# Heavy Bosons Other Than Higgs Bosons, Searches for

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

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

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **> 406** | 90 | [1] JODIDIO | 86 | ELEC | Any $\zeta$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| > 220 | 90 | [2] ALLET | 96 | CNTR | $\beta^+$ decay |
| > 281 | 90 | [3] KUZNETSOV | 95 | CNTR | Polarized neutron decay |
| > 282 | 90 | [4] KUZNETSOV | 94B | CNTR | Polarized neutron decay |
| > 439 | 90 | [5] BHATTACH... | 93 | RVUE | $Z$-$Z'$ mixing |
| > 250 | 90 | [6] SEVERIJNS | 93 | CNTR | $\beta^+$ decay |
| | | [7] IMAZATO | 92 | CNTR | $K^+$ decay |
| > 475 | 90 | [8] POLAK | 92B | RVUE | $\mu$ decay |
| > 240 | 90 | [9] AQUINO | 91 | RVUE | Neutron decay |
| > 496 | 90 | [9] AQUINO | 91 | RVUE | Neutron and muon decay |
| > 700 | | [10] COLANGELO | 91 | THEO | $m_{K_L^0} - m_{K_S^0}$ |
| > 477 | 90 | [11] POLAK | 91 | RVUE | $\mu$ decay |
| [none 540–23000] | | [12] BARBIERI | 89B | ASTR | SN 1987A; light $\nu_R$ |
| > 300 | 90 | [13] LANGACKER | 89B | RVUE | General |
| > 160 | 90 | [14] BALKE | 88 | CNTR | $\mu \to e\nu\overline{\nu}$ |
| > 482 | 90 | [1] JODIDIO | 86 | ELEC | $\zeta = 0$ |
| > 800 | | MOHAPATRA | 86 | RVUE | $SU(2)_L \times SU(2)_R \times U(1)$ |
| > 400 | 95 | [15] STOKER | 85 | ELEC | Any $\zeta$ |
| > 475 | 95 | [15] STOKER | 85 | ELEC | $\zeta$ <0.041 |
| | | [16] BERGSMA | 83 | CHRM | $\nu_\mu e \to \mu\nu_e$ |
| > 380 | 90 | [17] CARR | 83 | ELEC | $\mu^+$ decay |
| >1600 | | [18] BEALL | 82 | THEO | $m_{K_L^0} - m_{K_S^0}$ |
| [> 4000] | | STEIGMAN | 79 | COSM | Nucleosynthesis; light $\nu_R$ |

[1] JODIDIO 86 is the same TRIUMF experiment as STOKER 85 (and CARR 83); however, it uses a different technique. The results given here are combined results of the two techniques. The technique here involves precise measurement of the end-point $e^+$ spectrum in the decay of the highly polarized $\mu^+$.

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

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

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

[5] 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 $m_t$.

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

[7] IMAZATO 92 measure positron asymmetry in $K^+ \rightarrow \mu^+ \nu_\mu$ decay and obtain $\xi P_\mu > 0.990$ (90%CL). If $W_R$ couples to $u\bar{s}$ with full weak strength ($V^R_{us}$=1), the result corresponds to $m_{W_R}$ >653 GeV. See their Fig. 4 for $m_{W_R}$ limits for general $|V^R_{us}|^2 = 1 - |V^R_{ud}|^2$.

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

[9] 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.

[10] 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.

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

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

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

[14] 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.

[15] 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.

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

[17] CARR 83 is TRIUMF experiment with a highly polarized $\mu^+$ beam. Looked for deviation from $V-A$ at the high momentum end of the decay $e^+$ energy spectrum. Limit from previous world-average muon polarization parameter is $m_{W_R}$ >240 GeV. Assumes a light right-handed neutrino.

[18] 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.

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

Lighter mass eigenstate $W_1 = W_L \cos\zeta - W_R \sin\zeta$. Light $\nu_R$ assumed unless noted. Values in brackets are from cosmological and astrophysical considerations.

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 0.04 | 90 | [19] MISHRA | | 92 | CCFR | $\nu N$ scattering |
| −0.0006 to 0.0028 | 90 | [20] AQUINO | | 91 | RVUE | |
| [none 0.00001–0.02] | | [21] BARBIERI | | 89B | ASTR | SN 1987A |
| < 0.040 | 90 | [22] JODIDIO | | 86 | ELEC | $\mu$ decay |
| −0.056 to 0.040 | 90 | [22] JODIDIO | | 86 | ELEC | $\mu$ decay |

[19] MISHRA 92 limit is from the absence of extra large-$x$, large-$y$ $\overline{\nu}_\mu N \to \overline{\nu}_\mu X$ events at Tevatron, assuming left-handed $\nu$ 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 $\nu_R$ mass.

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

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

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

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

Couplings of $W'$ to quarks and leptons are taken to be identical with those of $W$. The following limits are obtained from $p\overline{p} \to W'X$ 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* |
|---|---|---|---|---|---|
| **>720** | 95 | [23] ABACHI | 96C | D0 | $W' \to e\nu_e$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >610 | 95 | [24] ABACHI | 95E | D0 | $W' \to e\nu_e$ and $W' \to \tau\nu_\tau \to e\nu\nu\overline{\nu}$ |
| >652 | 95 | [25] ABE | 95M | CDF | $W' \to e\nu_e$ |
| >251 | 90 | [26] ALITTI | 93 | UA2 | $W' \to q\overline{q}$ |
| none 260–600 | 95 | [27] RIZZO | 93 | RVUE | $W' \to q\overline{q}$ |
| >520 | 95 | [28] ABE | 91F | CDF | $W' \to e\nu$, $\mu\nu$ |
| none 101–158 | 90 | [29] ALITTI | 91 | UA2 | $W' \to q\overline{q}$ |
| >220 | 90 | [30] ALBAJAR | 89 | UA1 | $W' \to e\nu$ |
| >209 | 90 | [31] ANSARI | 87D | UA2 | $W' \to e\nu$ |
| >210 | 90 | [32] ARNISON | 86B | UA1 | $W' \to e\nu$ |
| >170 | 90 | [33] ARNISON | 83D | UA1 | $W' \to e\nu$ |

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

[24] 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 $m_{W'}$.

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

[26] 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.

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

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

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

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

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

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

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

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

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

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>505** | 95 | [34] ABE | 95 | CDF | $p\overline{p}$; $Z'_{SM} \to e^+e^-$ |
| **>779** | 95 | [35,36] LANGACKER | 92B | RVUE | Electroweak |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >490 | 95 | ABACHI | 96D | D0 | $p\overline{p}$; $Z'_{SM} \to e^+e^-$ |
| >398 | 95 | [37] VILAIN | 94B | CHM2 | $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ |
| >237 | 90 | [38] ALITTI | 93 | UA2 | $p\overline{p}$; $Z'_{SM} \to q\overline{q}$ |
| >119 | 90 | [39] ALLEN | 93 | CALO | $\nu e \to \nu e$ |
| none 490–560 | 95 | [40] RIZZO | 93 | RVUE | $p\overline{p}$; $Z'_{SM} \to q\overline{q}$ |
| >412 | 95 | ABE | 92B | CDF | $p\overline{p}$; $Z'_{SM} \to e^+e^-$, $\mu^+\mu^-$ |
| >387 | 95 | [41] ABE | 91D | CDF | $p\overline{p}$; $Z'_{SM} \to e^+e^-$ |
| >307 | 90 | [42] GEIREGAT | 91 | CHM2 | $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ |
| >426 | 90 | [43] ABE | 90F | VNS | $e^+e^-$ |
| >208 | 90 | [44] HAGIWARA | 90 | RVUE | $e^+e^-$ |
| >173 | 90 | [45] ALBAJAR | 89 | UA1 | $p\overline{p}$; $Z'_{SM} \to e^+e^-$ |
| >180 | 90 | [46] ANSARI | 87D | UA2 | $p\overline{p}$; $Z'_{SM} \to e^+e^-$ |
| >160 | 90 | [47] ARNISON | 86B | UA1 | $p\overline{p}$; $Z'_{SM} \to e^+e^-$ |

[34] ABE 95 limit is obtained assuming that $Z'$ decays to known fermions only.

[35] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t$ >89 GeV used.

[36] LANGACKER 92B give 95%CL limits on the $Z$-$Z'$ mixing $-0.0086 < \theta < 0.0005$.

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

[38] 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.

[39] ALLEN 93 limit is from total cross section for $\nu e \to \nu e$, where $\nu = \nu_e, \nu_\mu, \overline{\nu}_\mu$.

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

[41] ABE 91D give $\sigma(Z')\cdot B(e^+ e^-) < 1.31$ pb (95%CL) for $m_{Z'} > 200$ GeV at $E_{cm} = 1.8$ TeV. Limits ranging from 2 to 30 pb are given for $m_{Z'} = 100$–200 GeV.

[42] GEIREGAT 91 limit is from comparison of $g_V^e$ from $\nu_\mu e$ scattering with $\Gamma(Z \to e e)$ from LEP. Zero mixing assumed.

[43] 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.

