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Higgs Bosons — H^0 and $H^{\pm}$, Searches for

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H^0 (Higgs Boson) MASS LIMITS

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. Limits that depend on the $H t\overline{t}$ coupling may also apply to a Higgs boson of an extended Higgs sector whose couplings to up-type quarks are comparable to or larger than those of the standard one-doublet model H^0 couplings.

For comprehensive reviews, see Gunion, Haber, Kane, and Dawson, "The Higgs Hunter's Guide," (Addison-Wesley, Menlo Park, CA, 1990) and R.N. Cahn, Reports on Progress in Physics **52** 389 (1989). For a review of theoretical bounds on the Higgs mass, see M. Sher, Physics Reports (Physics Letters C) **179** 273 (1989).

Limits from Coupling to $Z/W^{\pm}$

'OUR LIMIT' is taken from the LEP Higgs Boson Searches Working group (LEP 99B), where the combination of the results of ABBIENDI 99E, ABREU 99I, ACCIARRI 98I, and BARATE 99B was performed.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>89.7	**(CL = 95%) OUR LIMIT**				
>88.3	95	[1] ABBIENDI	99E	OPAL	$e^+e^- \rightarrow H^0 Z$
>85.7	95	[2] ABREU	99I	DLPH	$e^+e^- \rightarrow H^0 Z$
>87.9	95	[3] BARATE	99B	ALEP	$e^+e^- \rightarrow H^0 Z$
>87.6	95	[4] ACCIARRI	98I	L3	$e^+e^- \rightarrow H^0 Z$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[5] ABE	98T	CDF	$p\overline{p} \rightarrow H^0 W X$, $H^0 Z X$
>66.2	95	[6] ABREU	98E	DLPH	$e^+e^- \rightarrow H^0 Z$
>69.4	95	[6] ACKERSTAFF	98H	OPAL	$e^+e^- \rightarrow H^0 Z$
		[7] ABE	97W	CDF	$p\overline{p} \rightarrow H^0 W X$
>69.5	95	[6] ACCIARRI	97O	L3	$e^+e^- \rightarrow H^0 Z$
>65.0	95	[8] ACKERSTAFF	97E	OPAL	$e^+e^- \rightarrow H^0 Z$
>59.6	95	[9] ALEXANDER	97	OPAL	$Z \rightarrow H^0 Z^*$
>70.7	95	[6] BARATE	97O	ALEP	$e^+e^- \rightarrow H^0 Z$
>60.2	95	[10] ACCIARRI	96I	L3	$Z \rightarrow H^0 Z^*$
		[11] ACCIARRI	96J	L3	$Z \rightarrow H^0 \gamma$
		[12] ALEXANDER	96H	OPAL	$Z \rightarrow H^0 \gamma$
>60.6	95	[13] ALEXANDER	96L	OPAL	$Z \rightarrow H^0 Z^*$
>63.9	95	[14] BUSKULIC	96R	ALEP	$Z \rightarrow H^0 Z^*$
>55.7	95	[15] ABREU	94G	DLPH	$Z \rightarrow H^0 Z^*$
>56.9	95	[16] AKERS	94B	OPAL	$Z \rightarrow H^0 Z^*$
>57.7	95	[17] ADRIANI	93C	L3	$Z \rightarrow H^0 Z^*$
>58.4	95	[18] BUSKULIC	93H	ALEP	$Z \rightarrow H^0 Z^*$
>60	95	[19] GROSS	93	RVUE	$Z \rightarrow H^0 Z^*$
		[20] ABREU	92D	DLPH	$Z \rightarrow H^0 \gamma$
>38	95	[21] ABREU	92J	DLPH	$Z \rightarrow H^0 Z^*$

>52	95	[22] ADEVA	92B	L3	$Z \to H^0 Z^*$
		[23] ADRIANI	92F	L3	$Z \to H^0 \gamma$
>48	95	[24] DECAMP	92	ALEP	$Z \to H^0 Z^*$
> 0.21	99	[25] ABREU	91B	DLPH	$Z \to H^0 Z^*$
>11.3	95	[26] ACTON	91	OPAL	$H^0 \to$ anything
>41.8	95	[27] ADEVA	91	L3	$Z \to H^0 Z^*$
		[28] ADEVA	91D	L3	$Z \to H^0 \gamma$
none 3–44	95	[29] AKRAWY	91	OPAL	$Z \to H^0 Z^*$
none 3–25.3	95	[30] AKRAWY	91C	OPAL	$Z \to H^0 Z^*$
none 0.21–0.818	90	[31] ABE	90E	CDF	$p\overline{p} \to H^0 W X$, $H^0 Z X$
none 0.846–0.987	90	[31] ABE	90E	CDF	$p\overline{p} \to H^0 W X$, $H^0 Z X$
none 0.21–14	95	[32] ABREU	90C	DLPH	$Z \to H^0 Z^*$
none 2–32	95	[33] ADEVA	90H	L3	$Z \to H^0 Z^*$
> 2	99	[34] ADEVA	90N	L3	$Z \to H^0 Z^*$
none 3.0–19.3	95	[35] AKRAWY	90C	OPAL	$Z \to H^0 Z^*$
> 0.21	95	[36] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
none 0.032–15	95	[37] DECAMP	90	ALEP	$Z \to H^0 Z^*$
none 11–24	95	[38] DECAMP	90H	ALEP	$Z \to H^0 Z^*$
> 0.057	95	[39] DECAMP	90M	ALEP	$Z \to H^0 ee$, $H^0 \mu\mu$
none 11–41.6	95	[40] DECAMP	90N	ALEP	$Z \to H^0 Z^*$

[1] ABBIENDI 99E search for $e^+ e^- \to Z H^0$ at E_{cm}= 183 GeV in the final states $H^0 \to q\overline{q}$ with $Z \to \ell^+ \ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \to \tau^+\tau^-$ with $Z \to q\overline{q}$.

[2] ABREU 99I searched for $e^+ e^- \to Z H^0$ at E_{cm}= 183 GeV in the final states $H^0 \to q\overline{q}$ with $Z \to \ell^+ \ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \to \tau^+\tau^-$ with $Z \to \ell^+ \ell^-$, $\nu\overline{\nu}$, and $q\overline{q}$. Lower energy data at E_{cm}= 161 and 172 GeV are combined for the limit.

[3] BARATE 99B searched for $e^+ e^- \to Z H^0$ at E_{cm}=183 GeV in the final states $H^0 \to q\overline{q}$ with $Z \to \ell^+ \ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \to \tau^+\tau^-$ with $Z \to \ell^+ \ell^-$, $\nu\overline{\nu}$, and $q\overline{q}$. The limit also includes the data at lower energies and Z decay. BARATE 99B replaces the misprinted version in BARATE 98Z.

[4] ACCIARRI 98I search for $e^+ e^- \to Z H^0$ at E_{cm}=183 GeV in the final states $H^0 \to q\overline{q}$ with $Z \to \ell^+ \ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \to \tau^+\tau^-$ with $Z \to q\overline{q}$. The limit also includes the data at lower energies and Z decay.

[5] ABE 98T search for associated $H^0 W$ and $H^0 Z$ production in $p\overline{p}$ collisions at $\sqrt{s}$= 1.8 TeV with $W(Z) \to q\overline{q}^{(\prime)}$, $H^0 \to b\overline{b}$. The results are combined with the search in ABE 97W, resulting in the cross-section limit $\sigma(H^0 + W/Z)\cdot$B($H^0 \to b\overline{b}$)<(23–17) pb (95%CL) for m_H= 70–140 GeV. This limit is one to two orders of magnitude larger than the expected cross section in the Standard Model.

[6] Search for $e^+ e^- \to Z H^0$ at E_{cm} = 161, 170, and 172 GeV in the final states $H^0 \to q\overline{q}$ with $Z \to \ell^+ \ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \to \tau^+\tau^-$ with $Z \to \ell^+ \ell^-$ and $q\overline{q}$. The limits also includes the data from Z decay by each experiment.

[7] ABE 97W search for associated $W H^0$ production in $p\overline{p}$ collisions at $\sqrt{s}$ = 1.8 TeV with $W \to \ell\nu_\ell$, $H^0 \to b\overline{b}$ and find the cross-section limit $\sigma \cdot$ B($H^0 \to b\overline{b}$) <(14–19) pb (95% CL) for m_H = 70–120 GeV. This limit is one to two orders of magnitude larger than the expected cross section in the Standard Model.

[8] ACKERSTAFF 97E searched for $e^+ e^- \to Z H^0$ at E_{cm} = 161 GeV for the final states $(q\overline{q})(b\overline{b})$, $(\nu\overline{\nu})(q\overline{q})$, $(\tau^+\tau^-)(q\overline{q})$, $(q\overline{q})(\tau^+\tau^-)$, $(e^+ e^-)(q\overline{q})$, and $(\mu^+\mu^-)(q\overline{q})$ [the Z (H^0) decay products are in the first (second) parentheses]. The limit includes the results of ALEXANDER 97. Two additional low-mass candidate events are seen, consistent with expected backgrounds.

[9] ALEXANDER 97 complements the study in ALEXANDER 96L with the inclusion of the search for $Z \to H^0 + (e^+e^-, \mu^+\mu^-)$, with $H^0 \to q\overline{q}$. One additional candidate event is found in the $\mu\mu$ channel, consistent with expected backgrounds.

[10] ACCIARRI 96I searched for $Z \to H^0 + (e^+e^-, \mu^+\mu^-, \nu\overline{\nu})$ with $H^0 \to q\overline{q}$. Two $e^+e^- H^0$ candidate events with large recoiling mass (above 30 GeV) were found consistent with the background expectations.

[11] ACCIARRI 96J give B($Z \to H^0\gamma$)$\times$B($H^0 \to q\overline{q}$) < 6.9–22.9×10^{-6} (95%CL) for 20 $< m_{H^0} <$80 GeV.

[12] ALEXANDER 96H give B($Z \to H^0\gamma$)$\times$B($H^0 \to q\overline{q}$) $<$ 1–4 $\times 10^{-5}$ (95%CL) and B($Z \to H^0\gamma$)$\times$B($H^0 \to b\overline{b}$) $<$ 0.7–2 $\times 10^{-5}$ (95%CL) in the range 20 $< m_{H^0} <$80 GeV.

[13] ALEXANDER 96L searched for final states with monojets or acoplanar dijets. Two observed candidate events are consistent with expected backgrounds.

[14] BUSKULIC 96R searched for $Z \to H^0 + (e^+e^-, \mu^+\mu^-, \nu\overline{\nu})$ with $H^0 \to q\overline{q}$. Three candidate events in the $\mu\mu$ channel are consistent with expected backgrounds.

[15] ABREU 94G searched for $Z \to H^0 + (e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu\overline{\nu})$ with $H^0 \to q\overline{q}$. Four $\ell^+\ell^-$ candidates were found (all yielding low mass) consistent with expected backgrounds.

[16] AKERS 94B searched for $Z \to H^0 + (e^+e^-, \mu^+\mu^-, \nu\overline{\nu})$ with $H^0 \to q\overline{q}$. One $\nu\overline{\nu}$ and one $\mu^+\mu^-$ candidate were found consistent with expected backgrounds.

[17] ADRIANI 93C searched for $Z \to H^0 + (\nu\overline{\nu}, e^+e^-, \mu^+\mu^-)$ with H^0 decaying hadronically or to $\tau\overline{\tau}$. Two e^+e^- and one $\mu^+\mu^-$ candidates are found consistent with expected background.

