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

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STANDARD MODEL H^0 (Higgs Boson) MASS LIMITS

These limits apply to the Higgs boson of the three-generation Standard Model with the minimal Higgs sector. For a review and a bibliography, see the above Note on 'Searches for Higgs Bosons' by P. Igo-Kemenes.

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

Limits on the Standard Model Higgs obtained from the study of Z^0 decays rule out conclusively its existence in the whole mass region $m_{H^0} \lesssim 60$ GeV. These limits, as well as stronger limits obtained from e^+e^- collisions at LEP at energies up to 172 GeV, and weaker limits obtained from other sources, have been superseded by the most recent data of LEP. They have been removed from this compliation, and are documented in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review of Particle Physics.

In this Section, unless otherwise stated, limits from the four LEP experiments (ALEPH, DELPHI, L3, and OPAL) are obtained from the study of the $e^+e^- \rightarrow H^0 Z$ process, at center-of-mass energies reported in the comment lines.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>109.7	95	[1] ABBIENDI	01C	OPAL	$E_{cm} \leq 209$ GeV
>114.3	95	[1] ABREU	01E	DLPH	$E_{cm} \leq 209$ GeV
>107.0	95	[2] ACCIARRI	01B	L3	$E_{cm} \leq 202$ GeV
>110.6	95	[1,3] BARATE	00U	ALEP	$E_{cm} \leq 209$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>107.7	95	[1] BARATE	01C	ALEP	$E_{cm} \leq 202$ GeV
		[1,4] ACCIARRI	00U	L3	$E_{cm} \leq 209$ GeV
		[5] ABE	98T	CDF	$p\overline{p} \rightarrow H^0 W X$, $H^0 Z X$

[1] Search for $e^+e^- \rightarrow H^0 Z$ in the final states $H^0 \rightarrow b\overline{b}$ with $Z \rightarrow \ell\overline{\ell}$, $\nu\overline{\nu}$, $q\overline{q}$, $\tau^+\tau^-$ and $H^0 \rightarrow \tau^+\tau^-$ with $Z \rightarrow q\overline{q}$.

[2] Search for $e^+e^- \rightarrow H^0 Z$ in the final states $H^0 \rightarrow q\overline{q}$ with $Z \rightarrow \ell^+\ell^-$, $\nu\overline{\nu}$, $q\overline{q}$, and $\tau^+\tau^-$, and $H^0 \rightarrow \tau^+\tau^-$ with $Z \rightarrow q\overline{q}$.

[3] A 3σ excess of candidate events compatible with m_{H^0} near 114 GeV is observed in the combined channels $q\overline{q}q\overline{q}$, $q\overline{q}\ell\overline{\ell}$, $q\overline{q}\tau^+\tau^-$.

[4] A 1.7σ excess of candidate events compatible with $m_{H^0} = 114.5$ GeV is found when all search channels are combined.

[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 $W(Z) \rightarrow q\overline{q}^{(\prime)}$, $H^0 \rightarrow b\overline{b}$. The results are combined with the search in ABE 97W, resulting in the cross-section limit $\sigma(H^0 + W/Z)\cdot B(H^0 \rightarrow b\overline{b}) < (23\text{–}17)$ 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.

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. Other studies based on data available prior to 1996 can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review. For indirect limits obtained from other considerations of theoretical nature, see the Note on "Searches for Higgs Bosons."

Because of the high current interest, we mention here the following unpublished result (LEP 00, and update, presented by A. Straessner at the 2000 Electroweak Rencontres de Moriond) although we do not include it in the Listings or Tables: $m_H = 66.5^{+60}_{-33}$ GeV. This is obtained from a fit to LEP, SLD, W mass, top mass, and neutrino scattering data available in the Spring of 2000, with $1/\alpha^{(5)}(m_Z) = 128.878 \pm 0.090$. The 95%CL upper limit is 188 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[6] CHANOWITZ	99	RVUE	
<290	95	[7] D'AGOSTINI	99	RVUE	
<211	95	[8] FIELD	99	RVUE	
		[9] CHANOWITZ	98	RVUE	
$170^{+150}_{-\ 90}$		[10] HAGIWARA	98B	RVUE	
$141^{+140}_{-\ 77}$		[11] DEBOER	97B	RVUE	
$127^{+143}_{-\ 71}$		[12] DEGRASSI	97	RVUE	$\sin^2\theta_W$(eff,lept)
$158^{+148}_{-\ 84}$		[13] DITTMAIER	97	RVUE	
$149^{+148}_{-\ 82}$		[14] RENTON	97	RVUE	
$145^{+164}_{-\ 77}$		[15] ELLIS	96C	RVUE	
185^{+251}_{-134}		[16] GURTU	96	RVUE	

[6] CHANOWITZ 99 studies LEP/SLD data on 9 observables related $\sin^2\theta^{\ell}_{\rm eff}$, available in the Spring of 1998. A scale factor method is introduced to perform a global fit, in view of the conflicting data. m_H as large as 750 GeV is allowed at 95% CL.