[44] HAGIWARA 90 perform a fit to $e^+ e^-$ data at PEP, PETRA, and TRISTAN including $\mu^+ \mu^-$, $\tau^+ \tau^-$, and hadron cross sections and asymmetries.

[45] ALBAJAR 89 cross section limit at 630 GeV is $\sigma(Z')$ B($ee$) $< 4.2$ pb (90% CL).

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

[47] ARNISON 86B find no excess $e^+ e^-$ pairs among 13 pairs from $Z$. Set limit $\sigma \times$B$(e^+ e^-)$ <13 pb at CL = 90% at $E_{cm} = 546$ and 630 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 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* |
|---|---|---|---|---|---|
| **>445** | 95 | [48] ABE | 95 | CDF | $p\overline{p}$; $Z'_{LR} \to e^+ e^-$ |
| **>389** | 95 | [49,50] LANGACKER | 92B | RVUE | Electroweak |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >253 | 95 | [51] VILAIN | 94B | CHM2 | $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ |
| >130 | 95 | [52] ADRIANI | 93D | L3 | $Z$ parameters |
| (> 1500) | 90 | [53] ALTARELLI | 93B | RVUE | $Z$ parameters |
| none 490–560 | 95 | [54] RIZZO | 93 | RVUE | $p\overline{p}$; $Z_{LR} \to q\overline{q}$ |
| >310 | 95 | [55] ABE | 92B | CDF | $p\overline{p}$ |
| >230 | 95 | [56] ABE | 92B | CDF | $p\overline{p}$ |
| (> 900) | 90 | [57] DELAGUILA | 92 | RVUE | |
| (> 1400) | | [58] LAYSSAC | 92B | RVUE | $Z$ parameters |
| (> 564) | 90 | [59] POLAK | 92 | RVUE | $\mu$ decay |
| >474 | 90 | [60] POLAK | 92B | RVUE | Electroweak |
| (> 1340) | | [61] RENTON | 92 | RVUE | |
| (> 800) | 90 | [62] ALTARELLI | 91B | RVUE | $Z$ parameters |
| (> 795) | 90 | [63] DELAGUILA | 91 | RVUE | |
| >382 | 90 | [64] POLAK | 91 | RVUE | Electroweak |
| [> 2000] | | WALKER | 91 | COSM | Nucleosynthesis; light $\nu_R$ |
| [> 500] | | [65] GRIFOLS | 90 | ASTR | SN 1987A; light $\nu_R$ |
| (> 460) | 90 | [66] HE | 90B | RVUE | |
| [> 2400–6800] | | [67] BARBIERI | 89B | ASTR | SN 1987A; light $\nu_R$ |
| >189 | | [68] DELAGUILA | 89 | RVUE | $p\overline{p}$ |
| [> 10000] | | RAFFELT | 88 | ASTR | SN 1987A; light $\nu_R$ |
| >325 | 90 | [69] AMALDI | 87 | RVUE | |
| >278 | 90 | [70] DURKIN | 86 | RVUE | |
| >150 | 95 | [71] ADEVA | 85B | MRKJ | $e^+ e^- \to \mu^+ \mu^-$ |

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

[49] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t$ >89 GeV used.

[50] LANGACKER 92B give 95%CL limits on the $Z$-$Z'$ mixing $-0.0025 < \theta < 0.0083$.

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

[52] ADRIANI 93D give limits on the $Z$-$Z'$ mixing $-0.002 < \theta < 0.015$ assuming the ABE 92B mass limit.

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

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

[55] These limits assume that $Z'$ decays to known fermions only.

[56] These limits assume that $Z'$ decays to all $E_6$ fermions and their superpartners.

[57] See Fig. 7b and 8 in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane and $m_{Z'} - m_t$ plane from electroweak fit including '90 LEP data.

[58] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[59] POLAK 92 limit is from $m_{W_R}$ >477 GeV, which is derived from muon decay parameters assuming light $\nu_R$. Specific Higgs sector is assumed.

[60] POLAK 92B limit is from a simultaneous fit to charged and neutral sector in $SU(2)_L \times SU(2)_R \times U(1)$ model using $Z$ parameters, $m_W$, and low-energy neutral current data as of 1991. Light $\nu_R$ assumed and $m_t$=$m_H$=100 GeV used. Supersedes POLAK 91.

[61] RENTON 92 limits use LEP data taken up to '90 as well as $m_W$, $\nu N$, and atomic parity violation data. Specific Higgs structure is assumed.

[62] ALTARELLI 91B is based on $Z$ mass, widths, and $A_{FB}$. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m_t > 90$ GeV and $m_{H^0} < 1$ TeV assumed. For large $m_t$, the bound improves drastically. Bounds for $Z$-$Z'$ mixing angle and $Z$ mass shift without this model assumption are also given in the paper.

[63] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From $\nu N$ neutral current data with $m_Z = 91.10 \pm 0.04$ GeV, $m_t > 77$ GeV, $m_{H^0} < 1$ TeV assumed.

[64] POLAK 91 limit is from a simultaneous fit to charged and neutral sector in $SU(2)_L \times SU(2)_R \times U(1)$ model using $m_W$, $m_Z$, and low-energy neutral current data as of 1990. Light $\nu_R$ assumed and $m_t$=$m_H$=100 GeV used. Superseded by POLAK 92B.

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

[66] HE 90B model assumes a specific Higgs sector. Neutral current data of COSTA 88 as well as $m_Z$ is used. $g_R$ is left free in the fit.

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

[68] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z') \cdot B(Z' \rightarrow e^+ e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[69] A wide range of neutral current data as of 1986 are used in the fit.

[70] A wide range of neutral current data as of 1985 are used in the fit.

[71] ADEVA 85B measure asymmetry of $\mu$-pair production, following formalism of RIZZO 81.

## Limits for $Z_\chi$

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>425** | 95 | [72] ABE | 95 | CDF | $p\overline{p}$; $Z'_\chi \rightarrow e^+ e^-$ |
| **>321** | 95 | [73,74] LANGACKER | 92B | RVUE | Electroweak |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >196 | 95 | [75] BUSKULIC | 96N | ALEP | Hadronic cross section |
| >147 | 95 | [76] ABREU | 95M | DLPH | $Z$ parameters and $e^+ e^- \rightarrow \mu^+ \mu^- (n\gamma)$ |
| | | [77] NARDI | 95 | RVUE | $Z$ parameters |
| | | [78] BUSKULIC | 94 | ALEP | $Z$ parameters |
| >262 | 95 | [79] VILAIN | 94B | CHM2 | $\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$ |
| >117 | 95 | [80] ADRIANI | 93D | L3 | $Z$ parameters |
| (>900) | 90 | [81] ALTARELLI | 93B | RVUE | $Z$ parameters |
| >340 | 95 | [82] ABE | 92B | CDF | $p\overline{p}$ |
| >280 | 95 | [83] ABE | 92B | CDF | $p\overline{p}$ |
| (>650) | 90 | [84] DELAGUILA | 92 | RVUE | |
| (>760) | | [85] LAYSSAC | 92B | RVUE | $Z$ parameters |
| >148 | 95 | [86] LEIKE | 92 | RVUE | $Z$ parameters |
| (>700) | | [87] RENTON | 92 | RVUE | |
| (> 500) | 90 | [88] ALTARELLI | 91B | RVUE | $Z$ parameters |
| (> 570) | | [89] BUCHMUEL... | 91 | RVUE | $Z$ parameters |
| (> 555) | 90 | [90] DELAGUILA | 91 | RVUE | |
| [>1470] | | [91] FARAGGI | 91 | COSM | Nucleosynthesis; light $\nu_R$ |
| >320 | 90 | [92] GONZALEZ-G.. | 91 | RVUE | |
| >221 | | [93] MAHANTHAP.. | 91 | RVUE | Cs |
| >231 | 90 | [94,95] ABE | 90F | VNS | $e^+ e^-$ |
| >206 | 90 | [95,96] ABE | 90F | RVUE | $e^+ e^-$, $\nu_\mu e$ |
| >335 | | [97] BARGER | 90B | RVUE | $p\overline{p}$ |
| (> 650) | 90 | [98] GLASHOW | 90 | RVUE | |
| [> 1140] | | [99] GONZALEZ-G.. | 90D | COSM | Nucleosynthesis; light $\nu_R$ |
| [> 2100] | | [100] GRIFOLS | 90 | ASTR | SN 1987A; light $\nu_R$ |
| none <150 or > 363 | 90 | [101] HAGIWARA | 90 | RVUE | $e^+ e^-$ |
| >177 | | [102] DELAGUILA | 89 | RVUE | $p\overline{p}$ |
| >280 | 95 | [103] DORENBOS... | 89 | CHRM | $g_\chi = g_Z$ |
| >352 | 90 | [104] COSTA | 88 | RVUE | |
| >170 | 90 | [105] ELLIS | 88 | RVUE | $p\overline{p}$ |
| >273 | 90 | [104] AMALDI | 87 | RVUE | |
| >266 | 90 | [106] MARCIANO | 87 | RVUE | |
| >283 | 90 | [107] DURKIN | 86 | RVUE | |

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

[73] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t$ >89 GeV used.

[74] LANGACKER 92B give 95%CL limits on the $Z$-$Z'$ mixing $-0.0048 < \theta < 0.0097$.