[18] BUSKULIC 93H searched for $Z \to H^0\nu\overline{\nu}$ (acoplanar jets) and $Z \to H^0 + (e^+e^-, \mu^+\mu^-)$ (lepton pairs in hadronic events).

[19] GROSS 93 combine data taken by four LEP experiments through 1991.

[20] ABREU 92D give $\sigma(e^+e^- \to Z \to H^0\gamma)\cdot$B($H^0 \to$ hadrons) $<$8 pb (95% CL) for $m_{H^0} <$75 GeV and $E_\gamma >$8 GeV.

[21] ABREU 92J searched for $Z \to H^0 + (ee, \mu\mu, \tau\tau, \nu\overline{\nu})$ with $H^0 \to q\overline{q}$. Only one candidate was found, in the channel ee + 2jets, with a dijet mass 35.4 $\pm$ 5 GeV/c^2, consistent with the expected background of 1.0 $\pm$ 0.2 events in the 3 channels e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, and of 2.8 $\pm$ 1.3 events in all 4 channels. This paper excludes 12–38 GeV. The range 0–12 GeV is eliminated by combining with the analyses of ABREU 90C and ABREU 91B.

[22] ADEVA 92B searched for $Z \to H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to$ anything, $Z \to H^0 + \tau\tau$ with $H^0 \to q\overline{q}$, and $Z \to H^0 + q\overline{q}$ with $H^0 \to \tau\tau$. The analysis excludes the range $30 < m_{H^0} < 52$ GeV.

[23] ADRIANI 92F give $\sigma(e^+e^- \to Z \to H^0\gamma)\cdot$B($H^0 \to$ hadrons) $<$(2–10) pb (95% CL) for $m_{X^0} = 25$–85 GeV. Using $\sigma(e^+e^- \to Z) = 30$ nb, we obtain B($Z \to H^0\gamma$)B($H^0 \to$ hadrons) $<$(0.7–3) $\times 10^{-4}$ (95% CL).

[24] DECAMP 92 searched for most possible final states for $Z \to H^0 Z^*$.

[25] ABREU 91B searched for $Z \to H^0 + \ell\overline{\ell}$ with missing H^0 and $Z \to H^0 + (\nu\overline{\nu}, \ell\overline{\ell}, q\overline{q})$ with $H^0 \to ee$.

[26] ACTON 91 searched for $e^+e^- \to Z^* H^0$ where $Z^* \to e^+e^-, \mu^+\mu^-$, or $\nu\overline{\nu}$ and $H^0 \to$ anything. Without assuming the minimal Standard Model mass-lifetime relationship, the limit is $m_{H^0} > 9.5$ GeV.

[27] ADEVA 91 searched for $Z \to H^0 + (\mu\mu, ee, \nu\overline{\nu})$. This paper only excludes $15 < m_{H^0} < 41.8$ GeV. The 0–15 GeV range is excluded by combining with the analyses of previous L3 papers.

[28] ADEVA 91D obtain a limit B($Z \to H^0\gamma$)$\cdot$B($H^0 \to$ hadrons) $<$ 4.7×10^{-4} (95%CL) for $m_{H^0} = 30$–86 GeV. The limit is not sensitive enough to exclude a standard H^0.

[29] AKRAWY 91 searched for the channels $Z \to H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to q\overline{q}, \tau\tau$, and $Z \to H^0 q\overline{q}$ with $H^0 \to \tau\tau$.
[30] AKRAWY 91C searched the decay channels $Z \to H^0 + (\nu\overline{\nu}, ee, \mu\mu)$ with $H^0 \to q\overline{q}$.
[31] ABE 90E looked for associated production of H^0 with $W^\pm$ or Z in $p\overline{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. Searched for H^0 decays into $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^-. Most of the excluded region is also excluded at 95% CL.
[32] ABREU 90C searched for the channels $Z \to H^0 + (\nu\overline{\nu}, ee, \mu\mu)$ and $H^0 + q\overline{q}$ for $m_H < 1$ GeV.
[33] ADEVA 90H searched for $Z \to H^0 + (\mu\mu, ee, \nu\overline{\nu})$.
[34] ADEVA 90N looked for $Z \to H^0 + (ee, \mu\mu)$ with missing H^0 and with $H^0 \to ee, \mu\mu, \pi^+\pi^-, K^+K^-$.
[35] AKRAWY 90C based on 825 nb^{-1}. The decay $Z \to H^0\nu\overline{\nu}$ with $H^0 \to \tau\overline{\tau}$ or $q\overline{q}$ provides the most powerful search means, but the quoted results sum all channels.
[36] AKRAWY 90P looked for $Z \to H^0 + (ee, \mu\mu)$ (H^0 missing) and $Z \to H^0\nu\overline{\nu}$, $H^0 \to e^+e^-, \gamma\gamma$.
[37] DECAMP 90 limits based on 11,550 Z events. They searched for $Z \to H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau, q\overline{q})$. The decay $Z \to H^0\nu\overline{\nu}$ provides the most powerful search means, but the quoted results sum all channels. Different analysis methods are used for $m_{H^0} < 2m_\mu$ where Higgs would be long-lived. The 99% confidence limits exclude m_{H^0} = 0.040–12 GeV.
[38] DECAMP 90H limits based on 25,000 $Z \to$ hadron events.
[39] DECAMP 90M looked for $Z \to H^0\ell\ell$, where H^0 decays outside the detector.
[40] DECAMP 90N searched for the channels $Z \to H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \to$ (hadrons, $\tau\tau$).

H^0 Indirect Mass Limits from Electroweak Analysis

For limits obtained before the direct measurement of the top quark mass, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review. For indirect limits obtained from other considerations of theoretical nature, see the review on "The Higgs boson."

Because of the high current interest, we mention here the following unpublished result (LEP 99), although we do not include it in the Listings or Tables: $m_H = 76^{+85}_{-47}$ GeV. This is obtained from a fit to LEP, SLD, W mass, top mass, and neutrino scattering data available in the Summer of 1998, with $1/\alpha^{(5)}(m_Z) = 128.878 \pm 0.090$. The 95%CL upper limit is 262 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[41] CHANOWITZ	98	RVUE	
170^{+150}_{-90}		[42] HAGIWARA	98B	RVUE	
141^{+140}_{-77}		[43] DEBOER	97B	RVUE	
127^{+143}_{-71}		[44] DEGRASSI	97	RVUE	$\sin^2\theta_W$(eff,lept)
158^{+148}_{-84}		[45] DITTMAIER	97	RVUE	
149^{+148}_{-82}		[46] RENTON	97	RVUE	
$\lesssim 550$	90	[47] DITTMAIER	96	RVUE	
145^{+164}_{-77}		[48] ELLIS	96C	RVUE	

185^{+251}_{-134}		[49] GURTU	96	RVUE
$63^{+\ 97}_{-\ \ 0}$		[50] CHANKOWSKI	95	RVUE
<730	95	[51] ERLER	95	RVUE
<740	95	[52] MATSUMOTO	95	RVUE
$45^{+\ 95}_{-\ 28}$		[53] ELLIS	94B	RVUE
$69^{+188}_{-\ \ 9}$		[54] GURTU	94	RVUE
		[55] MONTAGNA	94	RVUE

[41] CHANOWITZ 98 fits LEP and SLD Z-decay-asymmetry data (as reported in ABBANEO 97), and explores the sensitivity of the fit to the weight ascribed to measurements that are individually in significant contradiction with the direct-search limits. Various prescriptions are discussed, and significant variations of the 95%CL Higgs-mass upper limits are found. The Higgs-mass central value varies from 100 to 250 GeV and the 95%CL upper limit from 340 GeV to the TeV scale.

[42] HAGIWARA 98B fit to LEP, SLD, W mass, and neutrino scattering data as reported in ALCARAZ 96, with $m_t = 175 \pm 6$ GeV, $1/\alpha(m_Z)$= 128.90 $\pm$ 0.09 and $/\alpha_s(m_Z)$= 0.118 $\pm$ 0.003. Strong dependence on m_t is found.

[43] DEBOER 97B fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from CDF/DØ and CLEO $b \rightarrow s\gamma$ data (ALAM 95). $1/\alpha(m_Z) = 128.90 \pm 0.09$ and $\alpha_s(m_Z) = 0.120 \pm 0.003$ are used. Exclusion of SLC data yields $m_H = 241^{+218}_{-123}$ GeV. $\sin^2\theta_{\text{eff}}$ from SLC (0.23061 $\pm$ 0.00047) would give $m_H = 16^{+16}_{-\ 9}$ GeV.

[44] DEGRASSI 97 is a two-loop calculation of M_W and $\sin^2\theta^{\text{lept}}_{\text{eff}}$ as a function of m_H, using $\sin^2\theta^{\text{lept}}_{\text{eff}}$ 0.23165(24) as reported in ALCARAZ 96, $m_t = 175 \pm 6$ GeV, and $1/\alpha(m_Z)$=128.90 $\pm$ 0.09.

[45] DITTMAIER 97 fit to m_W and LEP/SLC data as reported in ALCARAZ 96, with m_t = 175 $\pm$ 6 GeV, $1/\alpha(m_Z^2) = 128.89 \pm 0.09$. Exclusion of the SLD data gives $m_H = 261^{+224}_{-128}$ GeV. Taking only the data on m_t, m_W, $\sin^2\theta^{\text{lept}}_{\text{eff}}$, and Γ^{lept}_Z, the authors get $m_H = 190^{+174}_{-102}$ GeV and $m_H = 296^{+243}_{-143}$ GeV, with and without SLD data, respectively. The 95% CL upper limit is given by 550 GeV (800 GeV removing the SLD data).

[46] RENTON 97 fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from $p\overline{p}$, and low-energy νN data available in early 1997. $1/\alpha(m_Z) = 128.90 \pm 0.09$ is used.

[47] DITTMAIER 96 fit to m_W, LEP, and SLD data available in the Summer of 1995 (with and without m_t=180 $\pm$ 12 GeV from CDF/DØ), leaving out R_b and R_c. They argue that the low Higgs mass obtained in some electroweak analyses is an artifact of including the observed value of R_b, which is incompatible with the rest of the data. Exclusion of the SLD data pushes the 90%CL limit on m_{H^0} above 1 TeV.

[48] ELLIS 96C fit to LEP, SLD, m_W, neutral-current data available in the summer of 1996, plus $m_t = 175 \pm 6$ GeV from CDF/DØ . The fit yields $m_t = 172 \pm 6$ GeV.

[49] GURTU 96 studies the effect of the mutually incompatible SLD and LEP asymmetry data on the determination of m_H. Use is made of data available in the Summer of 1996. The quoted value is obtained by increasing the errors *à la* PDG. A fit ignoring the SLD data yields 267^{+242}_{-135} GeV.

[50] CHANKOWSKI 95 fit to LEP, SLD, and W mass data available in the spring of 1995 plus $m_t = 176 \pm 13$ GeV. Exclusion of the SLD data increases the mass to $m_H = 121^{+207}_{-\ 58}$ GeV (m_H <800 GeV at 95% CL).

[51] ERLER 95 fit to LEP, SLC, W mass, and various low-energy data available in the summer of 1994 plus m_t=174 ± 16 GeV from CDF. The limit without m_t is 880 GeV. However, the preference for lighter m_H is due to R_b and A_{LR}, both of which do not agree well with the Standard Model prediction.

