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

THE HIGGS BOSON

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The Standard Model [1] contains one neutral scalar Higgs boson, which is a remnant of the mechanism that breaks the SU(2) $\times$ U(1) symmetry and generates the W and Z boson masses. The Higgs couples to quarks and leptons of mass m_f with a strength $gm_f/2M_W$. Its coupling to W and Z bosons is of strength g, where g is the coupling constant of the SU(2) gauge theory. The branching ratio of the Higgs boson into various final states is shown in Fig. 1.

The Higgs coupling to stable matter is very small while its coupling to the top quark and to W and Z bosons is substantial. Hence its production is often characterized by a low rate and a poor signal to background ratio. A notable exception would be its production in the decay of the Z boson (for example $Z \to Hq\overline{q}$). Since large numbers of Z's can be produced and the coupling of the Z to the Higgs is unsuppressed, experiments at LEP are now able to rule out a significant range of Higgs masses.

If the Higgs mass is very large, the couplings of the Higgs to itself and to longitudinally polarized gauge bosons become large. Requiring that these couplings remain weak enough so that perturbation theory is applicable implies that $M_H \lesssim 1$ TeV [2]. While this is not an absolute bound, it is an indication of the mass scale at which one can no longer speak of an elementary Higgs boson. This fact is made more clear if one notes that the width of the Higgs boson is proportional to the cube of its mass (for $M_H > 2M_Z$) and that a boson of mass 1 TeV has a width of 500 GeV.

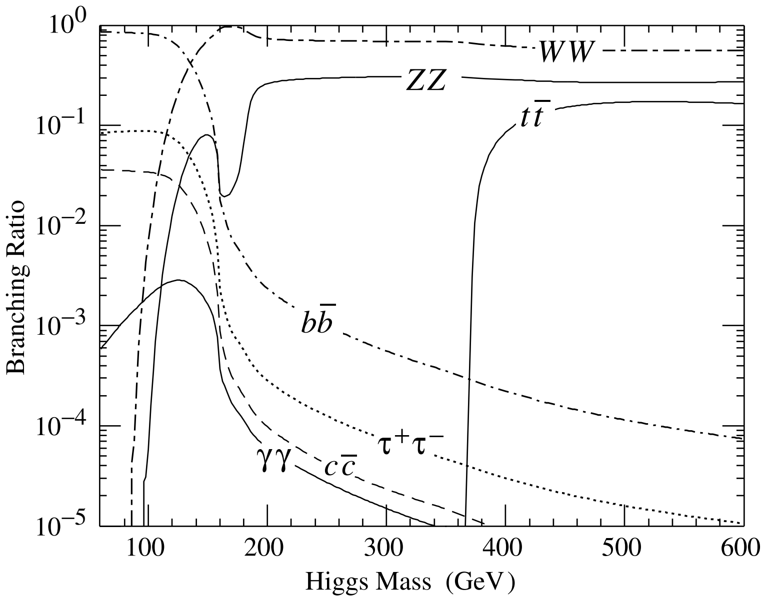

Figure 1: The branching ratio of the Higgs boson into $\gamma\gamma$, $\tau\overline{\tau}$, $b\overline{b}$, $t\overline{t}$, $c\overline{c}$, ZZ, and WW as a function of the Higgs mass. For ZZ and WW, if $M_H < 2M_Z$ (or $M_H < 2M_W$), the value indicated is the rate to ZZ^* (or WW^*) where Z^* (W^*) denotes a virtual Z (W). The $c\overline{c}$ rate depends sensitively on the poorly-determined charmed quark mass.

A scalar field theory of the type that is used to describe Higgs self-interactions can only be an effective theory (valid over a limited range of energies) if the Higgs self-coupling and hence the Higgs mass is finite. An upper bound on the Higgs mass can then be determined by requiring that the coupling has a finite value at all scales up to the Higgs mass [3]. Nonperturbative calculations using lattice [4] gauge theory that compute at arbitrary values of the Higgs coupling indicate that $M_H \lesssim 770$ GeV.

If the Higgs mass were small, then the vacuum (ground) state with the correct value of M_W would cease to be the true ground state of the theory [5]. A theoretical constraint can then be obtained from the requirement that our universe is in the true minimum of the Higgs potential [6]. The constraint depends upon the top quark mass and upon the scale (Λ) up to which the Standard Model remains valid. This scale must be at least 1 TeV, resulting in the constraint [7] $M_H > 52$ GeV + 0.64 ($M_{\rm top}$–175 GeV). This constraint is weaker than that from the failure to directly observe the Higgs boson. The bound increases monotonically with the scale, for $\Lambda = 10^{19}$ GeV, $M_H > 135\ \text{GeV} + 1.9\ (M_{\rm top}\text{–}175\ \text{GeV}) - 680\ (\alpha_s(M_Z) - 0.117)$. This constraint may be too restrictive. Strictly speaking we can only require that the predicted lifetime of our universe, if it is not at the true minimum of the Higgs potential, be longer than its observed age [8,9]. For $\Lambda = 1$ TeV there is no meaningful constraint; and for $\Lambda = 10^{19}$ GeV $M_H > 130$ GeV + $2.3\ (M_{\rm top} - 175\ \text{GeV}) - 815(\alpha_s(M_Z) - 0.117)$ [10].