[75] BUSKULIC 96N limit is from a combined fit to the hadronic cross sections measured at $\sqrt{s}$=130, 136 GeV (ALEPH) and $\sqrt{s}$=58 GeV (TOPAZ). Zero mixing is assumed.

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

[77] NARDI 95 give 90%CL limits on $Z$-$Z'$ mixing $-0.0032 < \theta < 0.0031$ for $M_{Z'}$ >500 GeV, $m_t$=170 GeV, $m_H$=250 GeV, $\alpha_s$=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0032 < \theta < 0.0079$.

[78] BUSKULIC 94 give 95%CL limits on the $Z$-$Z'$ mixing $-0.0091 < \theta < 0.0023$.

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

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

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

[82] These limits assume that $Z'$ decays to known fermions only.

[83] These limits assume that $Z'$ decays to all $E_6$ fermions and their superpartners.

[84] See Fig. 7a and 8 in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane and $m_{Z'} - m_t$ plane from electroweak fit including '90 LEP data.

[85] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[86] LEIKE 92 is based on '90 LEP data published in LEP 92.

[87] RENTON 92 limits use LEP data taken up to '90 as well as $m_W$, $\nu N$, and atomic parity violation data. Specific Higgs structure is assumed.

[88] ALTARELLI 91B is based on $Z$ mass, widths, and $A_{FB}$. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m_t > 90$ GeV and $m_{H^0} < 1$ TeV assumed. For large $m_t$, the bound improves drastically. Bounds for $Z$-$Z'$ mixing angle and $Z$ mass shift without this model assumption are also given in the paper.

[89] BUCHMUELLER 91 limit is from LEP data. Specific assumption is made for the Higgs sector.

[90] DELAGUILA 91 bounds have extra assumption of superstring motivated Higgs sector. From $\nu N$ neutral current data with $m_Z = 91.10 \pm 0.04$ GeV, $m_t > 77$ GeV, $m_{H^0} < 1$ TeV assumed.

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

[92] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, $Z$ mass and widths, $m_W$ from ABE 90G. 100 <$m_t$ < 200 GeV, $m_{H^0} = 100$ GeV assumed. Dependence on $m_t$ is shown in Fig. 7.

[93] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with $m_W$, $m_Z$.

[94] ABE 90F use data for $R$, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[95] ABE 90F fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[96] $e^+e^-$ data for $R$, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below $Z$ as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[97] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \rightarrow Z') \cdot B(Z' \rightarrow e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for $Z'$ decay.

[98] GLASHOW 90 model assumes a specific Higgs sector. See GLASHOW 90B.

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

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

[101] HAGIWARA 90 perform a fit to $e^+e^-$ data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries. The upper mass limit disappears at 2.7 s.d.

[102] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z') \cdot B(Z' \rightarrow e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[103] DORENBOSCH 89 obtain the limit $(g_\chi/g_Z)^2 \cdot (m_Z/m_{Z_\chi})^2 < 0.11$ at 95% CL from the processes $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$ and $\nu_\mu e \rightarrow \nu_\mu e$.

[104] A wide range of neutral current data as of 1986 are used in the fit.

[105] $Z'$ mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when $Z'$ decays only into light quarks and leptons.

[106] MARCIANO 87 limit from unitarity of Cabibbo-Kobayashi-Maskawa matrix.

[107] A wide range of neutral current data as of 1985 are used in the fit.

## Limits for $Z_\psi$

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>415** | 95 | [108] ABE | 95 | CDF | $p\overline{p}$; $Z'_\psi \rightarrow e^+e^-$ |
| **>160** | 95 | [109,110] LANGACKER | 92B | RVUE | Electroweak |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >148 | 95 | [111] BUSKULIC | 96N | ALEP | Hadronic cross section |
| >105 | 95 | [112] ABREU | 95M | DLPH | $Z$ parameters and $e^+e^- \rightarrow \mu^+\mu^-(n\gamma)$ |
| | | [113] NARDI | 95 | RVUE | $Z$ parameters |
| >135 | 95 | [114] VILAIN | 94B | CHM2 | $\nu_\mu e \rightarrow \nu_\mu e$ and $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$ |
| >118 | 95 | [115] ADRIANI | 93D | L3 | $Z$ parameters |
| >320 | 95 | [116] ABE | 92B | CDF | $p\overline{p}$ |
| >180 | 95 | [117] ABE | 92B | CDF | $p\overline{p}$ |
| >122 | 95 | [118] LEIKE | 92 | RVUE | $Z$ parameters |
| >105 | 90 | [119,120] ABE | 90F | VNS | $e^+e^-$ |
| >146 | 90 | [120,121] ABE | 90F | RVUE | $e^+e^-$, $\nu_\mu e$ |
| >320 | | [122] BARGER | 90B | RVUE | $p\overline{p}$ |
| [> 160] | | [123] GONZALEZ-G.. | 90D | COSM | Nucleosynthesis; light $\nu_R$ |
| [> 2000] | | [124] GRIFOLS | 90D | ASTR | SN 1987A; light $\nu_R$ |
| >136 | 90 | [125] HAGIWARA | 90 | RVUE | $e^+e^-$ |
| >154 | 90 | [126] AMALDI | 87 | RVUE | |
| >146 | 90 | [127] DURKIN | 86 | RVUE | |

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

[109] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t$ >89 GeV used.

[110] LANGACKER 92B give 95%CL limits on the $Z$-$Z'$ mixing $-0.0025 < \theta < 0.013$.

[111] BUSKULIC 96N limit is from a combined fit to the hadronic cross sections measured at $\sqrt{s}$=130, 136 GeV (ALEPH) and $\sqrt{s}$=58 GeV (TOPAZ). Zero mixing is assumed.

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

[113] NARDI 95 give 90%CL limits on $Z$-$Z'$ mixing $-0.0056 < \theta < 0.0055$ for $M_{Z'} > 500$ GeV, $m_t$=170 GeV, $m_H$=250 GeV, $\alpha_s$=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0066 < \theta < 0.0071$.
[114] VILAIN 94B assume $m_t$ = 150 GeV and $\theta$=0. See Fig. 2 for limit contours in the mass-mixing plane.
[115] ADRIANI 93D give limits on the $Z$-$Z'$ mixing $-0.003 < \theta < 0.020$ assuming the ABE 92B mass limit.
[116] These limits assume that $Z'$ decays to known fermions only.
[117] These limits assume that $Z'$ decays to all $E_6$ fermions and their superpartners.
[118] LEIKE 92 is based on '90 LEP data published in LEP 92.
[119] ABE 90F use data for $R$, $R_{\ell\ell}$, and $A_{\ell\ell}$.
[120] ABE 90F fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.
[121] $e^+e^-$ data for $R$, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below $Z$ as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.
[122] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \to Z') \cdot B(Z' \to e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for $Z'$ decay.
[123] These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ($\delta N_\nu < 1$) constrains $Z'$ masses if $\nu_R$ is light ($\lesssim 1$ MeV).
[124] GRIFOLS 90D limit holds for $m_{\nu_R} \lesssim 1$ MeV. See also RIZZO 91.
[125] HAGIWARA 90 perform a fit to $e^+e^-$ data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.
[126] A wide range of neutral current data as of 1986 are used in the fit.
[127] A wide range of neutral current data as of 1985 are used in the fit.

## Limits for $Z_\eta$

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>440** | 95 | [128] ABE | 95 | CDF | $p\overline{p}$; $Z'_\eta \to e^+e^-$ |
| **>182** | 95 | [129,130] LANGACKER | 92B | RVUE | Electroweak |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| >167 | 95 | [131] BUSKULIC | 96N | ALEP | Hadronic cross section |
| >109 | 95 | [132] ABREU | 95M | DLPH | $Z$ parameters and $e^+e^- \to \mu^+\mu^-(n\gamma)$ |
| | | [133] NARDI | 95 | RVUE | $Z$ parameters |
| >100 | 95 | [134] VILAIN | 94B | CHM2 | $\nu_\mu e \to \nu_\mu e$ and $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$ |
| >100 | 95 | [135] ADRIANI | 93D | L3 | $Z$ parameters |
| (>500) | 90 | [136] ALTARELLI | 93B | RVUE | $Z$ parameters |
| >340 | 95 | [137] ABE | 92B | CDF | $p\overline{p}$ |
| >230 | 95 | [138] ABE | 92B | CDF | $p\overline{p}$ |
| (>450) | 90 | [139] DELAGUILA | 92 | RVUE | |
| (>315) | | [140] LAYSSAC | 92B | RVUE | $Z$ parameters |
| >118 | 95 | [141] LEIKE | 92 | RVUE | $Z$ parameters |
| (>470) | | [142] RENTON | 92 | RVUE | |
| (> 300) | 90 | [143] ALTARELLI | 91B | RVUE | $Z$ parameters |
| >120 | 90 | [144] GONZALEZ-G.. | 91 | RVUE | |