[52] MATSUMOTO 95 fit to LEP, SLD, W mass, and various neutral current data available in the summer of 1994 plus m_t=180 ± 13 GeV from CDF/DØ , and the LEP direct limit m_H >63 GeV. $\alpha_s(m_Z) = 0.124$ is used. Fixing $\alpha_s(m_Z) = 0.116$ lowers the upper limit to 440 GeV. Dependence on $\alpha(m_Z)$ is given in the paper.

[53] ELLIS 94B fit to LEP, SLD, W mass, neutral current data available in the spring of 1994 plus $m_t = 167 \pm 12$ GeV determined from CDF/DØ $t\overline{t}$ direct searches. $\alpha_s(m_Z) = 0.118 \pm 0.007$ is used. The fit yields $m_t = 162 \pm 9$ GeV. A fit without the SLD data gives $m_H = 130^{+320}_{-\ 90}$ GeV.

[54] GURTU 94 fit to LEP, SLD, W mass, neutral current data available in the spring of 1994 as well as $m_t = 174 \pm 16$ GeV. A fit without $\Gamma(Z \rightarrow b\overline{b})/\Gamma(Z \rightarrow \text{hadrons})$ gives $m_H = 120^{+364}_{-\ 60}$ GeV.

[55] MONTAGNA 94 fit to LEP and SLD, W-mass data together with $m_t = 174 \pm 17$ GeV. Although the data favor smaller Higgs masses, the authors do not regard it significant.

H^0 (Higgs Boson) MASS LIMITS in Extended Higgs Models

The parameter x denotes the Higgs coupling to charge $-1/3$ quarks and charged leptons relative to the value in the standard one-Higgs-doublet model.

In order to prevent flavor-changing neutral currents in models with more than one Higgs doublet, only one of the Higgs doublets can couple to quarks of charge 2/3. The same requirement applies independently to charge $-1/3$ quarks and to leptons. Higgs couplings can be enhanced or suppressed.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>68.0	95	[56] ABBIENDI	99E	OPAL	$\tan\beta > 1$
>78.5	95	[57] ABBOTT	99B	D0	$p\overline{p} \rightarrow H^0 W/Z$, $H^0 \rightarrow \gamma\gamma$
>80	95	[58] BARATE	99C	ALEP	Invisible H^0
>69.6	95	[59] ACCIARRI	98B	L3	Invisible H^0
		[60] ACKERSTAFF	98B	OPAL	$e^+e^- \rightarrow H^0 Z^{(*)}$, $H^0 \rightarrow \gamma\gamma$
>56.0	95	[61] ACKERSTAFF	98S	OPAL	$\tan\beta > 1$
>90	95	[62] ACKERSTAFF	98Y	OPAL	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
		[63] GONZALEZ-G..	98B	RVUE	Anomalous coupling
		[64] KRAWCZYK	97	RVUE	$(g-2)_\mu$
		[65] ACCIARRI	96I	L3	$Z \rightarrow H^0 Z^*$
>66.7	95	[66] ACCIARRI	96I	L3	Invisible H^0
		[67] ACCIARRI	96J	L3	$Z \rightarrow H^0 Z^*$, $H^0 \rightarrow \gamma\gamma$
		[68] ALEXANDER	96H	OPAL	$Z \rightarrow H^0 Z^*$, $H^0 \rightarrow \gamma\gamma$
		[69] ABREU	95H	DLPH	$Z \rightarrow H^0 Z^*$, $H^0 A^0$
		[70] BRAHMACH...	93	RVUE	

		[71] BUSKULIC	93I	ALEP	$Z \to H^0 Z^*$
>65	95	[66] BUSKULIC	93I	ALEP	Invisible H^0
		[72] LOPEZ-FERN...	93	RVUE	
		[73] ADRIANI	92G	L3	$Z \to H^0 Z^*$
		[74] PICH	92	RVUE	Very light Higgs
> 3.57	95	[75] ACTON	91	OPAL	$Z \to H^0 Z^*$
		[76] DECAMP	91F	ALEP	$Z \to H^0 \ell^+ \ell^-$
		[77] DECAMP	91I	ALEP	Z decay
> 0.21	95	[78] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
		[79] DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ $(H^0 \to e^+ e^-)$
		[80] SNYDER	89	MRK2	$B \to H^0 X$ $(H^0 \to e^+ e^-)$
none 0.6–6.2	90	[81] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=2
none 0.6–7.9	90	[81] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=4
none 3.7–5.6	90	[82] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=2
none 3.7–8.2	90	[82] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=4

[56] ABBIENDI 99E search for $e^+ e^- \to H^0 A^0$ and $H^0 Z$ at E_{cm} = 183 GeV. The limit is with m_H=m_A in general two Higgs-doublet models. See their Fig. 18 for the exclusion limit in the m_H–m_A plane. The limit includes searches at lower energy between m_Z and 172 GeV.

[57] ABBOTT 99B search for associated production of a $\gamma\gamma$ resonance and a dijet pair. The limit assumes Standard Model values for the production cross section and for the couplings of the H^0 to W and Z bosons. Limits in the range of $\sigma(H^0+Z/W)\cdot$B$(H^0 \to \gamma\gamma)$= 0.80–0.34 pb are obtained in the mass range m_{H^0}= 65–150 GeV.

[58] BARATE 99C search for $e^+ e^- \to H^0 Z$ with H^0 decaying invisibly at $\sqrt{s}$ between 161 and 184 GeV, and update the search for $Z^0 \to H^0 Z^*$ at m_Z. The limit assumes SM production cross section, and B($H^0 \to$ invisible)= 100%. See their Fig. 6 for limit on the $Z Z H^0$ coupling vs. m_{H^0}.

[59] ACCIARRI 98B searches for $e^+ e^- \to Z H^0$ events, with $Z \to$ hadrons and H^0 decaying invisibly. The limit assumes SM production cross section, and B($H^0 \to$ invisible)=1. For limits under other assumptions, see their Fig. 5b.

[60] ACKERSTAFF 98B search for associate production of a $\gamma\gamma$ resonance and a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- annihilation at $\sqrt{s} \simeq$ 91, 130–140, and 161–172 GeV. The cross-section limit $\sigma(e^+ e^- \to H^0 Z^{(*)})\cdot$B$(H^0 \to \gamma\gamma) <$ 0.29–0.83 pb (95%CL) is obtained for m_H = 40–160 GeV at $\sqrt{s}$ = 161–172 GeV, $\sigma \cdot$ B< 0.09 pb for m_H = 40–80 GeV at $\sqrt{s} \simeq$ 91 GeV. See also their Fig. 9 for the limit on $\sigma(H^0)\cdot$B$(H^0 \to \gamma\gamma)/\sigma(H^0_{SM})$.

[61] ACKERSTAFF 98S search for $e^+ e^- \to H^0 A^0$ and $H^0 Z$ at E_{cm} between 130 and 172 GeV. The limit is for $m_H = m_A$. The limit is 41 GeV for all values of tanβ. See also their Fig. 10 for the exclusion limit in the m_H-m_A plane.

[62] ACKERSTAFF 98Y search for associate production of a $\gamma\gamma$ resonance and a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- annihilation at E_{cm}=183 GeV. The limit assumes SM production cross section and B($H^0 \to \gamma\gamma$)=1. See their Fig. 3 for limit on $\sigma(H^0)\cdot$B$(H^0 \to \gamma\gamma)/\sigma(H^0_{SM})$.

[63] GONZALEZ-GARCIA 98B use DØ limit for $\gamma\gamma$ events with missing E_T in $p\overline{p}$ collisions (ABBOTT 98) to constrain possible $Z H$ or $W H$ production followed by unconventional $H \to \gamma\gamma$ decay which is induced by higher-dimensional operators. See their Figs. 1 and 2 for limits on the anomalous couplings.

[64] KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no $H^0_1 Z Z$ coupling and obtain $m_{H^0_1} \gtrsim$

5 GeV or $m_{A^0} \gtrsim 5$ GeV for $\tan\beta > 50$. Other Higgs bosons are assumed to be much heavier.

65 See Figs. 5 and 6 of ACCIARRI 96I for the excluded region in the (m_{H^0}, $\Gamma(Z \to Z^* H^0)$) plane (normalized to the Standard Model Higgs) for a general Higgs having a similar decay signature to Standard Model Higgs boson or decaying invisibly.

66 These limits are for H^0 with the standard coupling to Z but decaying to weakly interacting particles.

67 ACCIARRI 96J give B($Z \to H^0 +$ hadrons)$\times$B($H^0 \to \gamma\gamma$) < 2.3–6.9×10^{-6} for 20 $< m_{H^0} <$70 GeV.

68 ALEXANDER 96H give B($Z \to H^0 + q\overline{q}$)$\times$B($H^0 \to \gamma\gamma$) $< 2 \times 10^{-6}$ in the range 40 $< m_{H^0} <$ 80 GeV.

69 See Fig. 4 of ABREU 95H for the excluded region in the $m_{H^0} - m_{A^0}$ plane for general two-doublet models. For $\tan\beta >$1, the region $m_{H^0} + m_{A^0} \lesssim 87$ GeV, $m_{H^0} <$47 GeV is excluded at 95% CL.

70 BRAHMACHARI 93 consider Higgs limit from Z decay when the Higgs decays to invisible modes. If H^0 coupling to Z is at least $1/\sqrt{2}$ of the Standard Model H^0, the DECAMP 92 limit of 48 GeV changes within $\pm$6 GeV for arbitrary B($H^0 \to$ SM-like)+B($H^0 \to$ invisible)=1.

71 See Fig. 1 of BUSKULIC 93I for the limit on ZZH^0 coupling for a general Higgs having a similar decay signature to Standard Model Higgs boson or decaying invisibly. If the decay rate for $Z \to H^0 Z^*$ is $>$10% of the minimal Standard Model rate, then $m_{H^0} >$40 GeV. For the standard rate the limit is 58 GeV.

72 LOPEZ-FERNANDEZ 93 consider Higgs limit from Z decay when the Higgs decays to invisible modes. See Fig. 2 for excluded region in m_{H^0}-ZZH coupling plane with arbitrary B($H^0 \to$ SM-like)+B($H^0 \to$ invisible)=1. $m_H >$50 GeV is obtained if the H^0 coupling strength to the Z is greater than 0.2 times the Standard Model rate.

73 See Fig. 1 of ADRIANI 92G for the limit on ZZH^0 coupling for a general Higgs having a similar decay signature to Standard Model Higgs boson. For most masses below 30 GeV, the rate for $Z \to H_1^0 Z^*$ is less than 10% of the Standard Model rate.

74 PICH 92 analyse H^0 with $m_{H^0} < 2m_\mu$ in general two-doublet models. Excluded regions in the space of mass-mixing angles from LEP, beam dump, and $\pi^\pm$, η rare decays are shown in Figs. 3,4. The considered mass region is not totally excluded.

75 ACTON 91 limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.24 (0.56) times that for the standard Higgs boson for Higgs masses below $2m_\mu$ ($2m_\tau$).

76 DECAMP 91F search for $Z \to H^0 \ell^+ \ell^-$ where H^0 escapes before decaying. Combining this with DECAMP 90M and DECAMP 90N, they obtain B($Z \to H^0 \ell^+ \ell^-$)/B($Z \to \ell^+ \ell^-$) $< 2.5 \times 10^{-3}$ (95%CL) for $m_{H^0} <$ 60 GeV.