Experiments at LEP are able to exclude a large range of Higgs masses. They search for the decay $Z \to HZ^*$ or $e^+e^- \to ZH$. Here Z^* refers to a virtual Z boson that can appear in the detector as e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\overline{\nu}$ (*i.e.*, missing energy) or hadrons. The experimental searches have considered both $H \to$ hadrons and $H \to \tau^+\tau^-$. The best limits are shown in the Particle Listings below.

Precision measurement of electroweak parameters such as M_W, $M_{\rm top}$, and the various asymmetries at LEP and SLC are sensitive enough that they can constrain the Higgs mass through its effect in radiative corrections. The current unpublished limit is $M_H < 450$ GeV, at 95% CL with a central value of

$M_H = 127^{+127}_{-72}$ GeV [11]. See also the article in this *Review* on the "Electroweak Model and Constraints on New Physics."

The process $e^+e^- \rightarrow ZH$ [12] should enable neutral Higgs bosons of masses up to 95 GeV to be discovered at LEP at a center-of-mass energy of 190 GeV [13]. The current unpublished limits corresponding to the failure to observe this process at LEP imply $M_H > 77.5$ GeV at 95% CL [14]. If the Higgs is too heavy to be observed at LEP, there is a possibility that it could be observed at the Tevatron via the processes $p\overline{p} \rightarrow HZX$ [15] and $p\overline{p} \rightarrow WHX$ [16]. Failing this, its discovery will have to wait until experiments at the LHC. If the neutral Higgs boson has mass greater than $2M_Z$, it will likely be discovered via its decay to ZZ and the subsequent decay of the Z's to charged leptons (electrons or muons) or of one Z to charged leptons and the other to neutrinos. A challenging region is that between the ultimate limit of LEP and $2M_Z$. At the upper end of this range the decay to a real and a virtual Z, followed by the decay to charged leptons is available. The decay rate of the Higgs boson into this channel falls rapidly as M_H is reduced and becomes too small for $M_H \lesssim 140$ GeV. For masses below this, the decays $H \rightarrow \gamma\gamma$ and possibly $H \rightarrow b\overline{b}$ [17] are expected to be used. The former has a small branching ratio and large background, the latter has a large branching ratio, larger background and a final state that is difficult to fully reconstruct [18].

Extensions of the Standard Model, such as those based on supersymmetry [19], can have more complicated spectra of Higgs bosons. The simplest extension has two Higgs doublets whose neutral components have vacuum expectation values v_1 and v_2, both of which contribute to the W and Z masses. The physical particle spectrum contains one charged Higgs boson ($H^{\pm}$), two neutral scalars (H_1^0, H_2^0),* and one pseudoscalar (A) [20]. See also the articles in this *Review* on Supersymmetry.

In the simplest version of the supersymmetric model (see the *Reviews* on Supersymmetry), the mass of the lightest of these scalars depends upon the top quark mass, the ratio v_2/v_1 ($\equiv \tan\beta$), and the masses of the other supersymmetric particles. For $M_{\rm top} = 174$ GeV, there is a bound $M_{H_1^0} \lesssim 130$ GeV [21,22] at large $\tan\beta$. The bound reduces as $\tan\beta$ is lowered.

The H_1^0, H_2^0, and A couplings to fermions depend on v_2/v_1 and are either enhanced or suppressed relative to the couplings in the Standard Model. As the masses of H_2^0 and A increase, the mass of H_1^0 approaches the bound, and the properties of this lightest state become indistinguishable from those a Standard Model Higgs boson of the same mass. This observation is important since the discovery of a single Higgs boson at LEP with Standard Model couplings would not be evidence either for or against the minimal supersymmetric model. However the failure to find a Higgs boson of mass less than 130 GeV would be definite evidence against the minimal supersymmetric Standard Model. In more complicated supersymmetric models, there is always a Higgs boson of mass less than 160 GeV.

Experiments at LEP are able to exclude ranges of masses for neutral Higgs particles in these models. Production processes that are exploited are $e^+e^- \to ZH_1^0$ and $e^+e^- \to AH_1^0$. No signal is seen; the mass limits are (weakly) dependent upon the masses of other supersymmetric particles and upon $\tan\beta$. Currently $M_{H_1^0}, M_A > 62$ GeV. See the Particle Listings below on H_1^0, Mass Limits in Supersymmetric Models.

