

[93] 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$_6$ → SO(10) × U(1)$_\psi$. g_ψ = e/cosθ_W is assumed unless otherwise stated. We list limits with the assumption ρ = 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
>675	95	[94] ABULENCIA	05A	CDF	$p\overline{p}$; $Z'_\psi \rightarrow e^+e^-$, $\mu^+\mu^-$
>366	95	[95] ABBIENDI	04G	OPAL	e^+e^-

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

>600		[96] BARGER	03B	COSM	Nucleosynthesis; light ν_R
>350	95	[97] ABREU	00S	DLPH	e^+e^-
>294	95	[98] BARATE	00I	ALEP	e^+e^-
>137	95	[99] CHO	00	RVUE	Electroweak
>146	95	[100] ERLER	99	RVUE	Electroweak
> 54	95	[101] CONRAD	98	RVUE	$\nu_\mu N$ scattering
>590	95	[102] ABE	97S	CDF	$p\overline{p}$; $Z'_\psi \to e^+e^-$, $\mu^+\mu^-$
>135	95	[103] VILAIN	94B	CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
>105	90	[104] ABE	90F	VNS	e^+e^-
[> 160]		[105] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 2000]		[106] GRIFOLS	90D	ASTR	SN 1987A; light ν_R

[94] ABULENCIA 05A search for resonances decaying to electron or muon pairs in $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV.

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

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

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

[98] 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.

[99] CHO 00 use various electroweak data to constrain Z' models assuming m_H=100 GeV. See Fig. 3 for limits in the mass-mixing plane.

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

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

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

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

[104] ABE 90F use data for R, $R_{\ell\ell}$, and $A_{\ell\ell}$. ABE 90F fix m_W = 80.49 ± 0.43 ± 0.24 GeV and m_Z = 91.13 ± 0.03 GeV.

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

[106] 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*
> 720	95	[107] ABULENCIA	05A	CDF	$p\overline{p}$; $Z'_\eta \to e^+e^-$, $\mu^+\mu^-$
> 515	95	[108] ABBIENDI	04G	OPAL	e^+e^-
> 619	95	[109] CHO	00	RVUE	Electroweak

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

>1600		[110] BARGER	03B	COSM	Nucleosynthesis; light ν_R
> 310	95	[111] ABREU	00S	DLPH	e^+e^-
> 329	95	[112] BARATE	00I	ALEP	e^+e^-
> 365	95	[113] ERLER	99	RVUE	Electroweak
> 87	95	[114] CONRAD	98	RVUE	$\nu_\mu N$ scattering
> 620	95	[115] ABE	97S	CDF	$p\overline{p}$; $Z'_\eta \to e^+e^-$, $\mu^+\mu^-$
> 100	95	[116] VILAIN	94B	CHM2	$\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
> 125	90	[117] ABE	90F	VNS	e^+e^-
[> 820]		[118] GONZALEZ-G..	90D	COSM	Nucleosynthesis; light ν_R
[> 3300]		[119] GRIFOLS	90	ASTR	SN 1987A; light ν_R
[> 1040]		[118] LOPEZ	90	COSM	Nucleosynthesis; light ν_R

[107] ABULENCIA 05A search for resonances decaying to electron or muon pairs in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

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

[109] CHO 00 use various electroweak data to constrain Z' models assuming m_H=100 GeV. See Fig. 3 for limits in the mass-mixing plane.

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

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

[112] 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.

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

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

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

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

[117] 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.

[118] 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).

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

Limits for other Z'

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

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

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

[122] CHO 00 use various electroweak data to constrain Z' models assuming m_H=100 GeV. See Fig. 2 for limits in general E_6-motivated models.

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

[124] Search for Z' decaying to dijets at $\sqrt{s}$=1.8 TeV. For Z' with electromagnetic strength coupling, no bound is obtained.

Indirect Constraints on Kaluza-Klein Gauge Bosons

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

VALUE (TeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 4.7		[125] MUECK	02	RVUE	Electroweak
> 3.3	95	[126] CORNET	00	RVUE	$e\nu q q'$
>5000		[127] DELGADO	00	RVUE	ϵ_K
> 2.6	95	[128] DELGADO	00	RVUE	Electroweak
> 3.3	95	[129] RIZZO	00	RVUE	Electroweak
> 2.9	95	[130] MARCIANO	99	RVUE	Electroweak
> 2.5	95	[131] MASIP	99	RVUE	Electroweak
> 1.6	90	[132] NATH	99	RVUE	Electroweak
> 3.4	95	[133] STRUMIA	99	RVUE	Electroweak

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

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

[127] Bound holds only if first two generations of quarks lives on separate branes. If quark mixing is not complex, then bound lowers to 400 TeV from Δm_K.