77 See Figs. 1, 3, 4, 5 of DECAMP 91I for excluded regions for the masses and mixing angles in general two-doublet models.

78 AKRAWY 90P limit is valid for any H^0 having $\Gamma(Z \to H^0 Z^*)$ more than 0.57 times that for the Standard Higgs boson.

79 DAVIER 89 give excluded region in m_{H^0}-x plane for m_{H^0} ranging from 1.2 MeV to 50 MeV.

80 SNYDER 89 give limits on B($B \to H^0$X)$\cdot$B($H^0 \to e^+ e^-$) for 100 $< m_{H^0} <$ 200 MeV, $c\tau <$ 24 mm.

81 First order QCD correction included with $\alpha_s \approx 0.2$. Their figure 4 shows the limits vs. x.

82 ALBRECHT 85J found no mono-energetic photons in both $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays in the range 0.5 GeV $< E(\gamma) <$4.0 GeV with typically BR$<$ 0.01 for $\Upsilon(1S)$ and BR$<$ 0.02 for $\Upsilon(2S)$ at 90% CL. These upper limits are 5–10 times the prediction of the standard Higgs-doublet model. The quoted 90% limit B($\Upsilon(1S) \to H^0\gamma$) $< 1.5\times10^{-3}$

at $E(\gamma)$ = 1.07 GeV contradicts previous Crystal Ball observation of $(4.7 \pm 1.1) \times 10^{-3}$; see their reference 3. Their figure 8a shows the upper limits of x^2 as a function of $E(\gamma)$ by assuming no QCD corrections. We used $m_{H^0} = m_{\Upsilon}\ (1-2E(\gamma)/m_{\Upsilon})^{1/2}$.

H_1^0 (Higgs Boson) MASS LIMITS in Supersymmetric Models

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H_1^0 and H_2^0, where we define $m_{H_1^0} < m_{H_2^0}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^{\pm}$). H_1^0 and H_2^0 are also called h and H in the literature. There are two free parameters in the theory which can be chosen to be m_{A^0} and $\tan\beta = v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets. Tree-level Higgs masses are constrained by the model to be $m_{H_1^0} \leq m_Z$, $m_{H_2^0} \geq m_Z$, $m_{A^0} \geq m_{H_1^0}$, and $m_{H^\pm} \geq m_W$. However, as described in the "Note on Supersymmetry," recent calculations of one-loop radiative corrections show that these relations may be violated. Many experimental analyses have not taken into account these corrections; footnotes indicate when these corrections are included. The results assume no invisible H^0 or A^0 decays.

'OUR LIMIT' is taken from the LEP Higgs Boson Searches Working group (LEP 99B), where the combination of the results of ABBIENDI 99E, ABREU 99I, ACCIARRI 98M, and BARATE 98A was performed. The limit assumes universal scalar and weak gaugino masses of m_0=1 TeV and M_2=1.6 TeV, respectively, at the electroweak scale, two-loop radiative corrections, m_{top}=175 GeV, $\tan\beta > 0.8$, and holds for the cases of minimal and maximal scalar top mixing.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>79.6 (CL = 95%) OUR LIMIT					
>70.5	95	[83] ABBIENDI	99E	OPAL	
>74.4	95	[84] ABREU	99I	DLPH	
>70.7	95	[85] ACCIARRI	98M	L3	$\tan\beta > 1$
>72.2	95	[86] BARATE	98A	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>59.5	95	[87] ABREU	98E	DLPH	$\tan\beta > 1$
>59.0	95	[88] ACKERSTAFF	98S	OPAL	
		[89] ACCIARRI	97N	L3	
>44.3	95	[90] ALEXANDER	97	OPAL	any $\tan\beta$
>62.5	95	[91] BARATE	97P	ALEP	
>44	95	[92] ABREU	95H	DLPH	any $\tan\beta$
		[93] ROSIEK	95	RVUE	
>44.4	95	[94] ABREU	94O	DLPH	$m_{H_1^0}=m_{A^0}$, any $\tan\beta$
>44.5	95	[95] AKERS	94I	OPAL	$\tan\beta > 1$
>44	95	[96] BUSKULIC	93I	ALEP	$\tan\beta > 1$
>34	95	[97] ABREU	92J	DLPH	$\tan\beta > 0.6$
>29	95	[97] ABREU	92J	DLPH	any $\tan\beta$
>42	95	[98] ADRIANI	92G	L3	$1 < \tan\beta < 50$
> 0.21	95	[99] ABREU	91B	DLPH	any $\tan\beta$
>28	95	[100] ABREU	91B	DLPH	any $\tan\beta$

none 3–38	95	[101] AKRAWY	91C	OPAL	$\tan\beta > 6$
none 3–22	95	[101] AKRAWY	91C	OPAL	$\tan\beta > 0.5$
		[102] BLUEMLEIN	91	BDMP	$pN \to H^0_1 X$ ($H^0_1 \to e^+e^-$, 2γ)
>41	95	[103] DECAMP	91I	ALEP	$\tan\beta > 1$
> 9	95	[104] ABREU	90E	DLPH	any $\tan\beta$
>13	95	[104] ABREU	90E	DLPH	$\tan\beta > 1$
>26	95	[105] ADEVA	90R	L3	$\tan\beta > 1$
none 0.05–3.1	95	[106] DECAMP	90E	ALEP	any $\tan\beta$
none 0.05–13	95	[106] DECAMP	90E	ALEP	$\tan\beta > 0.6$
none 0.006–20	95	[106] DECAMP	90E	ALEP	$\tan\beta > 2$
>37.1	95	[106] DECAMP	90E	ALEP	$\tan\beta > 6$
none 0.05–20	95	[107] DECAMP	90H	ALEP	$\tan\beta > 0.6$
none 0.006–21.4	95	[107] DECAMP	90H	ALEP	$\tan\beta > 2$
> 3.1	95	[108] DECAMP	90M	ALEP	any $\tan\beta$

[83] ABBIENDI 99E search for $e^+e^- \to H^0_1 A^0$ in the final states $b\overline{b}b\overline{b}$, $q\overline{q}\tau^+\tau^-$, and $6b$ and $e^+e^- \to H^0_1 Z$ for various final states at $E_{\rm cm}$= 183 GeV. Lower energy data at $\sqrt{s}$ between m_Z and 172 GeV are combined. Two-loop radiative corrections are included with $M_{\rm top}$=175 GeV, $M_{\rm SUSY}$=1 TeV, and minimal/maximal scalar top mixing. See paper for results of more general scan.

[84] ABREU 99I search for $e^+e^- \to H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$, and $q\overline{q}\tau^+\tau^-$ and $e^+e^- \to H^0_1 Z$ for various final states at $E_{\rm cm}$= 183 GeV. Lower energy data at $E_{\rm cm}$ between 130 and 172 GeV are combined. The limit is for the universal scalar mass of 1 TeV, SU(2) gaugino mass of 1.6 TeV, with minimal/typical/maximal stop mixing. Two-loop radiative corrections, and m_t= 173.9 GeV, are used.

[85] ACCIARRI 98M search for $e^+e^- \to H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \to H^0_1 Z$ at $E_{\rm cm}$ between 130 and 183 GeV. Two-loop radiative corrections are included with $m_{\rm top}$ = 175 GeV, $M_{\rm SUSY}$ = 1 TeV, SU(2) gaugino mass of 1 TeV and various scalar top mixing scenarios.

[86] BARATE 98A search for $e^+e^- \to H^0_1 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$ at $E_{\rm cm}$=181–184 GeV and combine with BARATE 99B limit on $e^+e^- \to H^0_1 Z$. The limit is for $M_{\rm SUSY}$= 1 TeV with minimal/maximal stop mixing. See paper for the result from a scan in more general MSSM parameters.

[87] ABREU 98E search for $e^+e^- \to H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$ and $q\overline{q}\tau^+\tau^-$ at $\sqrt{s}$ = 161–172 GeV. The results from the SM Higgs search described in the same paper are also used to set these limits. Two-loop radiative corrections are included with $m_{\rm top}$ = 175 GeV, $M_{\rm SUSY}$ = 1 TeV, and maximal scalar top mixings.

[88] ACKERSTAFF 98S search for $e^+e^- \to H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$, $q\overline{q}\tau^+\tau^-$, and $6b$ at $E_{\rm cm}$ between 130 and 172 GeV and combine with ACKERSTAFF 98H limit on $e^+e^- \to H^0_1 Z$. Two-loop radiative corrections are included with $m_{\rm top}$ = 175 GeV, $M_{\rm SUSY}$ = 1 TeV, SU(2) gaugino mass of 1 TeV and maximal scalar stop mixing. The scan of the MSSM parameter space does not reduce the limit significantly.

[89] ACCIARRI 97N search for $e^+e^- \to H^0_1 A^0$ in four-jet final states at $\sqrt{s}$ = 130–172 GeV. Cross-section limits are obtained for $|m_{H^0_1} - m_{A^0}|$ = 0, 10, and 20 GeV.

[90] ALEXANDER 97 search for $Z \to H^0_1 Z^*$ and $Z \to H^0_1 A^0$ and use Γ_Z (nonstandard) < 13.9 MeV. Radiative corrections using two-loop renormalization group equations are included with m_t < 195 GeV and the MSSM parameter space is widely scanned. Possible invisible decay mode $H^0_1 \to \widetilde{\chi}^0\widetilde{\chi}^0$ is included in the analysis.

[91] BARATE 97P search for $e^+e^- \rightarrow H_1^0 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$ at $\sqrt{s}$ = 130–172 GeV and combine with BARATE 97O limit on $e^+e^- \rightarrow H_1^0 Z$. Two-loop radiative corrections are included with m_{top} = 175 GeV and M_{SUSY} = 1 TeV, and maximal scalar top mixings. The invisible decays $H_1^0 \rightarrow \widetilde{\chi}^0 \widetilde{\chi}^0$ are not allowed in the analysis, as ruled out in the relevant kinematic region by BUSKULIC 96K.

[92] ABREU 95H search for $Z \rightarrow H_1^0 Z^*$ and $Z \rightarrow H_1^0 A^0$. Two-loop corrections are included with m_t=170 GeV, $m_{\widetilde{t}}$=1 TeV. Including only one-loop corrections does not change the limit.

[93] ROSIEK 95 study the dependence of $m_{H_1^0}$ limit on various supersymmetry parameters. They argue that H_1^0 as light as 25 GeV is not excluded by ADRIANI 92G data in the region $m_{A^0} \sim 60$ GeV if $m_{\widetilde{t}} \lesssim 200$ GeV and $\widetilde{t}_L$-$\widetilde{t}_R$ mixing is large.

[94] ABREU 94O study $H_1^0 A^0 \rightarrow$ four jets and combine with ABREU 94G analysis. The limit applies if the H_1^0-A^0 mass difference is <4 GeV.

[95] AKERS 94I search for $Z \rightarrow H_1^0 Z^*$ and $Z \rightarrow H_1^0 A^0$. One-loop corrections are included with m_t <200 GeV, $m_{\widetilde{t}}$ <1 TeV. See Fig. 10 for limits for tanβ <1.

[96] BUSKULIC 93I search for $Z \rightarrow H_1^0 Z^*$ and $Z \rightarrow H_1^0 A^0$. One-loop corrections are included with any m_t, $m_{\widetilde{t}} > m_t$.