Charged Higgs bosons can be pair-produced in e^+e^- annihilation. Searches for charged Higgs bosons depend on the assumed branching fractions to $\nu\tau$, $c\overline{s}$, and $c\overline{b}$. Data from LEP now exclude charged Higgs bosons of mass less than

54.5 GeV [23]. See the Particle Listings for details of the $H^{\pm}$ Mass Limit.

A charged Higgs boson could also be produced in the decay of a top quark, $t \to H^{+}b$. A search at CDF excludes $M_{H^+} < 147$ GeV for $\tan\beta > 100$ where the branching ratio $H^{+} \to \tau\nu$ is large and at $\tan\beta < 1$ where the BR($t \to H^{+}b$) is large [24]. The region at intermediate values of $\tan\beta$ will be probed as the number of produced top quarks increases. Searches for these non-standard Higgs bosons will be continued at LEP [13] and at LHC [25]

Notes and References

$^*H_1^0$ and H_2^0 are usually called h and H in the literature.

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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 (BOCK 97), where the combination of the results of ACCIARRI 97O, BARATE 97O, ACKERSTAFF 98H, and ABREU 98E was performed.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>77.5 (CL = 95%) OUR LIMIT					
>66.2	95	[1] ABREU	98E	DLPH	$e^+e^- \rightarrow ZH^0$
>69.4	95	[1] ACKERSTAFF	98H	OPAL	$e^+e^- \rightarrow ZH^0$
>69.5	95	[1] ACCIARRI	97O	L3	$e^+e^- \rightarrow ZH^0$
>70.7	95	[1] BARATE	97O	ALEP	$e^+e^- \rightarrow ZH^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[2] ABE	97W	CDF	$p\overline{p} \rightarrow WH^0$
>65.0	95	[3] ACKERSTAFF	97E	OPAL	$e^+e^- \rightarrow ZH^0$
>59.6	95	[4] ALEXANDER	97	OPAL	$Z \rightarrow H^0 Z^*$
>60.2	95	[5] ACCIARRI	96I	L3	$Z \rightarrow H^0 Z^*$
		[6] ACCIARRI	96J	L3	$Z \rightarrow H^0 \gamma$
		[7] ALEXANDER	96H	OPAL	$Z \rightarrow H^0 \gamma$
>60.6	95	[8] ALEXANDER	96L	OPAL	$Z \rightarrow H^0 Z^*$

>63.9	95	[9] BUSKULIC	96R	ALEP	$Z \to H^0 Z^*$
>55.7	95	[10] ABREU	94G	DLPH	$Z \to H^0 Z^*$
>56.9	95	[11] AKERS	94B	OPAL	$Z \to H^0 Z^*$
>57.7	95	[12] ADRIANI	93C	L3	$Z \to H^0 Z^*$
>58.4	95	[13] BUSKULIC	93H	ALEP	$Z \to H^0 Z^*$
>60	95	[14] GROSS	93	RVUE	$Z \to H^0 Z^*$
		[15] ABREU	92D	DLPH	$Z \to H^0 \gamma$
>38	95	[16] ABREU	92J	DLPH	$Z \to H^0 Z^*$
>52	95	[17] ADEVA	92B	L3	$Z \to H^0 Z^*$
		[18] ADRIANI	92F	L3	$Z \to H^0 \gamma$
>48	95	[19] DECAMP	92	ALEP	$Z \to H^0 Z^*$
> 0.21	99	[20] ABREU	91B	DLPH	$Z \to H^0 Z^*$
>11.3	95	[21] ACTON	91	OPAL	$H^0 \to$ anything
>41.8	95	[22] ADEVA	91	L3	$Z \to H^0 Z^*$
		[23] ADEVA	91D	L3	$Z \to H^0 \gamma$
none 3–44	95	[24] AKRAWY	91	OPAL	$Z \to H^0 Z^*$
none 3–25.3	95	[25] AKRAWY	91C	OPAL	$Z \to H^0 Z^*$
none 0.21–0.818	90	[26] ABE	90E	CDF	$p\overline{p} \to (W^{\pm}, Z) + H^0 + X$
none 0.846–0.987	90	[26] ABE	90E	CDF	$p\overline{p} \to (W^{\pm}, Z) + H^0 + X$
none 0.21–14	95	[27] ABREU	90C	DLPH	$Z \to H^0 Z^*$
none 2–32	95	[28] ADEVA	90H	L3	$Z \to H^0 Z^*$
> 2	99	[29] ADEVA	90N	L3	$Z \to H^0 Z^*$
none 3.0–19.3	95	[30] AKRAWY	90C	OPAL	$Z \to H^0 Z^*$
> 0.21	95	[31] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
none 0.032–15	95	[32] DECAMP	90	ALEP	$Z \to H^0 Z^*$
none 11–24	95	[33] DECAMP	90H	ALEP	$Z \to H^0 Z^*$
> 0.057	95	[34] DECAMP	90M	ALEP	$Z \to H^0 ee$, $H^0 \mu\mu$
none 11–41.6	95	[35] DECAMP	90N	ALEP	$Z \to H^0 Z^*$

[1] Search for $e^+ e^- \to Z H^0$ at $E_{\rm cm}$ = 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.