| | | | | | | |
|---|---|---|---|---|---|---|
| >125 | 90 | [145,146] | ABE | 90F | VNS | $e^+ e^-$ |
| >115 | 90 | [146,147] | ABE | 90F | RVUE | $e^+ e^-$, $\nu_\mu e$ |
| >340 | | [148] | BARGER | 90B | RVUE | $p\overline{p}$ |
| [> 820] | | [149] | GONZALEZ-G.. | 90D | COSM | Nucleosynthesis; light $\nu_R$ |
| [> 3300] | | [150] | GRIFOLS | 90 | ASTR | SN 1987A; light $\nu_R$ |
| >100 | 90 | [151] | HAGIWARA | 90 | RVUE | $e^+ e^-$ |
| [> 1040] | | [149] | LOPEZ | 90 | COSM | Nucleosynthesis; light $\nu_R$ |
| >173 | | [152] | DELAGUILA | 89 | RVUE | $p\overline{p}$ |
| >129 | 90 | [153] | COSTA | 88 | RVUE | |
| >156 | 90 | [154] | ELLIS | 88 | RVUE | |
| >167 | 90 | [155] | ELLIS | 88 | RVUE | $p\overline{p}$ |
| >111 | 90 | [153] | AMALDI | 87 | RVUE | |
| >143 | 90 | [156] | BARGER | 86B | RVUE | $p\overline{p}$ |
| >130 | 90 | [157] | DURKIN | 86 | RVUE | |
| [> 760] | | [149] | ELLIS | 86 | COSM | Nucleosynthesis; light $\nu_R$ |
| [> 500] | | [149] | STEIGMAN | 86 | COSM | Nucleosynthesis; light $\nu_R$ |

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

[129] LANGACKER 92B fit to a wide range of electroweak data including LEP results available early '91. $m_t$ >89 GeV used.

[130] LANGACKER 92B give 95%CL limits on the $Z$-$Z'$ mixing $-0.038 < \theta < 0.002$.

[131] BUSKULIC 96N limit is from a combined fit to the hadronic cross sections measured at $\sqrt{s}$=130, 136 GeV (ALEPH) and $\sqrt{s}$=58 GeV (TOPAZ). Zero mixing is assumed.

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

[133] NARDI 95 give 90%CL limits on $Z$-$Z'$ mixing $-0.0087 < \theta < 0.0075$ for $M_{Z'}$ >500 GeV, $m_t$=170 GeV, $m_H$=250 GeV, $\alpha_s$=0.12. The bound is relaxed under the simultaneous presence of the mixing of the known fermions with new heavy states, $-0.0087 < \theta < 0.010$.

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

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

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

[137] These limits assume that $Z'$ decays to known fermions only.

[138] These limits assume that $Z'$ decays to all $E_6$ fermions and their superpartners.

[139] See Fig. 7d in DELAGUILA 92 for the allowed region in $m_{Z'}$-mixing plane from electroweak fit including '90 LEP data.

[140] LAYSSAC 92B limit is from LEP data available spring '92. Specific Higgs sector is assumed. See also LAYSSAC 92.

[141] LEIKE 92 is based on '90 LEP data published in LEP 92.

[142] RENTON 92 limits use LEP data taken up to '90 as well as $m_W$, $\nu N$, and atomic parity violation data. Specific Higgs structure is assumed.

[143] ALTARELLI 91B is based on $Z$ mass, widths, and $A_{FB}$. The limits are for superstring motivated models with extra assumption on the Higgs sector. $m_t$ > 90 GeV and $m_{H^0}$ < 1 TeV assumed. For large $m_t$, the bound improves drastically. Bounds for $Z$-$Z'$ mixing angle and $Z$ mass shift without this model assumption are also given in the paper.

[144] GONZALEZ-GARCIA 91 limit is based on low-energy neutral current data, LEP $Z$ mass and widths, $m_W$ from ABE 90G. 100 $< m_t <$ 200 GeV, $m_{H^0} = 100$ GeV assumed. Dependence on $m_t$ is shown in Fig. 8.

[145] ABE 90F use data for $R$, $R_{\ell\ell}$, and $A_{\ell\ell}$.

[146] ABE 90F fix $m_W = 80.49 \pm 0.43 \pm 0.24$ GeV and $m_Z = 91.13 \pm 0.03$ GeV.

[147] $e^+e^-$ data for $R$, $R_{\ell\ell}$, $A_{\ell\ell}$, and $A_{c\overline{c}}$ below $Z$ as well as $\nu_\mu e$ scattering data of GEIREGAT 89 is used in the fit.

[148] BARGER 90B limit is based on CDF limit $\sigma(p\overline{p} \rightarrow Z') \cdot B(Z' \rightarrow e^+e^-) < 1$ pb (Nodulman, EPS Conf. '89). Assumes no new threshold is open for $Z'$ decay.

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

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

[151] HAGIWARA 90 perform a fit to $e^+e^-$ data at PEP, PETRA, and TRISTAN including $\mu^+\mu^-$, $\tau^+\tau^-$, and hadron cross sections and asymmetries.

[152] DELAGUILA 89 limit is based on $\sigma(p\overline{p} \rightarrow Z') \cdot B(Z' \rightarrow e^+e^-) < 1.8$ pb at CERN $p\overline{p}$ collider.

[153] A wide range of neutral current data as of 1986 are used in the fit.

[154] $Z_\eta$ mass limits obtained by combining constraints from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider and the global analysis of neutral current data by COSTA 88. Least favorable spectrum of three ($E_6$ 27) generations of particles and their superpartners are assumed.

[155] $Z'$ mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when $Z'$ decays only into light quarks and leptons.

[156] BARGER 86B limit is based on UA1/UA2 limit on $p\overline{p} \rightarrow Z'$, $Z' \rightarrow e^+e^-$ (Lepton Photon Symp., Kyoto, '85). Extra decay channels for $Z'$ are assumed not be open.

[157] A wide range of neutral current data as of 1985 are used in the fit.

## Limits for other $Z'$

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

| *VALUE* (GeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [158] DELAGUILA | 92 | RVUE | |
| >360 | | [159] ALTARELLI | 91 | RVUE | $Z_\beta$ with $\tan\beta = \sqrt{3/5}$; Cs |
| >190 | | [160] MAHANTHAP.. | 91 | RVUE | $Z_\beta$ with $\tan\beta = \sqrt{3/5}$; Cs |
| | | [161] GRIFOLS | 90C | RVUE | |
| | | [162] DELAGUILA | 89 | RVUE | $p\overline{p}$ |
| >180 | 90 | [163,164] COSTA | 88 | RVUE | $Z_\beta$ with $\tan\beta = \sqrt{15}$ |
| >158 | 90 | [165] ELLIS | 88 | RVUE | $Z_\beta$ ($\tan\beta = \sqrt{15}$), $p\overline{p}$ |

[158] Fig. 7c and 7e in DELAGUILA 92 give limits for $\tan\beta = -1/\sqrt{15}$ and $\sqrt{15}$ from electroweak fit including '90 LEP data.

[159] ALTARELLI 91 limit is from atomic parity violation in Cs together with LEP, CDF data. $Z$-$Z'$ mixing is assumed to be zero to set the limit.

[160] MAHANTHAPPA 91 limit is from atomic parity violation in Cs with $m_W$, $m_Z$. See Table III of MAHANTHAPPA 91 (corrected in erratum) for limits on various $Z'$ models.

[161] GRIFOLS 90C obtains a limit for $Z'$ mass as a function of mixing angle $\beta$ (his $\theta = \beta - \pi/2$), which is derived from a LAMPF experiment on $\sigma(\nu_e e)$ (ALLEN 90). The result is shown in Fig. 1.

[162] See Table I of DELAGUILA 89 for limits on various $Z'$ models.
[163] $g_\beta = e/\cos\theta_W$ and $\rho = 1$ assumed.
[164] A wide range of neutral current data as of 1986 are used in the fit.
[165] $Z'$ mass limits from non-observation of an excess of $\ell^+\ell^-$ pairs at the CERN $p\overline{p}$ collider [based on ANSARI 87D and GEER Uppsala Conf. 87]. The limits apply when $Z'$ decays only into light quarks and leptons.