[97] ABREU 92J searched for $Z \rightarrow H_1^0 Z^*$ and $Z \rightarrow H_1^0 A^0$ with H_1^0, $A^0 \rightarrow \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.

[98] ADRIANI 92G search for $Z \rightarrow H_1^0 Z^*$, $Z \rightarrow H_1^0 A^0 \rightarrow 4b$, $bb\tau\tau$, 4τ, $6b$ (via $H^0 \rightarrow A^0 A^0$), and include constraints from $\Gamma(Z)$. One-loop corrections to the Higgs potential are included with 90<m_t <250 GeV, $m_t < m_{\widetilde{t}}$ <1 TeV.

[99] ABREU 91B result is based on negative search for $Z \rightarrow H_1^0 f\overline{f}$ and the limit on invisible Z width $\Gamma(Z \rightarrow H_1^0 A^0) <$ 39 MeV (95%CL), assuming $m_{A^0} < m_{H_1^0}$.

[100] ABREU 91B result obtained by combining with analysis of ABREU 90I.

[101] AKRAWY 91C result from $Z \rightarrow H_1^0 A^0 \rightarrow$ 4jet or $\tau^+\tau^- jj$ or 4τ and $Z \rightarrow H_1^0 Z^*$ ($H_1^0 \rightarrow q\overline{q}$, $Z^* \rightarrow \nu\overline{\nu}$ or e^+e^- or $\mu^+\mu^-$). See paper for the excluded region for the case tanβ < 1. Although these limits do not take into account the one-loop radiative corrections, the authors have reported unpublished results including these corrections and showed that the excluded region becomes larger.

[102] BLUEMLEIN 91 excluded certain range of tanβ for $m_{H_1^0}$ < 120 MeV, m_{A^0} < 80 MeV.

[103] DECAMP 91I searched for $Z \rightarrow H_1^0 Z^*$, and $Z \rightarrow H_1^0 A^0 \rightarrow$ 4jets or $\tau\tau jj$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses.

[104] ABREU 90E searched for $Z \rightarrow H_1^0 A^0$ and $Z \rightarrow H_1^0 Z^*$. $m_{H_1^0}$ < 210 MeV is not excluded by this analysis.

[105] ADEVA 90R result is from $Z \rightarrow H_1^0 A^0 \rightarrow$ 4jet or $\tau\tau jj$ or 4τ and $Z \rightarrow H_1^0 Z^*$. Some region of $m_{H_1^0}$ < 4 GeV is not excluded by this analysis.

[106] DECAMP 90E look for $Z \rightarrow H_1^0 A^0$ as well as $Z \rightarrow H_1^0 \ell^+\ell^-$, $Z \rightarrow H_1^0 \nu\overline{\nu}$ with 18610 Z decays. Their search includes signatures in which H_1^0 and A^0 decay to $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, or $q\overline{q}$. See their figures of $m_{H_1^0}$ vs. tanβ.

[107] DECAMP 90H is similar to DECAMP 90E but with 25,000 Z decays.

[108] DECAMP 90M looked for $Z \rightarrow H^0 \ell\ell$, where H_1^0 decays outside the detector. This excludes a region in the ($m_{H_1^0}$, $\tan\beta$) plane centered at $m_{H_1^0}$ = 50 MeV, $\tan\beta = 0.5$. This limit together with DECAMP 90E result excludes $m_{H_1^0} < 3$ GeV for any $\tan\beta$.

A^0 (Pseudoscalar Higgs Boson) MASS LIMITS in Supersymmetric Models

Limits on the A^0 mass from e^+e^- collisions arise from direct searches in the $e^+e^- \rightarrow A^0 H_1^0$ channel and indirectly from the relations valid in the minimal supersymmetric model between m_{A^0} and $m_{H_1^0}$. As discussed in the "Note on Supersymmetry," at the one-loop level and in the simplest cases, these relations depend on the masses of the t quark and $\widetilde{t}$ squarks. The limits are weaker for larger t and $\widetilde{t}$ masses, while they increase with the inclusion of two-loop radiative corrections. Some specific examples of these dependences are provided in the footnotes to the listed papers.

'OUR LIMIT' is taken from the LEP Higgs Boson Searches Working group (LEP 99B), where the combination of the results of ABBIENDI 99E, ABREU 99I, ACCIARRI 98M, and BARATE 98A was performed. The limit assumes universal scalar and weak gaugino masses of m_0=1 TeV and M_2=1.6 TeV, respectively, at the electroweak scale, two-loop radiative corrections, m_{top}=175 GeV, $\tan\beta > 0.8$, and holds for the cases of minimal and maximal scalar top mixing.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>80.2 (CL = 95%) OUR LIMIT					
>72.0	95	[109] ABBIENDI	99E	OPAL	$\tan\beta > 1$
>75.3	95	[110] ABREU	99I	DLPH	$\tan\beta > 0.6$
>71.0	95	[111] ACCIARRI	98M	L3	$\tan\beta > 1$
>76.1	95	[112] BARATE	98A	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>51.0	95	[113] ABREU	98E	DLPH	$\tan\beta > 1$
>59.5	95	[114] ACKERSTAFF	98S	OPAL	$\tan\beta > 1$
		[115] DREES	98	RVUE	$p\overline{p} \rightarrow b\overline{b}H^0/A^0$+any
		[116] ACCIARRI	97N	L3	
>23.5	95	[117] ALEXANDER	97	OPAL	$\tan\beta > 1$, m_t <195 GeV
>62.5	95	[118] BARATE	97P	ALEP	$\tan\beta > 1$
>60	95	[119] KEITH	97	RVUE	$\tan\beta < 1$
>27	95	[120] ABREU	95H	DLPH	$\tan\beta > 1$, m_t = 170 GeV
>44.4	95	[121] ABREU	94O	DLPH	$m_{H_1^0}=m_{A^0}$, any $\tan\beta$
>24.3	95	[122] AKERS	94I	OPAL	$\tan\beta > 1$, m_t <200 GeV
>44.5	95	[122] AKERS	94I	OPAL	$\tan\beta > 1$, $m_{H_1^0}=m_{A^0}$
>21	95	[123] BUSKULIC	93I	ALEP	$\tan\beta > 1$, m_t = 140 GeV
		[124] ELLIS	93	RVUE	Electroweak

>34	95	[125] ABREU	92J	DLPH	$\tan\beta > 3$
>22	95	[126] ADRIANI	92G	L3	$1<\tan\beta<50$, $m_t<250$ GeV
> 0.21	95	[127] BUSKULIC	92	ALEP	$\tan\beta > 1$
none 3–40.5	95	[128] AKRAWY	91C	OPAL	$\tan\beta > 1$, if 3 GeV $< m_{H_1^0} < m_{A^0}$
>20	95	[129] DECAMP	91I	ALEP	$\tan\beta > 1$
>34	95	[130] ABREU	90E	DLPH	$\tan\beta > 1$, $m_{H_1^0} < m_{A^0}$
>12	95	[130] ABREU	90E	DLPH	$\tan\beta < 1$
>39	95	[131] ADEVA	90R	L3	$\tan\beta > 1$, $m_{H_1^0} < m_{A^0}$

[109] ABBIENDI 99E search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$, $q\overline{q}\tau^+\tau^-$, and $6b$ and $e^+e^- \rightarrow H_1^0 Z$ for various final states at E_{cm}= 183 GeV. Lower energy data at $\sqrt{s}$ between m_Z and 172 GeV are combined. Two-loop radiative corrections are included with M_{top}=175 GeV, M_{SUSY}=1 TeV, and minimal/maximal scalar top mixing. See paper for results of more general scan.

[110] ABREU 99I search for $e^+e^- \rightarrow H_1^0 A^0$ in the final state $b\overline{b}b\overline{b}$, and $q\overline{q}\tau^+\tau^-$ and $e^+e^- \rightarrow H_1^0 Z$ for various final states at E_{cm}= 183 GeV. Lower energy data at E_{cm} between 130 and 172 GeV are combined. The limit is for the universal scalar mass of 1 TeV, SU(2) gaugino mass of 1.6 TeV, with minimal/typical/maximal stop mixing. Two-loop radiative corrections, and m_t= 173.9 GeV, are used.

[111] ACCIARRI 98M search for $e^+e^- \rightarrow H_1^0 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H_1^0 Z$ at E_{cm} between 130 and 183 GeV. Two-loop radiative corrections are included with m_{top} = 175 GeV, M_{SUSY} = 1 TeV, SU(2) gaugino mass of 1 TeV and various scalar top mixing scenarios.

[112] BARATE 98A search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$ at E_{cm}=181–184 GeV and combine with BARATE 99B limit on $e^+e^- \rightarrow H_1^0 Z$. The limit is for M_{SUSY}= 1 TeV with minimal/maximal stop mixing. See paper for the result from a scan in more general MSSM parameters.

[113] ABREU 98E search for $e^+e^- \rightarrow H_1^0 A^0$ in the final state $b\overline{b}b\overline{b}$ and $q\overline{q}\tau^+\tau^-$ at $\sqrt{s}$ = 161–172 GeV. The results from the SM Higgs search described in the same paper are also used to set these limits. Two-loop radiative corrections are included with m_{top} = 175 GeV, M_{SUSY} = 1 TeV, and maximal scalar top mixings.

[114] ACKERSTAFF 98S search for $e^+e^- \rightarrow H_1^0 A^0$ in the final state $b\overline{b}b\overline{b}$, $q\overline{q}\tau^+\tau^-$, and $6b$ at E_{cm} between 130 and 172 GeV and combine with ACKERSTAFF 98H limit on $e^+e^- \rightarrow H_1^0 Z$. Two-loop radiative corrections are included with m_{top} = 175 GeV, M_{SUSY} = 1 TeV, SU(2) gaugino mass of 1 TeV and maximal scalar stop mixing. The scan of the MSSM parameter space does not reduce the limit significantly.

[115] DREES 98 (and Erratum in DREES 98B) use the CDF third-generation leptoquark search results (ABE 97F) to constrain possible Higgs production in association with $b\overline{b}$ in $p\overline{p}$ collision. In the framework of MSSM, m_A less than 130 GeV is excluded for $\tan\beta$=100. No significant limit is obtained for $\tan\beta < 80$.

[116] ACCIARRI 97N search for $e^+e^- \rightarrow H_1^0 A^0$ in four-jet final states at $\sqrt{s}$ = 130–172 GeV. Cross-section limits are obtained for $|m_{H_1^0} - m_{A^0}|$ = 0, 10, and 20 GeV.

[117] ALEXANDER 97 search for $Z \rightarrow H_1^0 Z^*$ and $Z \rightarrow H_1^0 A^0$ and use Γ_Z (nonstandard) $<$ 13.9 MeV. Radiative corrections using two-loop renormalization group equations are included with $m_t <$ 195 GeV and the MSSM parameter space is widely scanned. Possible

invisible decay mode $H^0_1 \rightarrow \widetilde{\chi}^0 \widetilde{\chi}^0$ is included in the analysis. The limit improves to 44 GeV for $\tan\beta \gtrsim 1.5$, but goes to 0 for $\tan\beta < 0.9$ and $m_t > 195$ GeV.

[118] BARATE 97P search for $e^+ e^- \rightarrow H^0_1 A^0$ in the final state $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$ at $\sqrt{s}$ = 130–172 GeV and combine with BARATE 97O limit on $e^+ e^- \rightarrow H^0_1 Z$. Two-loop radiative corrections are included with m_{top} = 175 GeV and M_{SUSY} = 1 TeV, and maximal scalar top mixings. The invisible decays $H^0_1 \rightarrow \widetilde{\chi}^0 \widetilde{\chi}^0$ are not allowed in the analysis, as ruled out in the relevant kinematic region by BUSKULIC 96K.