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

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

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

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

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

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

LEPTOQUARK QUANTUM NUMBERS

Revised September 2005 by M. Tanabashi (Tohoku University).

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. 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.

Spin	$3B+L$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_W$	$\mathrm{U}(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	1/3	$\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}^c_R e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}^c_L \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}^c_R \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

If we do not require leptoquark states to couple directly with SM fermions, different assignments of quantum numbers become possible [2,3].

The Pati-Salam model [4] 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 $SU(3)_C$ group (or $SU(3)_C \times U(1)_{B-L}$). The Pati-Salam leptoquark is a weak isosinglet and its hypercharge is 2/3. The coupling strength of the Pati-Salam leptoquark is given by the QCD coupling at the Pati-Salam symmetry breaking scale. Vector leptoquark states also exist in grand unification theories based on SU(5) [5], SO(10) [6] which includes Pati-Salam color SU(4), and larger gauge groups. Scalar quarks in supersymmetric models with R-parity violation may also have leptoquark-type Yukawa couplings. The bounds on the leptoquark states can therefore be applied to constraining R-parity violating supersymmetric models. Scalar leptoquarks are expected to exist at TeV scale in extended technicolor models [7,8], where leptoquark states appear as the bound states of techni-fermions. Compositeness of quarks and leptons also provides examples of models which may have light leptoquark states [9].

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.

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 [10]. Non-chiral scalar leptoquark also contributes to the muon anomalous magnetic moment [11], [12]. 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 a severe bound on the Pati-Salam leptoquark mass.

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 to as the first (second, third) generation leptoquarks. Davidson, Bailey and Campbell [13] and Leuler [14] give extensive lists of the bounds on the leptoquark induced four-fermion interactions. For the isoscalar scalar and vector leptoquarks S_0 and V_0, for example, which couple with the first (second) generation left-handed quark and the first generation left-handed lepton, the bounds of Ref. [13] read $\lambda^2 < 0.03 \times (M_{\rm LQ}/300{\rm GeV})^2$ for S_0, and $\lambda^2 < 0.02 \times (M_{\rm LQ}/300{\rm GeV})^2$ for V_0 ($\lambda^2 < 5 \times (M_{\rm LQ}/300{\rm GeV})^2$ for S_0, and $\lambda^2 < 3 \times (M_{\rm LQ}/300{\rm GeV})^2$ for V_0). The LEP experiments are sensitive to the indirect effects coming from t- and u-channel exchanges of leptoquarks in the $e^+e^- \to q\bar{q}$ process. The HERA experiments give bounds on the leptoquark induced four-fermion interaction. For detailed bounds obtained in this way, see the Boson Particle Listings for "Indirect Limits for Leptoquarks" and its references.

Collider experiments provide direct limits on the leptoquark states through their pair- and single-production cross sections.

The Tevatron and LEP experiments search for pair- production of the leptoquark states which arises from the leptoquark gauge interaction. The gauge couplings of a scalar leptoquark are determined uniquely according to its quantum numbers in Table 1. Since all of the leptoquark states belong to color triplet representation, the scalar leptoquark pair-production cross section at the Tevatron can be determined solely as a function of the leptoquark mass without making further assumptions. For the first and second generation scalar leptoquark states with decay branching fraction $B(eq) = 1$ and $B(\mu q) = 1$, the CDF and D0 experiments obtain the lower bounds on the leptoquark mass > 235GeV (first generation, CDF), > 256GeV (first generation, D0), > 224GeV (second generation, CDF) and > 251GeV (second generation, D0) at 95%CL [15]. On the other hand, the magnetic-dipole-type and the electric-quadrupole-type interactions of a vector leptoquark are not determined even if we fix its gauge quantum numbers as listed in the table [16]. We need extra assumptions about these interactions to evaluate the pair production cross section for a vector leptoquark.