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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* |
|---|---|---|---|---|---|---|
| **> 97** | 95 | [166] | ABACHI | 95G | D0 | Second generation |
| > 96 | 95 | [167] | ABE | 95U | CDF | Second generation |
| **>116** | 95 | [168] | ABACHI | 94B | D0 | First generation |
| > 80 | 95 | [169] | ABE | 93I | CDF | First generation |
| > 45.5 | 95 | [170,171] | ABREU | 93J | DLPH | First + second generation |
| > 44.4 | 95 | [172] | ADRIANI | 93M | L3 | First generation |
| > 44.6 | 95 | [173] | ADRIANI | 93M | L3 | Third generation |
| > 44 | 95 | [172] | DECAMP | 92 | ALEP | First or second generation |
| **> 45** | 95 | [172] | DECAMP | 92 | ALEP | Third generation |
| > 44.2 | 95 | [172] | ALEXANDER | 91 | OPAL | First or second generation |
| > 41.4 | 95 | [172] | ALEXANDER | 91 | OPAL | Third generation |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| > 44.5 | 95 | [172] | ADRIANI | 93M | L3 | Second generation |
| > 42.1 | 95 | [174] | ABREU | 92F | DLPH | Second generation |
| > 74 | 95 | [175] | ALITTI | 92E | UA2 | First generation |
| > 43.2 | 95 | [172] | ADEVA | 91B | L3 | First generation |
| > 43.4 | 95 | [172] | ADEVA | 91B | L3 | Second generation |
| none 8.9–22.6 | 95 | [176] | KIM | 90 | AMY | First generation |
| none 10.2–23.2 | 95 | [176] | KIM | 90 | AMY | Second generation |
| none 5–20.8 | 95 | [177] | BARTEL | 87B | JADE | |
| none 7–20.5 | 95 | 2 [178] | BEHREND | 86B | CELL | |

[166] ABACHI 95G search for scalar leptoquarks using $\mu\mu$+jets and $\mu\nu_\mu$+jets events in $p\overline{p}$ collisions at $E_{cm} = 1.8$ TeV. The limit is for $B(\mu q) = B(\nu q) = 0.5$ and improves to >119 GeV for $B(\mu q) = 1$.
[167] ABE 95U search for scalar leptoquarks of charge $Q$=2/3 and $-1/3$ using $\mu\mu jj$ events in $p\overline{p}$ collisions at $E_{cm}$=1.8 TeV. The limit is for $B(\mu q)=B(\nu q)=0.5$ and improves to > 131 GeV for $B(\mu q)=1$.
[168] ABACHI 94B search for $eejj$ and $e\nu jj$ events in $p\overline{p}$ collisions at $E_{cm}$=1.8 TeV. ABACHI 94B obtain the limit >120 GeV for $B(eq)=B(\nu q)=0.5$ and >133 GeV for $B(eq)=1$. A change in the DØ luminosity monitor constant reduces the first bound to >116 GeV quoted above (see FERMILAB-TM-1911). This limit does not depend on the electroweak quantum numbers of the leptoquark.
[169] ABE 93I search for $\ell\ell jj$ events in $p\overline{p}$ collisions at $E_{cm}$=1.8 TeV. The limit is for $B(eq) = B(\nu q) = 0.5$ and improves to >113 GeV for $B(eq) = 1$. This limit does not depend on electroweak quantum numbers of the leptoquark.
[170] Limit is for charge $-1/3$ isospin-0 leptoquark with $B(\ell q) = 2/3$.
[171] First and second generation leptoquarks are assumed to be degenerate. The limit is slightly lower for each generation.

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

[173] ADRIANI 93M limit for charge $-1/3$, isospin-0 leptoquark decaying to $\tau b$.

[174] ABREU 92F limit is for charge $-1/3$ isosin-0 leptoquark with B($\mu q$)=2/3. If first and second generation leptoquarks are degenerate, the limit is 43.0 GeV, and for a charge 2/3 second generation leptoquark 43.4 GeV. Cross-section limit for pair production of states decaying to $\ell q$ is given in the paper.

[175] ALITTI 92E search for $\ell\ell jj$ and $\ell\nu jj$ events in $p\overline{p}$ collisions at $E_{cm}$=630 GeV. The limit is for B($eq$) = 1 and is reduced to 67 GeV for B($eq$) = B($\nu q$) = 0.5. This limit does not depend on electroweak quantum numbers of the leptoquark.

[176] 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.

[177] 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.

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

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## MASS LIMITS for Leptoquarks from Single Production

These limits depend on the $q$-$\ell$-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* |
|---|---|---|---|---|---|---|
| **>237** | 95 | [179] | AID | 96B | H1 | First generation |
| **> 73** | 95 | [180] | ABREU | 93J | DLPH | Second generation |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| >230 | 95 | [181] | AHMED | 94B | H1 | Sup. by AID 96B |
| > 65 | 95 | [180] | ABREU | 93J | DLPH | First generation |
| >181 | 95 | [182] | ABT | 93 | H1 | First generation |
| >168 | 95 | [183] | DERRICK | 93 | ZEUS | First generation |

[179] AID 96B search for single leptoquark production at HERA taking into account possible decays of leptoquark into 2nd or 3rd generations. The quoted limit is for a scalar leptoquark which solely couples to the first generation with electromagnetic strength. For limits on states with different quantum numbers and the limits in the coupling-mass plane, see their Fig. 2, Fig. 3, and Table 2. AID 96B supersedes AHMED 94B.

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

[181] AHMED 94B limit is for the left-handed leptoquark decaying to $eq$ and $\nu q$ with B($eq$) = B($\nu q$)=1/2. Electromagnetic coupling strength is assumed for the scalar leptoquark interaction. For limits on states with different quantum numbers and the limits in the coupling-mass plane, see their Table 2 and Fig. 6.

[182] ABT 93 search for single leptoquark production in $ep$ collisions with the decays $eq$ and $\nu q$. The limit is for a leptoquark coupling of electromagnetic strength and assumes B($eq$) = B($\nu q$) = 1/2. The limit for B($eq$) = 1 is 178 GeV. For limits on states with different quantum numbers, see their Fig. 2. ABT 93 superseded by AHMED 94B.

[183] DERRICK 93 search for single leptoquark production in $ep$ collisions with the decay $eq$ and $\nu q$. The limit is for leptoquark coupling of electromagnetic strength and assumes B($eq$) = B($\nu q$) = 1/2. The limit for B($eq$) = 1 is 176 GeV. For limits on states with different quantum numbers, see their Table 3.

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## Indirect Limits for Leptoquarks

| *VALUE* (TeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $>$ 0.31 | 95 | [184] AID | 95 | H1 | First generation |
| $>$1200 | | [185] KUZNETSOV | 95B | RVUE | Pati-Salam type |
| | | [186] MIZUKOSHI | 95 | RVUE | Third generation lepto-quark |
| $>$ 0.3 | 95 | [187] BHATTACH... | 94 | RVUE | Spin-0 leptoquark coupled to $\overline{e}_R t_L$ |
| | | [188] DAVIDSON | 94 | RVUE | |
| $>$ 18 | | [189] KUZNETSOV | 94 | RVUE | Pati-Salam type |
| $>$ 0.43 | 95 | [190] LEURER | 94 | RVUE | First generation spin-1 leptoquark |
| $>$ 0.44 | 95 | [190] LEURER | 94B | RVUE | First generation spin-0 leptoquark |
| | | [191] MAHANTA | 94 | RVUE | $P$ and $T$ violation |
| $>$ 350 | | [192] DESHPANDE | 83 | RVUE | Sup. by KUZNETSOV 95B |
| $>$ 1 | | [193] SHANKER | 82 | RVUE | Nonchiral spin-0 lepto-quark |
| $>$ 125 | | [193] SHANKER | 82 | RVUE | Nonchiral spin-1 lepto-quark |

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

[185] KUZNETSOV 95B use $\pi$, $K$, $B$, $\tau$ decays and $\mu e$ conversion and give a list of bounds on the leptoquark mass and the fermion mixing matrix in the Pati-Salam model. The quoted limit is from $K_L \to \mu e$ decay assuming zero mixing. See also KUZNETSOV 94, DESHPANDE 83, and DIMOPOULOS 81.

[186] MIZUKOSHI 95 calculate the one-loop radiative correction to the $Z$-physics parameters in various leptoquark models. See their Fig. 4 for the exclusion plot of third generation leptoquark models in mass-coupling plane.

[187] 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.

[188] DAVIDSON 94 gives an extensive list of the bounds on leptoquark-induced four-fermion insteractions from $\pi$, $K$, $D$, $B$, $\mu$, $\tau$ decays and meson mixings, *etc.* See Table 15 of DAVIDSON 94 for detail.

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

[190] LEURER 94, LEURER 94B limits are obtained from atomic parity violation and apply to any chiral leptoquark which couples to the first generation with electromagnetic strength. For a nonchiral leptoquark, universality in $\pi_{\ell 2}$ decay provides a much more stringent bound. See also SHANKER 82.

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

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

[193] From $(\pi \to e\nu)/(\pi \to \mu\nu)$ 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 15–31.7 | 95 | [194] ABREU | 94O | DLPH | SUSY $E_6$ diquark |

[194] ABREU 94O limit is from $e^+ e^- \to \overline{cs}\,cs$. Range extends up to 43 GeV if diquarks are degenerate in mass.

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## 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. • • • | | | | | |
| none 200–870 | 95 | [195] ABE | 95N | CDF | $p\overline{p} \to g_A$X, $g_A \to q\overline{q}$ |
| none 240–640 | 95 | [196] ABE | 93G | CDF | $p\overline{p} \to g_A$X, $g_A \to$ 2jets |
| >50 | 95 | [197] CUYPERS | 91 | RVUE | $\sigma(e^+ e^- \to$ hadrons) |
| none 120–210 | 95 | [198] ABE | 90H | CDF | $p\overline{p} \to g_A$X, $g_A \to$ 2jets |
| >29 | | [199] ROBINETT | 89 | THEO | Partial-wave unitarity |
| none 150–310 | 95 | [200] ALBAJAR | 88B | UA1 | $p\overline{p} \to g_A$X, $g_A \to$ 2jets |
| >20 | | BERGSTROM | 88 | RVUE | $p\overline{p} \to \Upsilon$X via $g_A g$ |
| > 9 | | [201] CUYPERS | 88 | RVUE | $\Upsilon$ decay |
| >25 | | [202] DONCHESKI | 88B | RVUE | $\Upsilon$ decay |

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

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

[197] CUYPERS 91 compare $\alpha_s$ measured in $\Upsilon$ decay and that from $R$ at PEP/PETRA energies.