[119] KEITH 97 uses Tevatron data on $t\overline{t}$ production to estimate B($t \rightarrow H^+ b$)< 0.3 at 95%CL. The resulting constraints on m_{H^+} and the one-loop MSSM relation between m_{H^+} and m_{A^0} give rise to the limit shown on m_{A^0}.

[120] ABREU 95H search for $Z \rightarrow H^0_1 Z^*$ and $Z \rightarrow H^0_1 A^0$. One-loop corrections are included with m_t = 170 GeV, $m_{\widetilde{t}}$ = 1 TeV. The limit becomes weak for larger m_t: at m_t = 190 GeV, the limit is 14 GeV. The limit at m_t = 170 GeV would increase to 39 GeV if two-loop radiative corrections were included. m_t and $m_{\widetilde{t}}$ dependences are shown in Fig. 6.

[121] ABREU 94O study $H^0_1 A^0 \rightarrow$ four jets and combine with ABREU 94G analysis. The limit applies if the H^0_1-A^0 mass difference is <4 GeV.

[122] AKERS 94I search for $Z \rightarrow H^0_1 Z^*$ and $Z \rightarrow H^0_1 A^0$. One-loop corrections are included with m_t <200 GeV, $m_{\widetilde{t}}$ <1 TeV. See Fig. 10 for limits for $\tan\beta$ <1.

[123] BUSKULIC 93I search for $Z \rightarrow H^0_1 Z^*$ and $Z \rightarrow H^0_1 A^0$. One-loop corrections to the Higgs potential are included with any m_t, $m_{\widetilde{t}} > m_t$. For m_t = 140 GeV and $m_{\widetilde{t}}$ = 1 TeV, the limit is m_{A^0} >45 GeV. Assumes no invisible H^0 or A^0 decays.

[124] ELLIS 93 analyze possible constraints on the MSSM Higgs sector by electroweak precision measurements and find that m_{A^0} is not constrained by the electroweak data.

[125] ABREU 92J searched for $Z \rightarrow H^0_1 Z^*$ and $Z \rightarrow H^0_1 A^0$ with H^0_1, $A^0 \rightarrow \tau\tau$ or jet-jet. Small mass values are excluded by ABREU 91B.

[126] ADRIANI 92G search for $Z \rightarrow H^0_1 Z^*$, $Z \rightarrow H^0_1 A^0 \rightarrow 4b$, $bb\tau\tau$, 4τ, $6b$ (via $H^0 \rightarrow A^0 A^0$), and include constraints from $\Gamma(Z)$. One-loop corrections are included with 90<m_t <250 GeV, m_t <$m_{\widetilde{t}}$ <1 TeV. The region m_{A^0} <11 GeV is allowed if 42<$m_{H^0_1}$ <62 GeV, but is excluded by other experiments.

[127] BUSKULIC 92 limit is from $\Gamma(Z)$, $Z \rightarrow H^0_1 Z^*$, and $Z \rightarrow H^0_1 A^0$. The limit is valid for any $m_{H^0_1}$ below the the theoretical limit $m_{H^0_1}$ <64 GeV which holds for $m_{A^0} \sim 0$ in the minimal supersymmetric model. One-loop radiative corrections are included.

[128] AKRAWY 91C result from $Z \rightarrow H^0_1 A^0 \rightarrow$ 4jet or $\tau^+\tau^- jj$ or 4τ. See paper for the excluded region for the case $\tan\beta < 1$.

[129] DECAMP 91I searched for $Z \rightarrow H^0_1 Z^*$, and $Z \rightarrow H^0_1 A^0 \rightarrow$ 4jets or $\tau\tau jj$ or $3A^0$. Their limits take into account the one-loop radiative corrections to the Higgs potential with varied top and squark masses. For m_t = 140 GeV and $m_{\widetilde{q}}$ = 1 TeV, the limit is m_{A^0} > 31 GeV.

[130] ABREU 90E searched $Z \rightarrow H^0_1 A^0$ and $Z \rightarrow H^0_1 Z^*$. m_{A^0} < 210 MeV is not excluded by this analysis.

[131] ADEVA 90R result is from $Z \rightarrow H^0_1 A^0 \rightarrow$ 4jet or $\tau\tau jj$ or 4τ and $Z \rightarrow H^0_1 Z^*$. Some region of m_{A^0} < 5 GeV is not excluded by this analysis.

MASS LIMITS for Associated Higgs Production in e^+e^- Interactions

In multi-Higgs models, associated production of Higgs via virtual or real Z in e^+e^- annihilation, $e^+e^- \to H_1^0 H_2^0$, is possible if H_1^0 and H_2^0 have opposite CP eigenvalues. Limits are for the mass of the heavier Higgs H_2^0 in two-doublet models.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>53	95	[132] AKERS	94I	OPAL	$m_{H_1^0} < 12$ GeV
		[133] ADRIANI	92G	L3	
>45	95	[134] DECAMP	90H	ALEP	$m_{H_1^0} < 20$ GeV
>37.5	95	[134] DECAMP	90H	ALEP	$m_{H_1^0} < m_{H_2^0}$
none 5–45	95	[135] KOMAMIYA	90	MRK2	$m_{H_1^0} < 0.5$ GeV, $H_2^0 \to q\overline{q}$ or $\tau^+\tau^-$
> 8	90	[136] KOMAMIYA	89	MRK2	$H_1^0 \to \mu^+\mu^-$, $H_2^0 \to q\overline{q}$, $\tau^+\tau^-$
>28	95	[137] LOW	89	AMY	$m_{H_1^0} \lesssim 20$ MeV, $H_2^0 \to q\overline{q}$
none 2–9	90	[138] AKERLOF	85	HRS	$m_{H_1^0} = 0$, $H_2^0 \to f\overline{f}$
none 4–10	90	[139] ASH	85C	MAC	$m_{H_1^0} = 0.2$ GeV, $H_2^0 \to \tau^+\tau^-$, $c\overline{c}$
none 1.3–24.7	95	[138] BARTEL	85L	JADE	$m_{H_1^0} = 0.2$ GeV, $H_2^0 \to f\overline{f}$ or $f\overline{f}H_1^0$
none 1.2–13.6	95	[138] BEHREND	85	CELL	$m_{H_1^0} = 0$, $H_2^0 \to f\overline{f}$
none 1–11	90	[138] FELDMAN	85	MRK2	$m_{H_1^0} = 0$, $H_2^0 \to f\overline{f}$
none 1–9	90	[138] FELDMAN	85	MRK2	$m_{H_1^0} = m_{H_2^0}$, $H_2^0 \to f\overline{f}$

[132] AKERS 94I search for $Z \to H_1^0 H_2^0$ with various decay modes. See Fig. 11 for the full excluded mass region in the general two-doublet model, from which the limit above is taken. In particular, for $m_{H_1^0} = m_{H_2^0}$ the limit becomes >38 GeV.

[133] ADRIANI 92G excluded regions of the $m_{H_1^0} - m_{A^0}$ plane for various decay modes with limits B($Z \to H_1^0 H_2^0$) <(2–20) $\times 10^{-4}$ are shown in Figs. 2–5.

[134] DECAMP 90H search for $Z \to H_1^0 e^+e^-$, $H_1^0\mu^+\mu^-$, $H_1^0\tau^+\tau^-$, $H_1 q\overline{q}$, low multiplicity final states, τ-τ-jet-jet final states and 4-jet final states.

[135] KOMAMIYA 90 limits valid for $\cos^2(\alpha-\beta) \approx 1$. They also search for the cases $H_1^0 \to \mu^+\mu^-$, $\tau^+\tau^-$, and $H_2^0 \to H_1^0 H_1^0$. See their Fig. 2 for limits for these cases.

[136] KOMAMIYA 89 assume B($H_1^0 \to \mu^+\mu^-$) = 100 %, $2m_\mu < m_{H_1^0} < m_\tau$. The limit is for maximal mixing. A limit of $m_{H_2^0} > 18$ GeV for the case $H_2^0 \to H_1^0 H_1^0$ ($H_1^0 \to \mu^+\mu^-$) is also given. From PEP at $E_{\rm cm}$ = 29 GeV.

[137] LOW 89 assume that H_1^0 escapes the detector. The limit is for maximal mixing. A reduced limit of 24 GeV is obtained for the case $H_2^0 \to H_1^0 f\overline{f}$. Limits for a Higgs-triplet model are also discussed. $E_{\rm cm}^{ee}$ = 50–60.8 GeV.

[138] The limit assumes maximal mixing and that H_1^0 escapes the detector.

[139] ASH 85 assumes that H_1^0 escapes undetected. The bound applies up to a mixing suppression factor of 5.

$H^\pm$ (Charged Higgs) MASS LIMITS

Most of the following limits assume B($H^+ \to \tau^+\nu$) + B($H^+ \to c\overline{s}$) = 1. DECAMP 90I, BEHREND 87, and BARTEL 86 assume B($H^+ \to \tau^+\nu$) + B($H^+ \to c\overline{s}$) + B($H^+ \to c\overline{b}$) = 1. All limits from Z decays and LEP 2 as well as ADACHI 90B assume that H^+ has weak isospin $T_3 = +1/2$.

For limits obtained in hadronic collisions before the observation of the top quark, and based on the top mass values inconsistent with the current measurements, see the 1996 (Physical Review **D54** 1 (1996)) Edition of this Review.

The limits are also applicable to pointlike techni-pions. For a discussion of techniparticles, see EICHTEN 86.

In the following tanβ is the ratio of the two vacuum expectation values in the two-doublet model.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 59.5	95	[140] ABBIENDI	99E	OPAL	B($\tau\nu$) = 0–1
> 57.5	95	[140] ACCIARRI	99B	L3	B($\tau\nu$) = 0–1
> 59	95	[140] BARATE	99D	ALEP	B($\tau\nu$) = 0–1
> 54.5	95	[141] ABREU	98F	DLPH	B($\tau\nu$) = 0–1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 52.0	95	[141] ACKERSTAFF	98I	RVUE	B($\tau\nu$) = 0–1
> 52	95	[141] BARATE	98G	ALEP	B($\tau\nu$) = 0–1
		[142] ABE	97L	CDF	$t \to bH^+$, $H \to \tau\nu$
		[143] ACCIARRI	97F	L3	$B \to \tau\nu_\tau$
		[144] AMMAR	97B	CLEO	$\tau \to \mu\nu\nu$
		[145] COARASA	97	RVUE	$B \to \tau\nu_\tau X$
		[146] GUCHAIT	97	RVUE	$t \to bH^+$, $H \to \tau\nu$
		[147] MANGANO	97	RVUE	$B_{u(c)} \to \tau\nu_\tau$
		[148] STAHL	97	RVUE	$\tau \to \mu\nu\nu$
		[149] ABE	96G	CDF	$t \to bH^+$, $H^+ \to \tau^+\nu_\tau$
> 44.1	95	[150] ALEXANDER	96I	OPAL	B($\tau\nu$) = 0–1
>244	95	[151] ALAM	95	CLE2	$b \to s\gamma$
		[152] BUSKULIC	95	ALEP	$b \to \tau\nu_\tau X$
> 43.5	95	[153] ABREU	94O	DLPH	B($\tau\nu$) = 0–1
		[154] BARGER	93	RVUE	$b \to s\gamma$

		[155] BELANGER	93	RVUE	$b \to s\gamma$
		[154] HEWETT	93	RVUE	$b \to s\gamma$
>41	95	[156] ADRIANI	92G	L3	$B(\tau\nu) = 0$–1
>41.7	95	[157,158] DECAMP	92	ALEP	$B(\tau\nu) = 0$–1
none 8.0–20.2	95	[159] YUZUKI	91	VNS	$B(\ell\nu) = 0$–1
>29	95	[157,160] ABREU	90B	DLPH	$B(\tau\nu) = 0$–1
>19	95	[157,161] ADACHI	90B	TOPZ	$B(\tau\nu) = 0$–1
>36.5	95	[157,162] ADEVA	90M	L3	$B(\tau\nu) = 0$–1
>35	95	[157,163] AKRAWY	90K	OPAL	$B(\tau\nu) = 0$–1
>35.4	95	[157,164] DECAMP	90I	ALEP	$B(\tau\nu) = 0$–1
none 10–20	95	[165] SMITH	90B	AMY	$B(\tau\nu) > 0.7$
>19	95	[164] BEHREND	87	CELL	$B(\tau\nu) = 0$–1
>18	95	[166] BARTEL	86	JADE	$B(\tau\nu)=0.1$–1.0
>17	95	[166] ADEVA	85	MRKJ	$B(\tau\nu)=0.25$–1.0

[140] Search for $e^+e^- \to H^+H^-$ at E_{cm}= 130–183 GeV.