The searches for the leptoquark single-production are performed by the HERA experiments. Since the leptoquark single-production cross section depends on the leptoquark Yukawa coupling, the leptoquark limits from HERA are usually displayed in the mass-coupling plane. For leptoquark Yukawa coupling $\lambda = 0.1$, the ZEUS bounds on the first generation leptoquarks range from 248 to 290 GeV depending on the leptoquark species [17]. Similar bounds are obtained by H1 [18]. The LEP experiments also search for the single-production of leptoquark states from the process $e\gamma \to LQ + q$.

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MASS LIMITS for Leptoquarks from Pair Production

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

VALUE (GeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
>256	95		[134] ABAZOV	05H	D0	First generation
>236	95		[135] ACOSTA	05P	CDF	First generation
>200	95		[136] ABBOTT	00C	D0	Second generation
>148	95		[137] AFFOLDER	00K	CDF	Third generation
>202	95		[138] ABE	98S	CDF	Second generation
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>117	95		[139] ACOSTA	05I	CDF	First generation
> 99	95		[140] ABBIENDI	03R	OPAL	First generation
>100	95		[140] ABBIENDI	03R	OPAL	Second generation
> 98	95		[140] ABBIENDI	03R	OPAL	Third generation
> 98	95		[141] ABAZOV	02	D0	All generations
>225	95		[142] ABAZOV	01D	D0	First generation
> 85.8	95		[143] ABBIENDI	00M	OPAL	Superseded by ABBIENDI 03R
> 85.5	95		[143] ABBIENDI	00M	OPAL	Superseded by ABBIENDI 03R
> 82.7	95		[143] ABBIENDI	00M	OPAL	Superseded by ABBIENDI 03R
>123	95		[144] AFFOLDER	00K	CDF	Second generation
>160	95		[145] ABBOTT	99J	D0	Second generation
>225	95		[146] ABBOTT	98E	D0	First generation
> 94	95		[147] ABBOTT	98J	D0	Third generation
>242	95		[148] GROSS-PILCH...	98		First generation
> 99	95		[149] ABE	97F	CDF	Third generation
>213	95		[150] ABE	97X	CDF	First generation
> 45.5	95		[151,152] ABREU	93J	DLPH	First + second generation
> 44.4	95		[153] ADRIANI	93M	L3	First generation
> 44.5	95		[153] ADRIANI	93M	L3	Second generation
> 45	95		[153] DECAMP	92	ALEP	Third generation
none 8.9–22.6	95		[154] KIM	90	AMY	First generation
none 10.2–23.2	95		[154] KIM	90	AMY	Second generation
none 5–20.8	95		[155] BARTEL	87B	JADE	
none 7–20.5	95	2	[156] BEHREND	86B	CELL	

[134] ABAZOV 05H search for scalar leptoquarks using $eejj$ and $e\nu jj$ events in $\overline{p}p$ collisions at E_{cm} = 1.8 TeV and 1.96 TeV. The limit above assumes B(eq) = 1. For B(eq) = 0.5 the bound becomes 234 GeV.

[135] ACOSTA 05P search for scalar leptoquarks using $eejj$, $e\nu jj$ events in $\overline{p}p$ collisions at E_{cm} = 1.96TeV. The limit above assumes B(eq) = 1. For B(eq) = 0.5 and 0.1, the bound becomes 205 GeV and 145 GeV, respectively.

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

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

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

[139] ACOSTA 05I search for scalar leptoquarks using $\nu\nu jj$ events in $\overline{p}p$ collisions at E_{cm} = 1.96 TeV. The limit above assumes B(νq) = 1.

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

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

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

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

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

[145] ABBOTT 99J search for leptoquarks using $\mu\nu jj$ events in $p\overline{p}$ collisions at E_{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.

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

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

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

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

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

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

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

[153] 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.

[154] KIM 90 assume pair production of charge 2/3 scalar-leptoquark via photon exchange. The decay of the first (second) generation leptoquark is assumed to be any mixture of de^+ and $u\overline{\nu}$ ($s\mu^+$ and $c\overline{\nu}$). See paper for limits for specific branching ratios.

[155] 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.