[2] 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.

[3] ACKERSTAFF 97E searched for $e^+ e^- \to Z H^0$ at $E_{\rm cm}$ = 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.

[4] 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.

[5] 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.

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

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

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

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

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

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

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

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

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

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

[16] ABREU 92J searched for $Z \rightarrow H^0 + (ee, \mu\mu, \tau\tau, \nu\overline{\nu})$ with $H^0 \rightarrow q\overline{q}$. Only one candidate was found, in the channel ee + 2jets, with a dijet mass 35.4 ± 5 GeV/c^2, consistent with the expected background of 1.0 ± 0.2 events in the 3 channels e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, and of 2.8 ± 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.

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

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

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

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

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

[22] ADEVA 91 searched for $Z \rightarrow H^0 + (\mu\mu, ee, \nu\overline{\nu})$. 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.

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

[24] AKRAWY 91 searched for the channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \rightarrow q\overline{q}, \tau\tau$, and $Z \rightarrow H^0 q\overline{q}$ with $H^0 \rightarrow \tau\tau$.

[25] AKRAWY 91C searched the decay channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu)$ with $H^0 \rightarrow q\overline{q}$.

[26] 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.

[27] ABREU 90C searched for the channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu)$ and $H^0 + q\overline{q}$ for $m_H < 1$ GeV.
[28] ADEVA 90H searched for $Z \rightarrow H^0 + (\mu\mu, ee, \nu\overline{\nu})$.
[29] ADEVA 90N looked for $Z \rightarrow H^0 + (ee, \mu\mu)$ with missing H^0 and with $H^0 \rightarrow ee$, $\mu\mu$, $\pi^+\pi^-$, K^+K^-.
[30] AKRAWY 90C based on 825 nb^{-1}. The decay $Z \rightarrow H^0\nu\overline{\nu}$ with $H^0 \rightarrow \tau\overline{\tau}$ or $q\overline{q}$ provides the most powerful search means, but the quoted results sum all channels.
[31] AKRAWY 90P looked for $Z \rightarrow H^0 + (ee, \mu\mu)$ (H^0 missing) and $Z \rightarrow H^0\nu\overline{\nu}$, $H^0 \rightarrow e^+e^-$, $\gamma\gamma$.
[32] DECAMP 90 limits based on 11,550 Z events. They searched for $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau, q\overline{q})$. The decay $Z \rightarrow H^0\nu\overline{\nu}$ 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.
[33] DECAMP 90H limits based on 25,000 $Z \rightarrow$ hadron events.
[34] DECAMP 90M looked for $Z \rightarrow H^0\ell\ell$, where H^0 decays outside the detector.
[35] DECAMP 90N searched for the channels $Z \rightarrow H^0 + (\nu\overline{\nu}, ee, \mu\mu, \tau\tau)$ with $H^0 \rightarrow$ (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."

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[36] CHANOWITZ	98	RVUE	
141^{+140}_{-77}		[37] DEBOER	97B	RVUE	
127^{+143}_{-71}		[38] DEGRASSI	97	RVUE	$\sin^2\theta_W$(eff,lept)
158^{+148}_{-84}		[39] DITTMAIER	97	RVUE	
149^{+148}_{-82}		[40] RENTON	97	RVUE	
$\lesssim 550$	90	[41] DITTMAIER	96	RVUE	
145^{+164}_{-77}		[42] ELLIS	96C	RVUE	
185^{+251}_{-134}		[43] GURTU	96	RVUE	
63^{+97}_{-0}		[44] CHANKOWSKI	95	RVUE	
<730	95	[45] ERLER	95	RVUE	
<740	95	[46] MATSUMOTO	95	RVUE	
45^{+95}_{-28}		[47] ELLIS	94B	RVUE	
69^{+188}_{-9}		[48] GURTU	94	RVUE	
		[49] MONTAGNA	94	RVUE	

[36] 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.

[37] 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). $1/\alpha(m_Z) = 128.90 \pm 0.09$ is used.

[38] DEGRASSI 97 is a two-loop calculation of M_W and $\sin^2\theta^{\rm lept}_{\rm eff}$ as a function of m_H, using $\sin^2\theta^{\rm lept}_{\rm eff}$ 0.23165(24) as reported in ALCARAZ 96, $m_t = 175 \pm 6$ GeV, and $\Delta\alpha_{\rm had} =$ 0.0280(9).