[141] Search for $e^+e^- \to H^+H^-$ at E_{cm}= 130–172 GeV.

[142] ABE 97L search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at E_{cm} = 1.8 TeV, with $H^+ \to \tau^+\nu_\tau$, τ decaying hadronically. The limits depend on the choice of the $t\overline{t}$ cross section. See Fig. 3 for the excluded region. The excluded mass region extends to over 140 GeV for tanβ values above 100.

[143] ACCIARRI 97F give a limit $m_{H^+} > 2.6$ tanβ GeV (90%CL) from their limit on the exclusive $B \to \tau\nu_\tau$ branching ratio.

[144] AMMAR 97B measure the Michel parameter ρ from $\tau \to e\nu\nu$ decays and assmes e/μ universality to extract the Michel η parameter from $\tau \to \mu\nu\nu$ decays. The measurement is translated to a lower limit on m_{H^+} in a two-doublet model $m_{H^+} > 0.97$ tanβ GeV (90% CL).

[145] COARASA 97 reanalyzed the constraint on the ($m_{H^\pm}$,tanβ) plane derived from the inclusive $B \to \tau\nu_\tau X$ branching ratio in GROSSMAN 95B and BUSKULIC 95. They show that the constraint is quite sensitive to supersymmetric one-loop effects.

[146] GUCHAIT 97 studies the constraints on m_{H^+} set by Tevatron data on $\ell\tau$ final states in $t\overline{t} \to (W b)(H b)$, $W \to \ell\nu$, $H \to \tau\nu_\tau$. See Fig. 2 for the excluded region.

[147] MANGANO 97 reconsiders the limit in ACCIARRI 97F including the effect of the potentially large $B_c \to \tau\nu_\tau$ background to $B_u \to \tau\nu_\tau$ decays. Stronger limits are obtained.

[148] STAHL 97 fit τ lifetime, leptonic branching ratios, and the Michel parameters and derive limit $m_{H^+} > 1.5$ tanβ GeV (90% CL) for a two-doublet model. See also STAHL 94.

[149] ABE 96G search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at E_{cm}= 1.8 TeV. For the currently observed value of the top mass, the search is not sensitive enough to exclude a charged Higgs boson of any mass.

[150] ALEXANDER 96I search for the final states $H^+H^- \to \tau\nu_\tau\tau\nu_\tau$, $\tau\nu_\tau c\overline{s}$, $c\overline{s}\overline{c}s$. Limit for $B(\tau\nu_\tau) = 1$ is 45.5 GeV.

[151] ALAM 95 measure the inclusive $b \to s\gamma$ branching ratio at $\Upsilon(4S)$ and give $B(b \to s\gamma) < 4.2\times10^{-4}$ (95% CL), which translates to the limit $m_{H^+} >[244 + 63/(\tan\beta)^{1.3}]$ GeV in the Type II two-doublet model. Light supersymmetric particles can invalidate this bound.

[152] BUSKULIC 95 give a limit $m_{H^+} > 1.9$ tanβ GeV (90%CL) for Type-II models from $b \to \tau\nu_\tau X$ branching ratio, as proposed in GROSSMAN 94.

[153] ABREU 94O study $H^+H^- \to c\overline{s}s\overline{c}$ (four-jet final states) and $H^+H^- \to \tau\nu_\tau\tau\nu_\tau$. Limit for $B(\tau\nu_\tau)$= 1 is 45.4 GeV.

[154] HEWETT 93 and BARGER 93 analyze charged Higgs contribution to $b \to s\gamma$ in two-doublet models with the CLEO limit $B(b \to s\gamma) < 8.4\times10^{-4}$ (90% CL) and find lower limits on $m_{H^\pm}$ in the type of model (model II) in which different Higgs are responsible

for up-type and down-type quark masses. HEWETT 93 give m_{H^+} >110 (70) GeV for m_t >150 (120) GeV using m_b = 5 GeV. BARGER 93 give m_{H^+} >155 GeV for m_t = 150 GeV using m_b = 4.25 GeV. The authors employ leading logarithmic QCD corrections and emphasize that the limits are quite sensitve to m_b.

[155] BELANGER 93 make an analysis similar to BARGER 93 and HEWETT 93 with an improved CLEO limit B($b \to s\gamma$) < 5.4×10^{-4} (95%CL). For the Type II model, the limit m_{H^+} >540 (300) GeV for m_t >150 (120) GeV is obtained. The authors employ leading logarithmic QCD corrections.

[156] ADRIANI 92G limit improves to 44 GeV if B($\tau\nu_\tau$) > 0.4.

[157] Studied $H^+H^- \to (\tau\nu) + (\tau\nu)$, $H^+H^- \to (\tau\nu)$ + hadrons, $H^+H^- \to$ hadrons.

[158] DECAMP 92 limit improves to 45.3 GeV for B($\tau\nu$)=1.

[159] YUZUKI 91 assume photon exchange. The limit is valid for any decay mode $H^+ \to e\nu$, $\mu\nu$, $\tau\nu$, $q\overline{q}$ with five flavors. For B($\ell\nu$) = 1, the limit improves to 25.0 GeV.

[160] ABREU 90B limit improves to 36 GeV for B($\tau\nu$) = 1.

[161] ADACHI 90B limit improves to 22 GeV for B($\tau\nu$) = 0.6.

[162] ADEVA 90M limit improves to 42.5 GeV for B($\tau\nu$) = 1.

[163] AKRAWY 90K limit improves to 43 GeV for B($\tau\nu$) = 1.

[164] If B($H^+ \to \tau^+\nu$) = 100%, the DECAMP 90I limit improves to 43 GeV.

[165] SMITH 90B limit applies for v_2/v_1 > 2 in a model in which H_2 couples to u-type quarks and charged leptons.

[166] Studied $H^+H^- \to (\tau\nu) + (\tau\nu)$, $H^+H^- \to (\tau\nu)$ + hadrons. Search for muon opposite hadronic shower.

MASS LIMITS for $H^{\pm\pm}$ (doubly-charged Higgs boson)

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>45.6	95	[167] ACTON	92M	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[168] GORDEEV	97	SPEC	muonium conversion
		[169] ASAKA	95	THEO	
>30.4	95	[170] ACTON	92M	OPAL	$T_3(H^{++})= +1$
>25.5	95	[170] ACTON	92M	OPAL	$T_3(H^{++})= 0$
none 6.5–36.6	95	[171] SWARTZ	90	MRK2	$T_3(H^{++}) = +1$
none 7.3–34.3	95	[171] SWARTZ	90	MRK2	$T_3(H^{++}) = 0$

[167] ACTON 92M limit assumes $H^{\pm\pm} \to \ell^\pm\ell^\pm$ or $H^{\pm\pm}$ does not decay in the detector. Thus the region $g_{\ell\ell} \approx 10^{-7}$ is not excluded.

[168] GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\overline{M}}/G_F < 0.14$ (90% CL), where $G_{M\overline{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}}$ > 210 GeV if the Yukawa copulings of H^{++} to ee and $\mu\mu$ are as large as the weak gauge coupling. For similar limits on muonium-antimuonium conversion, see the muon Particle Listings.

[169] ASAKA 95 point out that H^{++} decays dominantly to four fermions in a large region of parameter space where the limit of ACTON 92M from the search of dilepton modes does not apply.

[170] ACTON 92M from $\Delta\Gamma_Z$ <40 MeV.

[171] SWARTZ 90 assume $H^{\pm\pm} \to \ell^\pm\ell^\pm$ (any flavor). The limits are valid for the Higgs-lepton coupling g($H\ell\ell$) $\gtrsim 7.4 \times 10^{-7}/[m_H/\text{GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