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

MASS LIMITS for Leptoquarks from Single Production

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>295	95	[157] AKTAS	05B	H1	First generation

		[158] CHEKANOV	05A ZEUS	Lepton-flavor violation
>298	95	[159] CHEKANOV	03B ZEUS	First generation
>197	95	[160] ABBIENDI	02B OPAL	First generation
		[161] CHEKANOV	02 ZEUS	Repl. by CHEKANOV 05A
>290	95	[162] ADLOFF	01C H1	First generation
>204	95	[163] BREITWEG	01 ZEUS	First generation
		[164] BREITWEG	00E ZEUS	First generation
>161	95	[165] ABREU	99G DLPH	First generation
>200	95	[166] ADLOFF	99 H1	First generation
		[167] DERRICK	97 ZEUS	Lepton-flavor violation
> 73	95	[168] ABREU	93J DLPH	Second generation
>168	95	[169] DERRICK	93 ZEUS	First generation

[157] AKTAS 05B limit is for a scalar, weak isoscalar, charge $-1/3$ leptoquark coupled with e_R. See their Fig. 3 for limits on states with different quantum numbers.

[158] CHEKANOV 05 search for various leptoquarks with lepton-flavor violating couplings. See their Figs.6–10 and Tables 1–8 for detailed limits.

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

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

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

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

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

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

[165] 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.

[166] 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.

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

[168] 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.

[169] 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. • • •				
		[170] CHEKANOV	05A ZEUS	Lepton-flavor violation
> 1.7	96	[171] ADLOFF	03 H1	First generation

> 46	90	[172] CHANG	03	BELL	Pati-Salam type
		[173] CHEKANOV	02	ZEUS	Repl. by CHEKANOV 05A
> 1.7	95	[174] CHEUNG	01B	RVUE	First generation
> 0.39	95	[175] ACCIARRI	00P	L3	$e^+e^- \rightarrow qq$
> 1.5	95	[176] ADLOFF	00	H1	First generation
> 0.2	95	[177] BARATE	00I	ALEP	e^+e^-
		[178] BARGER	00	RVUE	Cs
		[179] GABRIELLI	00	RVUE	Lepton flavor violation
> 0.74	95	[180] ZARNECKI	00	RVUE	S_1 leptoquark
		[181] ABBIENDI	99	OPAL	
> 19.3	95	[182] ABE	98V	CDF	$B_s \rightarrow e^{\pm}\mu^{\mp}$, Pati-Salam type
		[183] ACCIARRI	98J	L3	$e^+e^- \rightarrow q\overline{q}$
		[184] ACKERSTAFF	98V	OPAL	$e^+e^- \rightarrow q\overline{q}$, $e^+e^- \rightarrow b\overline{b}$
> 0.76	95	[185] DEANDREA	97	RVUE	$\widetilde{R}_2$ leptoquark
		[186] DERRICK	97	ZEUS	Lepton-flavor violation
		[187] GROSSMAN	97	RVUE	$B \rightarrow \tau^+\tau^-(X)$
		[188] JADACH	97	RVUE	$e^+e^- \rightarrow q\overline{q}$
>1200		[189] KUZNETSOV	95B	RVUE	Pati-Salam type
		[190] MIZUKOSHI	95	RVUE	Third generation scalar leptoquark
> 0.3	95	[191] BHATTACH...	94	RVUE	Spin-0 leptoquark coupled to $\overline{e}_R t_L$
		[192] DAVIDSON	94	RVUE	
> 18		[193] KUZNETSOV	94	RVUE	Pati-Salam type
> 0.43	95	[194] LEURER	94	RVUE	First generation spin-1 leptoquark
> 0.44	95	[194] LEURER	94B	RVUE	First generation spin-0 leptoquark
		[195] MAHANTA	94	RVUE	P and T violation
> 1		[196] SHANKER	82	RVUE	Nonchiral spin-0 leptoquark
> 125		[196] SHANKER	82	RVUE	Nonchiral spin-1 leptoquark

[170] CHEKANOV 05 search for various leptoquarks with lepton-flavor violating couplings. See their Figs.6–10 and Tables 1–8 for detailed limits.

[171] ADLOFF 03 limit is for the weak isotriplet spin-0 leptoquark at strong coupling $\lambda=\sqrt{4\pi}$. For the limits of leptoquarks with different quantum numbers, see their Table 3. Limits are derived from bounds on $e^{\pm}q$ contact interactions.

[172] The bound is derived from B($B^0 \rightarrow e^{\pm}\mu^{\mp}$) $< 1.7 \times 10^{-7}$.