[39] DITTMAIER 97 fit to m_W and LEP/SLC data as reported in ALCARAZ 96, with m_t $= 175 \pm 6$ GeV, $1/\alpha(m^2_Z) = 128.89 \pm 0.09$. Exclusion of the SLD data gives $m_H =$ 261^{+224}_{-128} GeV. Taking only the data on m_t, m_W, $\sin^2\theta^{\rm lept}_{\rm eff}$, and $\Gamma^{\rm lept}_Z$, 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).

[40] 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.

[41] DITTMAIER 96 fit to m_W, LEP, and SLD data available in the Summer of 1995 (with and without m_t=180 ± 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.

[42] 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.

[43] 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.

[44] 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).

[45] 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.

[46] 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.

[47] 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 ± 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.

[48] 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.

[49] 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. • • •					
>69.6	95	[50] ACCIARRI	98B	L3	Invisible H^0
		[51] ACKERSTAFF	98B	OPAL	$e^+e^- \to H^0 Z^{(*)}$, $H^0 \to \gamma\gamma$
		[52] KRAWCZYK	97	RVUE	$(g-2)_\mu$
		[53] ACCIARRI	96I	L3	$Z \to H^0 Z^*$
>66.7	95	[54] ACCIARRI	96I	L3	Invisible H^0
		[55] ACCIARRI	96J	L3	$Z \to H^0 Z^*$, $H^0 \to \gamma\gamma$
		[56] ALEXANDER	96H	OPAL	$Z \to H^0 Z^*$, $H^0 \to \gamma\gamma$
		[57] ABREU	95H	DLPH	$Z \to H^0 Z^*$, $H^0 A^0$
		[58] BRAHMACH...	93	RVUE	
		[59] BUSKULIC	93I	ALEP	$Z \to H^0 Z^*$
>65	95	[54] BUSKULIC	93I	ALEP	Invisible H^0
		[60] LOPEZ-FERN...	93	RVUE	
		[61] ADRIANI	92G	L3	$Z \to H^0 Z^*$
		[62] PICH	92	RVUE	Very light Higgs
> 3.57	95	[63] ACTON	91	OPAL	$Z \to H^0 Z^*$
		[64] DECAMP	91F	ALEP	$Z \to H^0 \ell^+\ell^-$
		[65] DECAMP	91I	ALEP	Z decay
> 0.21	95	[66] AKRAWY	90P	OPAL	$Z \to H^0 Z^*$
		[67] DAVIER	89	BDMP	$e^- Z \to e H^0 Z$ ($H^0 \to e^+e^-$)
		[68] SNYDER	89	MRK2	$B \to H^0 X$ ($H^0 \to e^+e^-$)
none 0.6–6.2	90	[69] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=2
none 0.6–7.9	90	[69] FRANZINI	87	CUSB	$\Upsilon(1S) \to \gamma H^0$, x=4
none 3.7–5.6	90	[70] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=2
none 3.7–8.2	90	[70] ALBRECHT	85J	ARG	$\Upsilon(1S) \to \gamma H^0$, x=4

[50] 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($Z \to$ invisible)=100%. For limits under other assumptions, see their Fig. 5b.

[51] 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$(H^0 \to \gamma\gamma)/\sigma(H^0_{SM})$.

[52] KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no $H^0_1 ZZ$ 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.

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

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

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

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

[57] 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.

[58] 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 ± 6 GeV for arbitrary $B(H^0 \rightarrow \text{SM-like}) + B(H^0 \rightarrow \text{invisible}) = 1$.

[59] 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 $Z \rightarrow H^0 Z^*$ is >10% of the minimal Standard Model rate, then $m_{H^0} > 40$ GeV. For the standard rate the limit is 58 GeV.

[60] 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 $B(H^0 \rightarrow \text{SM-like}) + B(H^0 \rightarrow \text{invisible}) = 1$. $m_H > 50$ GeV is obtained if the H^0 coupling strength to the Z is greater than 0.2 times the Standard Model rate.

[61] 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 $Z \rightarrow H^0_1 Z^*$ is less than 10% of the Standard Model rate.

[62] 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.

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

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

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

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

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

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

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

[70] 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 $B(\Upsilon(1S) \rightarrow H^0 \gamma) < 1.5 \times 10^{-3}$