[198] 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.

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

[200] 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.

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

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

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

Searches for radiative transition of $Z$ to a lighter spin-0 state $X^0$ decaying to hadrons, a lepton pair, or a photon pair 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. • • • | | | | | |
| | | [203] ACTON | | 93E OPAL | $X^0 \to \gamma\gamma$ |
| | | [204] ABREU | | 92D DLPH | $X^0 \to$ hadrons |
| | | [205] ADRIANI | | 92F L3 | $X^0 \to$ hadrons |
| | | [206] ACTON | | 91 OPAL | $X^0 \to$ anything |
| $<1.1 \times 10^{-4}$ | 95 | [207] ACTON | | 91B OPAL | $X^0 \to e^+ e^-$ |
| $<9 \times 10^{-5}$ | 95 | [207] ACTON | | 91B OPAL | $X^0 \to \mu^+ \mu^-$ |
| $<1.1 \times 10^{-4}$ | 95 | [207] ACTON | | 91B OPAL | $X^0 \to \tau^+ \tau^-$ |
| $<2.8 \times 10^{-4}$ | 95 | [208] ADEVA | | 91D L3 | $X^0 \to e^+ e^-$ |
| $<2.3 \times 10^{-4}$ | 95 | [208] ADEVA | | 91D L3 | $X^0 \to \mu^+ \mu^-$ |
| $<4.7 \times 10^{-4}$ | 95 | [209] ADEVA | | 91D L3 | $X^0 \to$ hadrons |
| $<8 \times 10^{-4}$ | 95 | [210] AKRAWY | | 90J OPAL | $X^0 \to$ hadrons |

[203] 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 $\gamma$ 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.

[204] 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 $X^0$.

[205] ADRIANI 92F search for isolated $\gamma$ 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.

[206] 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.

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

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

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

[210] 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 | | [211] ODAKA | 89 | VNS | $\Gamma(X^0 \to e^+ e^-)$ $\cdot$B($X^0 \to$ hadrons) $\gtrsim$ 0.2 MeV |
| >45 | 95 | [212] DERRICK | 86 | HRS | $\Gamma(X^0 \to e^+ e^-)$=6 MeV |
| >46.6 | 95 | [213] ADEVA | 85 | MRKJ | $\Gamma(X^0 \to e^+ e^-)$=10 keV |
| >48 | 95 | [213] ADEVA | 85 | MRKJ | $\Gamma(X^0 \to e^+ e^-)$=4 MeV |
| | | [214] BERGER | 85B | PLUT | |
| none 39.8–45.5 | | [215] ADEVA | 84 | MRKJ | $\Gamma(X^0 \to e^+ e^-)$=10 keV |
| >47.8 | 95 | [215] ADEVA | 84 | MRKJ | $\Gamma(X^0 \to e^+ e^-)$=4 MeV |
| none 39.8–45.2 | | [215] BEHREND | 84C | CELL | |
| >47 | 95 | [215] BEHREND | 84C | CELL | $\Gamma(X^0 \to e^+ e^-)$=4 MeV |

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

[212] 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.

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

[214] 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.

[215] ADEVA 84 and BEHREND 84C have $E_{cm}$ = 39.8–45.5 GeV. MARK-J searched $X^0$ in $e^+ e^- \to$ hadrons, $2\gamma$, $\mu^+ \mu^-$, $e^+ e^-$ and CELLO in the same channels plus $\tau$ pair. No narrow or broad $X^0$ is found in the energy range. They also searched for the effect of $X^0$ with $m_X > E_{cm}$. 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 | [216] ABE | 93C | VNS | $\Gamma(e\,e)$ |
| <(0.4–10) | 95 | [217] ABE | 93C | VNS | $f = \gamma\gamma$ |
| <(0.3–5) | 95 | [218,219] ABE | 93D | TOPZ | $f = \gamma\gamma$ |
| <(2–12) | 95 | [218,219] ABE | 93D | TOPZ | $f$ = hadrons |
| <(4–200) | 95 | [219,220] ABE | 93D | TOPZ | $f = e\,e$ |
| <(0.1–6) | 95 | [219,220] ABE | 93D | TOPZ | $f = \mu\mu$ |
| <(0.5–8) | 90 | [221] STERNER | 93 | AMY | $f = \gamma\gamma$ |

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

[217] 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 $\Gamma$ = 1,2 GeV.
[218] Limit is for $m_{X^0}$ = 57.2–60 GeV.
[219] Limit is valid for $\Gamma(X^0) \ll 100$ MeV. See paper for limits for $\Gamma$ = 1 GeV and those for $J$ = 2 resonances.
[220] Limit is for $m_{X^0}$ = 56.6–60 GeV.
[221] STERNER 93 limit is for $m_{X^0}$ = 57–59.6 GeV and is valid for $\Gamma(X^0)$<100 MeV. See their Fig. 2 for limits for $\Gamma$ = 1,3 GeV.

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

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

| *VALUE* (MeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <2.6 | 95 | [222] ACTON | 93E | OPAL | $m_{X^0}$=60 ± 1 GeV |
| <2.9 | 95 | BUSKULIC | 93F | ALEP | $m_{X^0} \sim$ 60 GeV |

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

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

| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [223] ADAM | 96C | DLPH | $X^0$ decaying invisibly |

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

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

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

| *VALUE* (MeV) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<6.8 \times 10^{-6}$ | 95 | [224] ACTON | 93E | OPAL | $f$=$e$,$\mu$,$\tau$; $F$=$\gamma\gamma$ |
| $<5.5 \times 10^{-6}$ | 95 | [224] ACTON | 93E | OPAL | $f$=$q$; $F$=$\gamma\gamma$ |
| $<3.1 \times 10^{-6}$ | 95 | [224] ACTON | 93E | OPAL | $f$=$\nu$; $F$=$\gamma\gamma$ |
| $<6.5 \times 10^{-6}$ | 95 | [224] ACTON | 93E | OPAL | $f$=$e$,$\mu$; $F$=$\ell\bar{\ell}$, $q\bar{q}$, $\nu\bar{\nu}$ |
| $<7.1 \times 10^{-6}$ | 95 | [224] BUSKULIC | 93F | ALEP | $f$=$e$,$\mu$; $F$=$\ell\bar{\ell}$, $q\bar{q}$, $\nu\bar{\nu}$ |
| | | [225] ADRIANI | 92F | L3 | $f$=$q$; $F$=$\gamma\gamma$ |

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

## 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 | [226] BALEST | 95 | CLE2 | $\Upsilon(1S) \rightarrow X^0 \gamma$, $m_{X^0} < 5$ GeV |
| $< 3 \times 10^{-5}$–$6 \times 10^{-3}$ | 90 | [227] BALEST | 95 | CLE2 | $\Upsilon(1S) \rightarrow X^0 \overline{X}^0 \gamma$, $m_{X^0} < 3.9$ GeV |
| $<5.6 \times 10^{-5}$ | 90 | [228] ANTREASYAN | 90C | CBAL | $\Upsilon(1S) \rightarrow X^0 \gamma$, $m_{X^0} < 7.2$ GeV |
| | | [229] ALBRECHT | 89 | ARG | |

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

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

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

[229] 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.