H^0 and $H^\pm$ REFERENCES

ABBIENDI	99E	EPJ C7 407	G. Abbiendi+	(OPAL Collab.)
ABBOTT	99B	PRL 82 2244	B. Abbott+	(D0 Collab.)
ABREU	99I	CERN-EP/99-06	P. Abreu+	(DELPHI Collab.)
EPJ C (to be publ.)				
ACCIARRI	99B	PL B446 368	M. Acciarri+	(L3 Collab.)
BARATE	99B	PL B447 336	R. Barate+	(ALEPH Collab.)
BARATE 99B replaces the misprinted version in BARATE 98Z.				
BARATE	99C	PL B450 301	R. Barate+	(ALEPH Collab.)
BARATE	99D	PL B450 467	R. Barate+	(ALEPH Collab.)
LEP	99	CERN-EP/99-15		(ALEPH, DELPHI, L3, OPAL, LEP EWWG, SLD)
LEP	99B	CERN-EP/99-060		(ALEPH, DELPHI, L3, OPAL, LEP Higgs Working Group)
ABBOTT	98	PRL 80 442	B. Abbott+	(D0 Collab.)
ABE	98T	PRL 81 5748	F. Abe+	(CDF Collab.)
ABREU	98E	EPJ C2 1	P. Abreu+	(DELPHI Collab.)
ABREU	98F	PL B420 140	P. Abreu+	(DELPHI Collab.)
ACCIARRI	98B	PL B418 389	M. Acciarri+	(L3 Collab.)
ACCIARRI	98I	PL B431 437	M. Acciarri+	(L3 Collab.)
ACCIARRI	98M	PL B436 389	M. Acciarri+	(L3 Collab.)
ACKERSTAFF	98B	EPJ C1 31	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	98H	EPJ C1 425	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	98I	PL B426 180	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	98S	EPJ C5 19	K. Ackerstaff+	(OPAL Collab.)
ACKERSTAFF	98Y	PL B437 218	K. Ackerstaff+	(OPAL Collab.)
BARATE	98A	PL B440 419	R. Barate+	(ALEPH Collab.)
Also	99H	PL B447 355 (erratum)		
BARATE	98G	PL B418 419	R. Barate+	(ALEPH Collab.)
BARATE	98Z	PL B440 403	R. Barate+	(ALEPH Collab.)
Reprinted as BARATE 99B.				
CHANOWITZ	98	PRL 80 2521	M. Chanowitz	
DREES	98	PRL 80 2047	M. Drees, M. Guchait, P. Roy	
Also	98B	PRL 81 2394 (erratum)	M. Drees, M. Guchait, P. Roy	
DREES	98B	PRL 81 2394 (erratum)	M. Drees, M. Guchait, P. Roy	
GONZALEZ-G...	98B	PR D57 7045	M.C. Gonzalez-Garcia, S.M. Lietti, S.F. Novaes	
HAGIWARA	98B	EPJ C2 95	K. Hagiwara, D. Haidt, S. Matsumoto	
ABBANEO	97	CERN-PPE/97-154	D. Abbaneo+	
ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and the LEP Electroweak Working Group.				
ABE	97F	PRL 78 2906	+Akimoto, Akopian, Albrow, Amendolia+	(CDF Collab.)
ABE	97L	PRL 79 357	F. Abe+	(CDF Collab.)
ABE	97W	PRL 79 3819	F. Abe+	(CDF Collab.)
ACCIARRI	97F	PL B396 327	M. Acciarri+	(L3 Collab.)
ACCIARRI	97N	PL B411 330	M. Acciarri+	(L3 Collab.)
ACCIARRI	97O	PL B411 373	M. Acciarri+	(L3 Collab.)
ACKERSTAFF	97E	PL B393 231	K. Ackerstaff+	(OPAL Collab.)
ALEXANDER	97	ZPHY C73 189	G. Alexander+	(OPAL Collab.)
AMMAR	97B	PRL 78 4686	R. Ammar+	(CLEO Collab.)
BARATE	97O	PL B412 155	R. Barate+	(ALEPH Collab.)
BARATE	97P	PL B412 173	R. Barate+	(ALEPH Collab.)
COARASA	97	PL B406 337	J.A. Coarasa, R.A. Jimenez, J. Sola	
DEBOER	97B	ZPHY C75 627	W. de Boer, A. Dabelstein, W. Hollik+	
DEGRASSI	97	PL B394 188	G. Degrassi, P. Gambino, A. Sirlin	(MPIM, NYU)
DITTMAIER	97	PL B391 420	S. Dittmaier, D. Schildknecht	(BIEL)
GORDEEV	97	PAN 60 1164	V.A. Gordeev+	(PNPI)
		Translated from YAF 60 1291.		
GUCHAIT	97	PR D55 7263	M. Guchait, D.P. Roy	(TATA)
KEITH	97	PR D56 R5306	E. Keith, E. Ma, D.P. Roy	
KRAWCZYK	97	PR D55 6968	M. Krawczyk, J. Zochowski	(WARS)
MANGANO	97	PL B410 299	M. Mangano, S. Slabospitsky	
RENTON	97	IJMP A12 4109	P.B. Renton	
STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ABE	96G	PR D54 735	+	(CDF Collab.)
ACCIARRI	96I	PL B385 454	+	(L3 Collab.)
ACCIARRI	96J	PL B388 409	+	(L3 Collab.)
ALCARAZ	96	CERN-PPE/96-183	J. Alcaraz+	
The ALEPH, DELPHI, L3, OPAL, and SLD Collaborations and the LEP Electroweak Working Group				
ALEXANDER	96H	ZPHY C71 1	+	(OPAL Collab.)
ALEXANDER	96I	PL B370 174	+	(OPAL Collab.)
ALEXANDER	96L	PL B377 273	+Allison, Altekamp, Ametewee+	(OPAL Collab.)
BUSKULIC	96K	PL B373 246	+De Bonis, Decamp, Ghez+	(ALEPH Collab.)
BUSKULIC	96R	PL B384 427	+	(ALEPH Collab.)
DITTMAIER	96	PL B386 247	+Schildknecht, Weiglein	(BIEL, KARL)

ELLIS	96C	PL B389 321	+Fogli, Lisi	(CERN, BARI)
GURTU	96	PL B385 415		(TATA)
PDG	96	PR D54 1		
ABREU	95H	ZPHY C67 69	+Adam, Adye, Agasi, Ajinenko, Aleksan+	(DELPHI Collab.)
ALAM	95	PRL 74 2885	+Kim, Ling, Mahmood+	(CLEO Collab.)
ASAKA	95	PL B345 36	+Hikasa	(TOHOK)
BUSKULIC	95	PL B343 444	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
CHANKOWSKI	95	PL B356 307	+Pokorski	(WARS, MPIM)
ERLER	95	PR D52 441	+Langacker	(PENN)
GROSSMAN	95B	PL B357 630	Y. Grossman, H. Haber, Y. Nir	
MATSUMOTO	95	MPL A10 2553		(KEK)
ROSIEK	95	PL B341 419	+Sopczak	(IFIC, CERN)
ABREU	94G	NP B421 3	+Adam, Adye, Agasi, Ajinenko+	(DELPHI Collab.)
ABREU	94O	ZPHY C64 183	+Adam, Adye, Agasi, Ajinenko, Aleksan+	(DELPHI Collab.)
AKERS	94B	PL B327 397	+Alexander, Allison, Anderson, Arcelli+	(OPAL Collab.)
AKERS	94I	ZPHY C64 1	+Alexander, Allison, Anderson, Arcelli, Asai+	(OPAL Collab.)
ELLIS	94B	PL B333 118	+Fogli, Lisi	(CERN, BARI)
GROSSMAN	94	PL B332 373	Y. Grossman, Z. Ligeti	
GURTU	94	MPL A9 3301		(TATA)
MONTAGNA	94	PL B335 484	+Nicrosini, Passarino, Piccinini	(INFN, PAVI, CERN, TORI)
STAHL	94	PL B324 121	A. Stahl	(BONN)
ADRIANI	93C	PL B303 391	+Aguilar-Benitez, Ahlen, Alcaraz, Aloiso+	(L3 Collab.)
BARGER	93	PRL 70 1368	+Berger, Phillips	(WISC, RAL)
BELANGER	93	PR D48 5419	+Geng, Turcotte	(MONT, ISU, AMES)
BRAHMACH...	93	PR D48 4224	Brahmachari, Joshipura, Rindani+	(AHMED, TATA, CERN)
BUSKULIC	93H	PL B313 299	+De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
BUSKULIC	93I	PL B313 312	+De Bonis, Decamp, Ghez, Goy, Lees+	(ALEPH Collab.)
ELLIS	93	NP B393 3	+Fogli, Lisi	(CERN, BARI)
GROSS	93	IJMP A8 407	+Yepes	(CERN)
HEWETT	93	PRL 70 1045		(ANL, OREG)
LOPEZ-FERN...	93	PL B312 240	Lopez-Fernandez, Romao+	(CERN, LISB, VALE)
ABREU	92D	ZPHY C53 555	+Adam, Adami, Adye, Akesson, Alekseev+	(DELPHI Collab.)
ABREU	92J	NP B373 3	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ACTON	92M	PL B295 347	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ADEVA	92B	PL B283 454	+Adriani, Aguilar-Benitez, Ahlen, Akbari+	(L3 Collab.)
ADRIANI	92F	PL B292 472	+Aguilar-Benitez, Ahlen, Akbari, Alcarez+	(L3 Collab.)
ADRIANI	92G	PL B294 457	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
Also	93B	ZPHY C57 355	Adriani, Aguilar-Benitez, Ahlen, Alcaraz+	(L3 Collab.)
BUSKULIC	92	PL B285 309	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	92	PRPL 216 253	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
PICH	92	NP B388 31	+Prades, Yepes	(CERN, CPPM)
ABREU	91B	ZPHY C51 25	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ACTON	91	PL B268 122	+Alexander, Allison, Allport+	(OPAL Collab.)
ADEVA	91	PL B257 450	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	91D	PL B262 155	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	91	PL B253 511	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	91C	ZPHY C49 1	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
BLUEMLEIN	91	ZPHY C51 341	+Brunner, Grabosch+	(BERL, BUDA, JINR, SERP)
DECAMP	91F	PL B262 139	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	91I	PL B265 475	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
YUZUKI	91	PL B267 309	+Haba, Abe, Amako, Arai, Asano+	(VENUS Collab.)
ABE	90E	PR D41 1717	+Amidei, Appollinari, Atac, Auchincloss+	(CDF Collab.)
ABREU	90B	PL B241 449	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ABREU	90C	NP B342 1	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ABREU	90E	PL B245 276	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ABREU	90I	HEP-90 Singapore unpub. CERN-PPE/90-163	+Adam, Adami, Adye, Alekseev+	(DELPHI Collab.)
ADACHI	90B	PL B240 513	+Aihara, Doeser, Enomoto+	(TOPAZ Collab.)
ADEVA	90H	PL B248 203	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90M	PL B252 511	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90N	PL B252 518	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
ADEVA	90R	PL B251 311	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	90C	PL B236 224	+Alexander, Allison, Allport+	(OPAL Collab.)
AKRAWY	90K	PL B242 299	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90P	PL B251 211	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
DECAMP	90	PL B236 233	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90E	PL B237 291	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)
DECAMP	90H	PL B241 141	+Deschizeaux, Lees, Minard+	(ALEPH Collab.)

DECAMP	90I	PL B241 623	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	90M	PL B245 289	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
DECAMP	90N	PL B246 306	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
KOMAMIYA	90	PRL 64 2881	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)
SMITH	90B	PR D42 949	+McNeil, Breedon, Kim, Ko+	(AMY Collab.)
SWARTZ	90	PRL 64 2877	+Abrams, Adolphsen, Averill, Ballam+	(Mark II Collab.)
CAHN	89	RPP 52 389		
DAVIER	89	PL B229 150	+Nguyen Ngoc	(LALO)
KOMAMIYA	89	PR D40 721	+Fordham, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
LOW	89	PL B228 548	+Xu, Abashian, Gotow, Hu, Mattson+	(AMY Collab.)
SHER	89	PRPL 179 273		
SNYDER	89	PL B229 169	+Murray, Abrams, Adolphsen, Akerlof+	(Mark II Collab.)
BEHREND	87	PL B193 376	+Buerger, Criegee, Dainton+	(CELLO Collab.)
FRANZINI	87	PR D35 2883	+Son, Tuts, Youssef, Zhao+	(CUSB Collab.)
BARTEL	86	ZPHY C31 359	+Becker, Felst, Haidt+	(JADE Collab.)
EICHTEN	86	PR D34 1547	+Hinchliffe, Lane, Quigg+	(FNAL, LBL, OSU)
ADEVA	85	PL 152B 439	+Becker, Becker-Szendy+	(Mark-J Collab.)
AKERLOF	85	PL 156B 271	+Bonvicini, Chapman, Errede+	(HRS Collab.)
ALBRECHT	85J	ZPHY C29 167	+Binder, Harder+	(ARGUS Collab.)
ASH	85	PRL 55 1831	+Band, Blume, Camporesi+	(MAC Collab.)
ASH	85C	PRL 54 2477	+Band, Blume, Camporesi+	(MAC Collab.)
BARTEL	85L	PL 155B 288	+Becker, Cords, Felst, Hagiwara+	(JADE Collab.)
BEHREND	85	PL 161B 182	+Burger, Criegee, Fenner+	(CELLO Collab.)
FELDMAN	85	PRL 54 2289	+Abrams, Amidei, Baden+	(Mark II Collab.)