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

[174] CHEUNG 01B quoted limit is for a scalar, weak isoscalar, charge $-1/3$ leptoquark with a coupling of electromagnetic strength. The limit is derived from bounds on contact interactions in a global electroweak analysis. For the limits of leptoquarks with different quantum numbers, see Table 5.

[175] ACCIARRI 00P limit is for the weak isoscalar spin-0 leptoquark with the coupling of electromagnetic strength. For the limits of leptoquarks with different quantum numbers, see their Table 4.

[176] ADLOFF 00 limit is for the weak isotriplet spin-0 leptoquark at strong coupling, $\lambda=\sqrt{4\pi}$. For the limits of leptoquarks with different quantum numbers, see their Table 2. ADLOFF 00 limits are from the Q^2 spectrum measurement of $e^+p \rightarrow e^+X$.

[177] 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.

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

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

[180] ZARNECKI 00 limit is derived from data of HERA, LEP, and Tevatron and from various low-energy data including atomic parity violation. Leptoquark coupling with electromagnetic strength is assumed.

[181] 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.

[182] 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).

[183] 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.

[184] 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.

[185] 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.

[186] 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.

[187] 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.

[188] 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.

[189] 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.

[190] 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.

[191] 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.

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

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

[194] 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.

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

[196] 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	[197] ABE	97G	CDF	E_6 diquark
none 15–31.7	95	[198] ABREU	94O	DLPH	SUSY E_6 diquark

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

[198] 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	[199] DONCHESKI	98	RVUE	$\Gamma(Z \rightarrow$ hadron)
none 200–980	95	[200] ABE	97G	CDF	$p\overline{p} \rightarrow g_A X$, $X \rightarrow 2$ jets
none 200–870	95	[201] ABE	95N	CDF	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow q\overline{q}$
none 240–640	95	[202] ABE	93G	CDF	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
> 50	95	[203] CUYPERS	91	RVUE	$\sigma(e^+ e^- \rightarrow$ hadrons)
none 120–210	95	[204] ABE	90H	CDF	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
> 29		[205] ROBINETT	89	THEO	Partial-wave unitarity
none 150–310	95	[206] ALBAJAR	88B	UA1	$p\overline{p} \rightarrow g_A X$, $g_A \rightarrow$ 2jets
> 20		BERGSTROM	88	RVUE	$p\overline{p} \rightarrow \Upsilon X$ via $g_A g$
> 9		[207] CUYPERS	88	RVUE	Υ decay
> 25		[208] DONCHESKI	88B	RVUE	Υ decay

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

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

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

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

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

[204] 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.

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

[206] 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.

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

[208] DONCHESKI 88B requires $\Gamma(\Upsilon \rightarrow g q\overline{q})/\Gamma(\Upsilon \rightarrow g g g) < 0.25$, where the former decay proceeds via axigluon exchange. A more conservative estimate of < 0.5 leads to $m_{g_A} > 21$ GeV.

X^0 (Heavy Boson) Searches in Z Decays

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

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[209] BARATE	98U	ALEP	$X^0 \to \ell\overline{\ell}, q\overline{q}, gg, \gamma\gamma, \nu\overline{\nu}$
		[210] ACCIARRI	97Q	L3	$X^0 \to$ invisible particle(s)
		[211] ACTON	93E	OPAL	$X^0 \to \gamma\gamma$
		[212] ABREU	92D	DLPH	$X^0 \to$ hadrons
		[213] ADRIANI	92F	L3	$X^0 \to$ hadrons
		[214] ACTON	91	OPAL	$X^0 \to$ anything
$<1.1 \times 10^{-4}$	95	[215] ACTON	91B	OPAL	$X^0 \to e^+e^-$
$<9 \times 10^{-5}$	95	[215] ACTON	91B	OPAL	$X^0 \to \mu^+\mu^-$
$<1.1 \times 10^{-4}$	95	[215] ACTON	91B	OPAL	$X^0 \to \tau^+\tau^-$
$<2.8 \times 10^{-4}$	95	[216] ADEVA	91D	L3	$X^0 \to e^+e^-$
$<2.3 \times 10^{-4}$	95	[216] ADEVA	91D	L3	$X^0 \to \mu^+\mu^-$
$<4.7 \times 10^{-4}$	95	[217] ADEVA	91D	L3	$X^0 \to$ hadrons
$<8 \times 10^{-4}$	95	[218] AKRAWY	90J	OPAL	$X^0 \to$ hadrons

[209] 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.