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


| | | | | |
|---|---|---|---|---|
| ABACHI | 96C | PRL 76 3271 | +Abbott, Abolins, Acharya, Adam+ | (D0 Collab.) |
| ABACHI | 96D | PL B385 471 | +Abbott, Abolins, Acharya, Adam+ | (D0 Collab.) |
| ADAM | 96C | PL B380 471 | +Adye, Agasi, Ajinenko, Aleksan+ | (DELPHI Collab.) |
| AID | 96B | PL B369 173 | +Andreev, Andrieu, Appuhn, Arpagaus+ | (H1 Collab.) |
| ALLET | 96 | PL B383 139 | +Bodek, Camps, Deutsch+ | (VILL, LEUV, LOUV, WISC) |
| BUSKULIC | 96N | PL B378 373 | +De Bonis, Decamp, Ghez, Goy, Lees+ | (ALEPH Collab.) |
| ABACHI | 95E | PL B358 405 | +Abbott, Abolins, Acharya, Adam, Adams+ | (D0 Collab.) |
| ABACHI | 95G | PRL 75 3618 | +Abbott, Abolins, Acharya, Adam, Adams+ | (D0 Collab.) |
| ABE | 95 | PR D51 R949 | +Albrow, Amidei, Antos, Anway-Wiese+ | (CDF Collab.) |
| ABE | 95M | PRL 74 2900 | +Albrow, Amidei, Antos, Anway-Wiese+ | (CDF Collab.) |
| ABE | 95N | PRL 74 3538 | +Albrow, Amendolia, Amidei, Antos+ | (CDF Collab.) |
| ABE | 95U | PRL 75 1012 | +Albrow, Amendolia, Amidei, Antos+ | (CDF Collab.) |
| ABREU | 95M | ZPHY C65 603 | +Adam, Adye, Agasi, Ajinenko+ | (DELPHI Collab.) |
| AID | 95 | PL B353 578 | +Andreev, Andrieu, Appuhn, Arpagaus+ | (H1 Collab.) |
| BALEST | 95 | PR D51 2053 | +Cho, Ford, Johnson+ | (CLEO Collab.) |
| KUZNETSOV | 95 | PRL 75 794 | +Serebrov, Stepanenko+ | (PNPI, KIAE, HARV, NIST) |
| KUZNETSOV | 95B | PAN 58 2113 | +Mikheev | (YARO) |
| | | Translated from YAF 58 2228. | | |
| MIZUKOSHI | 95 | NP B444 20 | +Eboli, Gonzalez-Garcia | (SPAUL, CERN) |
| NARDI | 95 | PL B344 225 | +Roulet, Tommasini | (MICH, CERN) |
| ABACHI | 94B | PRL 72 965 | +Abbott, Abolins, Acharya, Adam+ | (D0 Collab.) |
| ABREU | 94O | ZPHY C64 183 | +Adam, Adye, Agasi, Ajinenko, Aleksan+ | (DELPHI Collab.) |
| AHMED | 94B | ZPHY C64 545 | +Aid, Andreev, Andrieu, Appuhn, Arpagaus+ | (H1 Collab.) |
| BHATTACH... | 94 | PL B336 100 | Bhattacharyya, Ellis, Sridhar | (CERN) |
| Also | 94B | PL B338 522 (erratum) | Bhattacharyya, Ellis, Sridhar | (CERN) |
| BHATTACH... | 94B | PL B338 522 (erratum) | Bhattacharyya, Ellis, Sridhar | (CERN) |
| BUSKULIC | 94 | ZPHY C62 539 | +Casper, De Bonis, Decamp, Ghez, Goy+ | (ALEPH Collab.) |
| DAVIDSON | 94 | ZPHY C61 613 | +Bailey, Campbell | (CFPA, TNTO, ALBE) |
| KUZNETSOV | 94 | PL B329 295 | +Mikheev | (YARO) |
| KUZNETSOV | 94B | JETPL 60 315 | +Serebrov, Stepanenko+ | (PNPI, KIAE, HARV, NIST) |
| | | Translated from ZETFP 60 311. | | |

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| LEURER | 94 | PR D50 536 | | (REHO) |
| LEURER | 94B | PR D49 333 | | (REHO) |
| Also | 93 | PRL 71 1324 | Leurer | (REHO) |
| MAHANTA | 94 | PL B337 128 | | (MEHTA) |
| SEVERIJNS | 94 | PRL 73 611 (erratum) | + | (LOUV, WISC, LEUV, ETH, MASA) |
| VILAIN | 94B | PL B332 465 | +Wilquet, Beyer, Flegel, Grote+ | (CHARM II Collab.) |
| ABE | 93C | PL B302 119 | +Amako, Arai, Arima, Asano, Chiba+ | (VENUS Collab.) |
| ABE | 93D | PL B304 373 | +Adachi, Awa, Aoki, Belusevic, Emi+ | (TOPAZ Collab.) |
| ABE | 93G | PRL 71 2542 | +Albrow, Akimoto, Amidei, Anway-Wiese+ | (CDF Collab.) |
| ABE | 93I | PR D48 R3939 | +Albrow, Amidei, Anway-Wiese, Apollinari+ | (CDF Collab.) |
| ABREU | 93J | PL B316 620 | +Adam, Adye, Agasi, Aleksan, Alekseev+ | (DELPHI Collab.) |
| ABT | 93 | NP B396 3 | +Andreev, Andrieu, Appuhn, Arpagaus+ | (H1 Collab.) |
| ACTON | 93E | PL B311 391 | +Akers, Alexander+ | (OPAL Collab.) |
| ADRIANI | 93D | PL B306 187 | +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ | (L3 Collab.) |
| ADRIANI | 93M | PRPL 236 1 | +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ | (L3 Collab.) |
| ALITTI | 93 | NP B400 3 | +Ambrosini, Ansari, Autiero, Bareyre+ | (UA2 Collab.) |
| ALLEN | 93 | PR D47 11 | +Chen, Doe, Hausammann+ | (UCI, LANL, ANL, UMD) |
| ALTARELLI | 93B | PL B318 139 | +Casalbuoni+ | (CERN, FIRZ, GEVA, PADO) |
| BHATTACH... | 93 | PR D47 R3693 | Bhattacharyya+ | (CALC, JADA, ICTP, AHMED, BOSE) |
| BUSKULIC | 93F | PL B308 425 | +De Bonis, Decamp, Chez, Goy, Lees+ | (ALEPH Collab.) |
| DERRICK | 93 | PL B306 173 | +Krakauer, Magill, Musgrave, Repond+ | (ZEUS Collab.) |
| RIZZO | 93 | PR D48 4470 | | (ANL) |
| SEVERIJNS | 93 | PRL 70 4047 | +Gimeno-Nogues+ | (LOUV, WISC, LEUV, ETH, MASA) |
| Also | 94 | PRL 73 611 (erratum) | Severijns+ | (LOUV, WISC, LEUV, ETH, MASA) |
| STERNER | 93 | PL B303 385 | +Abashian, Gotow, Haim, Mattson, Morgan+ | (AMY Collab.) |
| ABE | 92B | PRL 68 1463 | +Amidei, Apollinari, Atac, Auchincloss+ | (CDF Collab.) |
| ABREU | 92D | ZPHY C53 555 | +Adam, Adami, Adye, Akesson, Alekseev+ | (DELPHI Collab.) |
| ABREU | 92F | PL B275 222 | +Adam, Adami, Adye, Akesson, Alekseev+ | (DELPHI Collab.) |
| ADRIANI | 92F | PL B292 472 | +Aguilar-Benitez, Ahlen, Akbari, Alcarez+ | (L3 Collab.) |
| ALITTI | 92E | PL B274 507 | +Ambrosini, Ansari, Autiero, Bareyre+ | (UA2 Collab.) |
| DECAMP | 92 | PRPL 216 253 | +Deschizeaux, Goy, Lees, Minard+ | (ALEPH Collab.) |
| DELAGUILA | 92 | NP B372 3 | del Aguila+ | (CERN, GRAN, MPIM, BRUXT, MADE) |
| Also | 91C | NP B361 45 | del Aguila, Moreno, Quiros | (BARC, MADE) |
| IMAZATO | 92 | PRL 69 877 | +Kawashima, Tanaka+ | (KEK, INUS, TOKY, TOKMS) |
| LANGACKER | 92B | PR D45 278 | +Luo | (PENN) |
| LAYSSAC | 92 | ZPHY C53 97 | +Renard, Verzegnassi | (MONP, LAPP) |
| LAYSSAC | 92B | PL B287 267 | +Renard, Verzegnassi | (MONP, TRSTT) |
| LEIKE | 92 | PL B291 187 | +Riemann, Riemann | (BERL, CERN) |
| LEP | 92 | PL B276 247 | +ALEPH, DELPHI, L3, OPAL | (LEP Collabs.) |
| MISHRA | 92 | PRL 68 3499 | +Leung, Arroyo+ | (COLU, CHIC, FNAL, ROCH, WISC) |
| POLAK | 92 | PL B276 492 | +Zralek | (SILES) |
| POLAK | 92B | PR D46 3871 | +Zralek | (SILES) |
| RENTON | 92 | ZPHY C56 355 | | (OXF) |
| ABE | 91D | PRL 67 2418 | +Amidei, Apollinari, Atac, Auchincloss+ | (CDF Collab.) |
| ABE | 91F | PRL 67 2609 | +Amidei, Apollinari, Atac, Auchincloss+ | (CDF Collab.) |
| ACTON | 91 | PL B268 122 | +Alexander, Allison, Allport+ | (OPAL Collab.) |
| ACTON | 91B | PL B273 338 | +Alexander, Allison, Allport, Anderson+ | (OPAL Collab.) |
| ADEVA | 91B | PL B261 169 | +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ | (L3 Collab.) |
| ADEVA | 91D | PL B262 155 | +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ | (L3 Collab.) |
| ALEXANDER | 91 | PL B263 123 | +Allison, Allport, Anderson, Arcelli+ | (OPAL Collab.) |
| ALITTI | 91 | ZPHY C49 17 | +Ansari, Ansorge, Autiero, Bareyre+ | (UA2 Collab.) |
| ALTARELLI | 91 | PL B261 146 | +Casalbuoni, De Curtis+ | (CERN, FIRZ, GEVA) |
| ALTARELLI | 91B | PL B263 459 | +Casalbuoni, De Curtis+ | (CERN, FIRZ, GEVA) |
| Also | 90 | PL B245 669 | Altarelli, Casalbuoni, Feruglio, Gatto | (CERN, LECE, GEVA) |
| AQUINO | 91 | PL B261 280 | +Fernandez, Garcia | (CINV, PUEB) |
| BUCHMUEL... | 91 | PL B267 395 | Buchmueller, Greub, Minkowski | (DESY, BERN) |
| COLANGELO | 91 | PL B253 154 | +Nardulli | (BARI) |
| CUYPERS | 91 | PL B259 173 | +Falk, Frampton | (DURH, HARV, UNCCH) |
| DELAGUILA | 91 | PL B254 497 | del Aguila, Moreno, Quiros | (BARC, MADE, CERN) |
| FARAGGI | 91 | MPL A6 61 | +Nanopoulos | (TAMU) |
| GEIREGAT | 91 | PL B259 499 | +Vilain, Wilquet, Binder, Burkard+ | (CHARM II Collab.) |
| GONZALEZ-G... | 91 | PL B259 365 | Gonzalez-Garcia, Valle | (VALE) |
| Also | 90C | NP B345 312 | Gonzalez-Garcia, Valle | (VALE) |
| MAHANTHAP... | 91 | PR D43 3093 | Mahanthappa, Mohapatra | (COLO) |
| Also | 91B | PR D44 1616 erratum | Mahanthappa, Mohapatra | (COLO) |
| POLAK | 91 | NP B363 385 | +Zralek | (SILES) |
| RIZZO | 91 | PR D44 202 | | (WISC, ISU) |
| WALKER | 91 | APJ 376 51 | +Steigman, Schramm, Olive+ | (HSCA, OSU, CHIC, MINN) |
| ABE | 90F | PL B246 297 | +Amako, Arai, Asano, Chiba+ | (VENUS Collab.) |