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 $\tan\beta = \nu_2/\nu_1$, 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.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>59.5	95	[71] ABREU	98E	DLPH	$\tan\beta > 1$
>62.5	95	[72] BARATE	97P	ALEP	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[73] ACCIARRI	97N	L3	
>44.3	95	[74] ALEXANDER	97	OPAL	any $\tan\beta$
>44	95	[75] ABREU	95H	DLPH	any $\tan\beta$
		[76] ROSIEK	95	RVUE	
>44.4	95	[77] ABREU	94O	DLPH	$m_{H_1^0}=m_{A^0}$, any $\tan\beta$
>44.5	95	[78] AKERS	94I	OPAL	$\tan\beta > 1$
>44	95	[79] BUSKULIC	93I	ALEP	$\tan\beta > 1$
>34	95	[80] ABREU	92J	DLPH	$\tan\beta > 0.6$
>29	95	[80] ABREU	92J	DLPH	any $\tan\beta$
>42	95	[81] ADRIANI	92G	L3	$1 < \tan\beta < 50$
> 0.21	95	[82] ABREU	91B	DLPH	any $\tan\beta$
>28	95	[83] ABREU	91B	DLPH	any $\tan\beta$
none 3–38	95	[84] AKRAWY	91C	OPAL	$\tan\beta > 6$
none 3–22	95	[84] AKRAWY	91C	OPAL	$\tan\beta > 0.5$
		[85] BLUEMLEIN	91	BDMP	$pN \rightarrow H_1^0 X$ ($H_1^0 \rightarrow e^+e^-$, 2γ)
>41	95	[86] DECAMP	91I	ALEP	$\tan\beta > 1$
> 9	95	[87] ABREU	90E	DLPH	any $\tan\beta$
>13	95	[87] ABREU	90E	DLPH	$\tan\beta > 1$
>26	95	[88] ADEVA	90R	L3	$\tan\beta > 1$
none 0.05–3.1	95	[89] DECAMP	90E	ALEP	any $\tan\beta$
none 0.05–13	95	[89] DECAMP	90E	ALEP	$\tan\beta > 0.6$
none 0.006–20	95	[89] DECAMP	90E	ALEP	$\tan\beta > 2$
>37.1	95	[89] DECAMP	90E	ALEP	$\tan\beta > 6$
none 0.05–20	95	[90] DECAMP	90H	ALEP	$\tan\beta > 0.6$
none 0.006–21.4	95	[90] DECAMP	90H	ALEP	$\tan\beta > 2$
> 3.1	95	[91] DECAMP	90M	ALEP	any $\tan\beta$

[71] 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.

[72] 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.

[73] 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.

[74] 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 $H_1^0 \rightarrow \widetilde{\chi}^0\widetilde{\chi}^0$ is included in the analysis.

[75] 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.

[76] 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.

[77] 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.

[78] 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 $\tan\beta$ <1.

[79] 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, $m_{\widetilde{t}} > m_t$.

[80] 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.

[81] 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.

[82] 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 $m_{A^0} < m_{H_1^0}$.

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

[84] 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 $\tan\beta < 1$. 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.

[85] BLUEMLEIN 91 excluded certain range of $\tan\beta$ for $m_{H_1^0} <$ 120 MeV, $m_{A^0} <$ 80 MeV.

[86] 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.

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

[88] 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 $m_{H^0_1} < 4$ GeV is not excluded by this analysis.

[89] DECAMP 90E look for $Z \rightarrow H^0_1 A^0$ as well as $Z \rightarrow H^0_1 \ell^+ \ell^-$, $Z \rightarrow H^0_1 \nu\overline{\nu}$ with 18610 Z decays. Their search includes signatures in which H^0_1 and A^0 decay to $\gamma\gamma$, $e^+ e^-$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, or $q\overline{q}$. See their figures of $m_{H^0_1}$ vs. $\tan\beta$.

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

[91] DECAMP 90M looked for $Z \rightarrow H^0 \ell\ell$, where H^0_1 decays outside the detector. This excludes a region in the ($m_{H^0_1}$, $\tan\beta$) plane centered at $m_{H^0_1} = 50$ MeV, $\tan\beta = 0.5$. This limit together with DECAMP 90E result excludes $m_{H^0_1} < 3$ 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 $e^+ e^- \rightarrow A^0 H^0_1$ channel and indirectly from the relations valid in the minimal supersymmetric model between m_{A^0} and $m_{H^0_1}$. 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.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>51.0	95	[92] ABREU	98E	DLPH	$\tan\beta > 1$
>62.5	95	[93] BARATE	97P	ALEP	$\tan\beta > 1$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[94] ACCIARRI	97N	L3	
>23.5	95	[95] ALEXANDER	97	OPAL	$\tan\beta > 1$, $m_t < 195$ GeV
>60	95	[96] KEITH	97	RVUE	$\tan\beta < 1$
>27	95	[97] ABREU	95H	DLPH	$\tan\beta > 1$, $m_t = 170$ GeV
>44.4	95	[98] ABREU	94O	DLPH	$m_{H^0_1} = m_{A^0}$, any $\tan\beta$
>24.3	95	[99] AKERS	94I	OPAL	$\tan\beta > 1$, $m_t < 200$ GeV
>44.5	95	[99] AKERS	94I	OPAL	$\tan\beta > 1$, $m_{H^0_1} = m_{A^0}$
>21	95	[100] BUSKULIC	93I	ALEP	$\tan\beta > 1$, $m_t = 140$ GeV
		[101] ELLIS	93	RVUE	Electroweak
>34	95	[102] ABREU	92J	DLPH	$\tan\beta > 3$
>22	95	[103] ADRIANI	92G	L3	$1 < \tan\beta < 50$, $m_t < 250$ GeV
> 0.21	95	[104] BUSKULIC	92	ALEP	$\tan\beta > 1$
none 3–40.5	95	[105] AKRAWY	91C	OPAL	$\tan\beta > 1$, if 3 GeV $< m_{H^0_1} < m_{A^0}$
>20	95	[106] DECAMP	91I	ALEP	$\tan\beta > 1$
>34	95	[107] ABREU	90E	DLPH	$\tan\beta > 1$, $m_{H^0_1} < m_{A^0}$
>12	95	[107] ABREU	90E	DLPH	$\tan\beta < 1$
>39	95	[108] ADEVA	90R	L3	$\tan\beta > 1$, $m_{H^0_1} < m_{A^0}$