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

[211] 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 $\pm$ 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 $m_{X^0} = 60 \pm 1$ GeV.

[212] ABREU 92D give $\sigma_Z \cdot$ B($Z \to \gamma X^0$) $\cdot$ 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.

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

[214] 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.

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

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

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

[218] 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		[219] ODAKA	89	VNS	$\Gamma(X^0 \to e^+e^-) \cdot B(X^0 \to \text{hadrons}) \gtrsim 0.2$ MeV
>45	95	[220] DERRICK	86	HRS	$\Gamma(X^0 \to e^+e^-)$=6 MeV
>46.6	95	[221] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
>48	95	[221] ADEVA	85	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
		[222] BERGER	85B	PLUT	
none 39.8–45.5		[223] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=10 keV
>47.8	95	[223] ADEVA	84	MRKJ	$\Gamma(X^0 \to e^+e^-)$=4 MeV
none 39.8–45.2		[223] BEHREND	84C	CELL	
>47	95	[223] BEHREND	84C	CELL	$\Gamma(X^0 \to e^+e^-)$=4 MeV

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

[220] 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.

[221] 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.

[222] 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.

[223] 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	[224] ABE	93C	VNS	$\Gamma(ee)$
<(0.4–10)	95	[225] ABE	93C	VNS	$f = \gamma\gamma$
<(0.3–5)	95	[226,227] ABE	93D	TOPZ	$f = \gamma\gamma$
<(2–12)	95	[226,227] ABE	93D	TOPZ	f = hadrons
<(4–200)	95	[227,228] ABE	93D	TOPZ	$f = ee$
<(0.1–6)	95	[227,228] ABE	93D	TOPZ	$f = \mu\mu$
<(0.5–8)	90	[229] STERNER	93	AMY	$f = \gamma\gamma$

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

[225] 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.

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

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

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

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

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

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

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

Search for X^0 Resonance in Two-Photon Process

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

VALUE (MeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<2.6	95	[231] ACTON 93E	OPAL	m_{X^0}=60 ± 1 GeV
<2.9	95	BUSKULIC 93F	ALEP	$m_{X^0} \sim 60$ GeV

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

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

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

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

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

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

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

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

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

		[235] ABREU	96T	DLPH	f=e,μ,τ; F=$\gamma\gamma$
$<3.7 \times 10^{-6}$	95	[236] ABREU	96T	DLPH	f=ν; F=$\gamma\gamma$
		[237] ABREU	96T	DLPH	f=q; F=$\gamma\gamma$
$<6.8 \times 10^{-6}$	95	[236] ACTON	93E	OPAL	f=e,μ,τ; F=$\gamma\gamma$
$<5.5 \times 10^{-6}$	95	[236] ACTON	93E	OPAL	f=q; F=$\gamma\gamma$
$<3.1 \times 10^{-6}$	95	[236] ACTON	93E	OPAL	f=ν; F=$\gamma\gamma$
$<6.5 \times 10^{-6}$	95	[236] ACTON	93E	OPAL	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
$<7.1 \times 10^{-6}$	95	[236] BUSKULIC	93F	ALEP	f=e,μ; F=$\ell\overline{\ell}$, $q\overline{q}$, $\nu\overline{\nu}$
		[238] ADRIANI	92F	L3	f=q; F=$\gamma\gamma$

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

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

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

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

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

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

[239] 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}.

Heavy Particle Production in Quarkonium Decays

Limits are for branching ratios to modes shown.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-5}$	90	[240] BALEST	95	CLE2	$\Upsilon(1S) \rightarrow X^0\gamma$, $m_{X^0} < 5$ GeV
$< 3 \times 10^{-5}$–6×10^{-3}	90	[241] BALEST	95	CLE2	$\Upsilon(1S) \rightarrow X^0\overline{X}^0\gamma$, $m_{X^0} < 3.9$ GeV
$<5.6 \times 10^{-5}$	90	[242] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \rightarrow X^0\gamma$, $m_{X^0} < 7.2$ GeV
		[243] ALBRECHT	89	ARG	