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| ABE | 90G | PRL 65 2243 | +Amidei, Apollinari, Atac+ | (CDF Collab.) |
| ABE | 90H | PR D41 1722 | +Amidei, Apollinari, Ascoli, Atac+ | (CDF Collab.) |
| AKRAWY | 90J | PL B246 285 | +Alexander, Allison, Allport, Anderson+ | (OPAL Collab.) |
| ALLEN | 90 | PRL 64 1330 | +Chen, Doe+ | (UCI, LASL, UMD) |
| ANTREASYAN | 90C | PL B251 204 | +Bartels, Besset, Bieler, Bienlein+ | (Crystal Ball Collab.) |
| BARGER | 90B | PR D42 152 | +Hewett, Rizzo | (WISC, ISU) |
| GLASHOW | 90 | PR D42 3224 | +Sarid | (HARV) |
| GLASHOW | 90B | PRL 64 725 | +Sarid | (HARV) |
| GONZALEZ-G... | 90D | PL B240 163 | Gonzalez-Garcia, Valle | (VALE) |
| GRIFOLS | 90 | NP B331 244 | +Masso | (BARC) |
| GRIFOLS | 90C | MPL A5 2657 | | (BARC) |
| GRIFOLS | 90D | PR D42 3293 | +Masso, Rizzo | (BARC, CERN, WISC, ISU) |
| HAGIWARA | 90 | PR D41 815 | +Najima, Sakuda, Terunuma | (KEK, DURH, YCC, HIRO) |
| HE | 90B | PL B240 441 | +Joshi, Volkas | (MELB) |
| Also | 90C | PL B244 580 erratum | He, Joshi, Volkas | (MELB) |
| KIM | 90 | PL B240 243 | +Breedon, Ko, Lander, Maeshima, Malchow+ | (AMY Collab.) |
| LOPEZ | 90 | PL B241 392 | +Nanopoulos | (TAMU) |
| ALBAJAR | 89 | ZPHY C44 15 | +Albrow, Allkofer, Arnison, Astbury+ | (UA1 Collab.) |
| ALBRECHT | 89 | ZPHY C42 349 | +Boeckmann, Glaeser, Harder+ | (ARGUS Collab.) |
| BARBIERI | 89B | PR D39 1229 | +Mohapatra | (PISA, UMD) |
| DELAGUILA | 89 | PR D40 2481 | del Aguila, Moreno, Quiros | (BARC, MADE) |
| Also | 90B | PR D41 134 | del Aguila, Moreno, Quiros | (BARC, MADE) |
| Also | 90C | PR D42 262 erratum | del Aguila, Moreno, Quiros | (BARC, MADE) |
| DORENBOS... | 89 | ZPHY C41 567 | Dorenbosch, Udo, Allaby, Amaldi+ | (CHARM Collab.) |
| GEIREGAT | 89 | PL B232 539 | +Vilain, Wilquet, Bergsma, Binder+ | (CHARM II Collab.) |
| LANGACKER | 89B | PR D40 1569 | +Uma Sankar | (PENN) |
| ODAKA | 89 | JPSJ 58 3037 | +Kondo, Abe, Amako+ | (VENUS Collab.) |
| ROBINETT | 89 | PR D39 834 | | (PSU) |
| ALBAJAR | 88B | PL B209 127 | +Albrow, Allkofer, Astbury, Aubert+ | (UA1 Collab.) |
| BAGGER | 88 | PR D37 1188 | +Schmidt, King | (HARV, BOST) |
| BALKE | 88 | PR D37 587 | +Gidal, Jodidio+ | (LBL, UCB, COLO, NWES, TRIU) |
| BERGSTROM | 88 | PL B212 386 | | (STOH) |
| COSTA | 88 | NP B297 244 | +Ellis, Fogli+ | (PADO, CERN, BARI, WISC, LBL) |
| CUYPERS | 88 | PRL 60 1237 | +Frampton | (UNCCH) |
| DONCHESKI | 88 | PL B206 137 | +Grotch, Robinett | (PSU) |
| DONCHESKI | 88B | PR D38 412 | +Grotch, Robinett | (PSU) |
| ELLIS | 88 | PL B202 417 | Ellis, Franzini, Zwirner | (CERN, UCB, LBL) |
| RAFFELT | 88 | PRL 60 1793 | +Seckel | (UCB, LLL, UCSC) |
| AMALDI | 87 | PR D36 1385 | +Bohm, Durkin, Langacker+ | (CERN, AACH3, OSU+) |
| ANSARI | 87D | PL B195 613 | +Bagnaia, Banner+ | (UA2 Collab.) |
| BARTEL | 87B | ZPHY C36 15 | +Becker, Felst+ | (JADE Collab.) |
| MARCIANO | 87 | PR D35 1672 | +Sirlin | (BNL, NYU) |
| ARNISON | 86B | EPL 1 327 | +Albrow, Allkofer+ | (UA1 Collab.) |
| BARGER | 86B | PRL 56 30 | +Deshpande, Whisnant | (WISC, OREG, FSU) |
| BEHREND | 86B | PL B178 452 | +Buerger, Criegee, Fenner, Field+ | (CELLO Collab.) |
| DERRICK | 86 | PL 166B 463 | +Gan, Kooijman, Loos+ | (HRS Collab.) |
| Also | 86B | PR D34 3286 | Derrick, Gan, Kooijman, Loos, Musgrave+ | (HRS Collab.) |
| DURKIN | 86 | PL 166B 436 | +Langacker | (PENN) |
| ELLIS | 86 | PL 167B 457 | +Enqvist, Nanopoulos, Sarkar | (CERN, OXFTP) |
| JODIDIO | 86 | PR D34 1967 | +Balke, Carr, Gidal, Shinsky+ | (LBL, NWES, TRIU) |
| Also | 88 | PR D37 237 erratum | Jodidio, Balke, Carr+ | (LBL, NWES, TRIU) |
| MOHAPATRA | 86 | PR D34 909 | | (UMD) |
| STEIGMAN | 86 | PL B176 33 | +Olive, Schramm, Turner | (BART, MINN+) |
| ADEVA | 85 | PL 152B 439 | +Becker, Becker-Szendy+ | (Mark-J Collab.) |
| ADEVA | 85B | PRL 55 665 | +Becker, Becker-Szendy+ | (Mark-J Collab.) |
| BERGER | 85B | ZPHY C27 341 | +Deuter, Genzel, Lackas, Pielorz+ | (PLUTO Collab.) |
| STOKER | 85 | PRL 54 1887 | +Balke, Carr, Gidal+ | (LBL, NWES, TRIU) |
| ADEVA | 84 | PRL 53 134 | +Barber, Becker, Berdugo+ | (Mark-J Collab.) |
| BEHREND | 84C | PL 140B 130 | +Burger, Criegee, Fenner+ | (CELLO Collab.) |
| ARNISON | 83D | PL 129B 273 | +Astbury, Aubert, Bacci+ | (UA1 Collab.) |
| BERGSMA | 83 | PL 122B 465 | +Dorenbosch, Jonker+ | (CHARM Collab.) |
| CARR | 83 | PRL 51 627 | +Gidal, Gobbi, Jodidio, Oram+ | (LBL, NWES, TRIU) |
| DESHPANDE | 83 | PR D27 1193 | +Johnson | (OREG) |
| BEALL | 82 | PRL 48 848 | +Bander, Soni | (UCI, UCLA) |
| SHANKER | 82 | NP B204 375 | | (TRIU) |
| DIMOPOUL... | 81 | NP B182 77 | Dimopoulos, Raby, Kane | (STAN, MICH) |
| RIZZO | 81 | PR D24 704 | +Senjanovic | (BNL) |
| STEIGMAN | 79 | PRL 43 239 | +Olive, Schramm | (BART, EFI) |