[92] 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.

[93] 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.

[94] 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.

[95] 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 $H_1^0 \rightarrow \widetilde{\chi}^0\widetilde{\chi}^0$ 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.

[96] 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}.

[97] ABREU 95H search for $Z \rightarrow H_1^0 Z^*$ and $Z \rightarrow H_1^0 A^0$. 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.

[98] 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.

[99] 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 $\tan\beta$ <1.

[100] BUSKULIC 93I search for $Z \rightarrow H_1^0 Z^*$ and $Z \rightarrow H_1^0 A^0$. 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.

[101] 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.

[102] 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.

[103] 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 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<$m_{H_1^0}$ <62 GeV, but is excluded by other experiments.

[104] BUSKULIC 92 limit is from $\Gamma(Z)$, $Z \rightarrow H_1^0 Z^*$, and $Z \rightarrow H_1^0 A^0$. The limit is valid for any $m_{H_1^0}$ below the the theoretical limit $m_{H_1^0}$ <64 GeV which holds for $m_{A^0} \sim 0$ in the minimal supersymmetric model. One-loop radiative corrections are included.

[105] AKRAWY 91C result from $Z \rightarrow H_1^0 A^0 \rightarrow$ 4jet or $\tau^+\tau^- jj$ or 4τ. See paper for the excluded region for the case $\tan\beta < 1$.

[106] 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. For $m_t = 140$ GeV and $m_{\tilde{q}} = 1$ TeV, the limit is $m_{A^0} > 31$ GeV.

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

[108] 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 $m_{A^0} < 5$ 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, $e^+e^- \rightarrow H_1^0 H_2^0$, 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	[109] AKERS	94I	OPAL	$m_{H_1^0} < 12$ GeV
		[110] ADRIANI	92G	L3	
>45	95	[111] DECAMP	90H	ALEP	$m_{H_1^0} < 20$ GeV
>37.5	95	[111] DECAMP	90H	ALEP	$m_{H_1^0} < m_{H_2^0}$
none 5–45	95	[112] KOMAMIYA	90	MRK2	$m_{H_1^0} < 0.5$ GeV, $H_2^0 \rightarrow q\overline{q}$ or $\tau^+\tau^-$
> 8	90	[113] KOMAMIYA	89	MRK2	$H_1^0 \rightarrow \mu^+\mu^-$, $H_2^0 \rightarrow q\overline{q}$, $\tau^+\tau^-$
>28	95	[114] LOW	89	AMY	$m_{H_1^0} \lesssim 20$ MeV, $H_2^0 \rightarrow q\overline{q}$
none 2–9	90	[115] AKERLOF	85	HRS	$m_{H_1^0} = 0$, $H_2^0 \rightarrow f\overline{f}$
none 4–10	90	[116] ASH	85C	MAC	$m_{H_1^0} = 0.2$ GeV, $H_2^0 \rightarrow \tau^+\tau^-$, $c\overline{c}$
none 1.3–24.7	95	[115] BARTEL	85L	JADE	$m_{H_1^0} = 0.2$ GeV, $H_2^0 \rightarrow f\overline{f}$ or $f\overline{f}H_1^0$
none 1.2–13.6	95	[115] BEHREND	85	CELL	$m_{H_1^0} = 0$, $H_2^0 \rightarrow f\overline{f}$
none 1–11	90	[115] FELDMAN	85	MRK2	$m_{H_1^0} = 0$, $H_2^0 \rightarrow f\overline{f}$
none 1–9	90	[115] FELDMAN	85	MRK2	$m_{H_1^0} = m_{H_2^0}$, $H_2^0 \rightarrow f\overline{f}$

[109] AKERS 94I search for $Z \rightarrow H_1^0 H_2^0$ 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.

[110] 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.

[111] 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.

[112] 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.

[113] 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.

[114] 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.

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

[116] 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 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 techni-particles, see EICHTEN 86.