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

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

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

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

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CHEKANOV	05	PL B610 212	S. Chekanov *et al.*	(HERA ZEUS Collab.)
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ABBIENDI	04G	EPJ C33 173	G. Abbiendi *et al.*	(OPAL Collab.)
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CHANG	03	PR D68 111101R	M.-C. Chang *et al.*	(BELLE Collab.)
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ABE	00	PRL 84 5716	F. Abe *et al.*	(CDF Collab.)
ABREU	00S	PL B485 45	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	00P	PL B489 81	M. Acciarri *et al.*	(L3 Collab.)
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ABREU	99G	PL B446 62	P. Abreu *et al.*	(DELPHI Collab.)
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COLANGELO	91	PL B253 154	P. Colangelo, G. Nardulli	(BARI)
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WALKER	91	APJ 376 51	T.P. Walker *et al.*	(HSCA, OSU, CHIC+)
ABE	90F	PL B246 297	K. Abe *et al.*	(VENUS Collab.)
ABE	90H	PR D41 1722	F. Abe *et al.*	(CDF Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy *et al.*	(OPAL Collab.)
ANTREASYAN	90C	PL B251 204	D. Antreasyan *et al.*	(Crystal Ball Collab.)
GONZALEZ-G...	90D	PL B240 163	M.C. Gonzalez-Garcia, J.W.F. Valle	(VALE)
GRIFOLS	90	NP B331 244	J.A. Grifols, E. Masso	(BARC)
GRIFOLS	90D	PR D42 3293	J.A. Grifols, E. Masso, T.G. Rizzo	(BARC, CERN+)
KIM	90	PL B240 243	G.N. Kim *et al.*	(AMY Collab.)
LOPEZ	90	PL B241 392	J.L. Lopez, D.V. Nanopoulos	(TAMU)
ALBAJAR	89	ZPHY C44 15	C. Albajar *et al.*	(UA1 Collab.)
ALBRECHT	89	ZPHY C42 349	H. Albrecht *et al.*	(ARGUS Collab.)
BARBIERI	89B	PR D39 1229	R. Barbieri, R.N. Mohapatra	(PISA, UMD)
LANGACKER	89B	PR D40 1569	P. Langacker, S. Uma Sankar	(PENN)
ODAKA	89	JPSJ 58 3037	S. Odaka *et al.*	(VENUS Collab.)
ROBINETT	89	PR D39 834	R.W. Robinett	(PSU)
ALBAJAR	88B	PL B209 127	C. Albajar *et al.*	(UA1 Collab.)
BAGGER	88	PR D37 1188	J. Bagger, C. Schmidt, S. King	(HARV, BOST)
BALKE	88	PR D37 587	B. Balke *et al.*	(LBL, UCB, COLO, NWES+)
BERGSTROM	88	PL B212 386	L. Bergstrom	(STOH)
CUYPERS	88	PRL 60 1237	F. Cuypers, P.H. Frampton	(UNCCH)
DONCHESKI	88	PL B206 137	M.A. Doncheski, H. Grotch, R. Robinett	(PSU)
DONCHESKI	88B	PR D38 412	M.A. Doncheski, H. Grotch, R.W. Robinett	(PSU)
ANSARI	87D	PL B195 613	R. Ansari *et al.*	(UA2 Collab.)
BARTEL	87B	ZPHY C36 15	W. Bartel *et al.*	(JADE Collab.)
BEHREND	86B	PL B178 452	H.J. Behrend *et al.*	(CELLO Collab.)
DERRICK	86	PL 166B 463	M. Derrick *et al.*	(HRS Collab.)
Also		PR D34 3286	M. Derrick *et al.*	(HRS Collab.)
JODIDIO	86	PR D34 1967	A. Jodidio *et al.*	(LBL, NWES, TRIU)
Also		PR D37 237 (erratum)	A. Jodidio *et al.*	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909	R.N. Mohapatra	(UMD)
ADEVA	85	PL 152B 439	B. Adeva *et al.*	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	C. Berger *et al.*	(PLUTO Collab.)
STOKER	85	PRL 54 1887	D.P. Stoker *et al.*	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	B. Adeva *et al.*	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	H.J. Behrend *et al.*	(CELLO Collab.)
BERGSMA	83	PL 122B 465	F. Bergsma *et al.*	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr *et al.*	(LBL, NWES, TRIU)
BEALL	82	PRL 48 848	G. Beall, M. Bander, A. Soni	(UCI, UCLA)
SHANKER	82	NP B204 375	O. Shanker	(TRIU)