In the following $\tan\beta$ is the ratio of the two vacuum expectation values in the two-doublet model.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 54.5	95	[117] ABREU	98F	DLPH	B($\tau\nu$) = 0–1
> 52.0	95	[117] ACKERSTAFF	98I	RVUE	B($\tau\nu$) = 0–1
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[118] ABE	97L	CDF	$t \to b H^+$, $H \to \tau\nu$
		[119] ACCIARRI	97F	L3	$B \to \tau\nu_\tau$
		[120] AMMAR	97B	CLEO	$\tau \to \mu\nu\nu$
		[121] COARASA	97	RVUE	$B \to \tau\nu_\tau X$
		[122] GUCHAIT	97	RVUE	$t \to b H^+$, $H \to \tau\nu$
		[123] MANGANO	97	RVUE	$B_{u(c)} \to \tau\nu_\tau$
		[124] STAHL	97	RVUE	$\tau \to \mu\nu\nu$
		[125] ABE	96G	CDF	$t \to b H^+$, $H^+ \to \tau^+\nu_\tau$
> 44.1	95	[126] ALEXANDER	96I	OPAL	B($\tau\nu$) = 0–1

>244	95	[127] ALAM	95	CLE2	$b \to s\gamma$
		[128] BUSKULIC	95	ALEP	$b \to \tau\nu_\tau X$
> 43.5	95	[129] ABREU	94O	DLPH	$B(\tau\nu) = 0$–1
		[130] BARGER	93	RVUE	$b \to s\gamma$
		[131] BELANGER	93	RVUE	$b \to s\gamma$
		[130] HEWETT	93	RVUE	$b \to s\gamma$
> 41	95	[132] ADRIANI	92G	L3	$B(\tau\nu) = 0$–1
> 41.7	95	[133,134] DECAMP	92	ALEP	$B(\tau\nu) = 0$–1
none 8.0–20.2	95	[135] YUZUKI	91	VNS	$B(\ell\nu) = 0$–1
> 29	95	[133,136] ABREU	90B	DLPH	$B(\tau\nu) = 0$–1
> 19	95	[133,137] ADACHI	90B	TOPZ	$B(\tau\nu) = 0$–1
> 36.5	95	[133,138] ADEVA	90M	L3	$B(\tau\nu) = 0$–1
> 35	95	[133,139] AKRAWY	90K	OPAL	$B(\tau\nu) = 0$–1
> 35.4	95	[133,140] DECAMP	90I	ALEP	$B(\tau\nu) = 0$–1
none 10–20	95	[141] SMITH	90B	AMY	$B(\tau\nu) > 0.7$
> 19	95	[140] BEHREND	87	CELL	$B(\tau\nu) = 0$–1
> 18	95	[142] BARTEL	86	JADE	$B(\tau\nu)$=0.1–1.0
> 17	95	[142] ADEVA	85	MRKJ	$B(\tau\nu)$=0.25–1.0

[117] Search for $e^+e^- \to H^+H^-$ at $\sqrt{s}$=130–172 GeV.

[118] 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.

[119] 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.

[120] 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).

[121] 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.

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

[123] 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.

[124] 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.

[125] 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.

[126] 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.

[127] ALAM 95 measure the inclusive $b \to s\gamma$ branching ratio at $\Upsilon(4S)$ and give $B(b \to s\gamma) < 4.2 \times 10^{-4}$ (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.

[128] 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.

[129] 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.

[130] HEWETT 93 and BARGER 93 analyze charged Higgs contribution to $b \rightarrow s\gamma$ in two-doublet models with the CLEO limit B($b \rightarrow s\gamma$)< 8.4×10^{-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.

[131] BELANGER 93 make an analysis similar to BARGER 93 and HEWETT 93 with an improved CLEO limit B($b \rightarrow s\gamma$) < 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.

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

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

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

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

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

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

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

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

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

[141] 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.

[142] Studied $H^+H^- \rightarrow (\tau\nu) + (\tau\nu)$, $H^+H^- \rightarrow (\tau\nu)$ + 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	[143] ACTON	92M	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[144] GORDEEV	97	SPEC	muonium conversion
		[145] ASAKA	95	THEO	
>30.4	95	[146] ACTON	92M	OPAL	$T_3(H^{++})= +1$
>25.5	95	[146] ACTON	92M	OPAL	$T_3(H^{++})= 0$
none 6.5–36.6	95	[147] SWARTZ	90	MRK2	$T_3(H^{++}) = +1$
none 7.3–34.3	95	[147] SWARTZ	90	MRK2	$T_3(H^{++}) = 0$

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

[144] 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.

[145] 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.

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

[147] SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm$ (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.

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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.)
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ABE 97W PRL 79 3819 F. Abe+ (CDF Collab.)
ACCIARRI 97F PL B396 327 M. Acciarri+ (L3 Collab.)
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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
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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.)