[7] D'AGOSTINI 99 use m_t, m_W, and effective $\sin^2\theta_W$ from LEP/SLD available in the Fall 1998 and combine with direct Higgs search constraints from LEP2 at $E_{\rm cm}$=183 GeV. $\alpha(m_Z)$ given by DAVIER 98.

[8] FIELD 99 studies the data on b asymmetries from $Z^0 \rightarrow b\overline{b}$ decays at LEP and SLD (from LEP 99). The limit uses $1/\alpha(M_Z) = 128.90 \pm 0.09$, the variation in the fitted top quark mass, $m_t = 171.2^{+3.7}_{-3.8}$ GeV, and excludes b-asymmetry data. It is argued that exclusion of these data, which deviate from the Standard Model expectation, from the electroweak fits reduces significantly the upper limit on m_H. Including the b-asymmetry data gives instead the 95%CL limit $m_H < 284$ GeV. See also FIELD 00.

[9] 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.

[10] 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.

[11] 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 ± 0.00047) would give m_H=16^{+16}_{-9} GeV.

[12] 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 ± 0.09.

[13] 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, $\sin^2\theta^{\text{lept}}_{\text{eff}}$, 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).

[14] 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.

[15] 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.

[16] 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.

MASS LIMITS FOR NON-STANDARD MODEL HIGGS BOSONS

This section covers the following cases:

(i) Neutral scalar and pseudoscalar Higgs bosons in the MSSM,

(ii) Neutral Higgs bosons in extended Higgs models,

(iii) Charged Higgs bosons, and

(iv) Doubly-charged Higgs bosons

H^0_1 (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^0_1 and H^0_2, where we define $m_{H^0_1} < m_{H^0_2}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^\pm$). H^0_1 and H^0_2 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 $m_{H^0_1} \leq m_Z$, $m_{H^0_2} \geq m_Z$, $m_{A^0} \geq m_{H^0_1}$, and $m_{H^\pm} \geq m_W$. However, as described in the Review on Supersymmetry in this Volume these relations are violated by radiative corrections.

The mass region $m_{H^0_1} \lesssim 45$ GeV has been by now entirely ruled out by measurements at the Z pole. The relative limits, as well as other by now obsolete limits from different techniques, have been removed from this compilation, and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review. Unless otherwise stated, the following results assume no invisible H^0_1 or A^0 decays.

VALUE (GeV)	*CL%*		*DOCUMENT ID*		*TECN*	*COMMENT*
$>$ 83.4	95	[17,18]	ACCIARRI	01C	L3	$E_{\text{cm}} \leq 202$ GeV, $\tan\beta > 0.8$

>100	95	[19] AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}H_1^0$, $\tan\beta \gtrsim 55$
> 91.2	95	[17,20] BARATE	01C	ALEP	$E_{cm} \leq 202$ GeV, $\tan\beta > 0.5$
> 74.8	95	[21] ABBIENDI	00F	OPAL	$E_{cm} \leq 189$ GeV, $\tan\beta > 1$
> 75	95	[22] ABREU,P	00B	DLPH	$E_{cm} \leq 189$ GeV

[17] Search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H_1^0 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and $\mu= -200$ GeV are assumed, and two-loop radiative corrections incorporated. The limits hold for m_t=175 GeV and for stop mixing leading to the most conservative Higgs mass limit.

[18] Updates the results of ACCIARRI 99U.

[19] AFFOLDER 01D search for final states with 3 or more b-tagged jets. See Figs. 2 and 3 for Higgs mass limits as a function of $\tan\beta$, and for different stop mixing scenarios. Stronger limits are obtained at larger $\tan\beta$ values.

[20] Updates the results of BARATE 00F.

[21] ABBIENDI 00F search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, and $A^0A^0A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$, and $e^+e^- \rightarrow H_1^0 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 1.63 TeV and Higgsino mass parameter μ=−0.1 TeV are assumed. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. Limits obtained from scans of the Supersymmetric parameter space can be found in the paper. Updates the results of ABBIENDI 99E.

[22] ABREU,P 00B 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 $e^+e^- \rightarrow H_1^0 Z$. Full two-loop radiative corrections are incorporated. A scan of the MSSM parameters space is performed, assuming $m_{A^0} > 20$ GeV, universal scalar mass m_0 and SU(2) gaugino mass in the range 0.2–1 TeV and Higgsino mass parameter $|\mu| < 0.5$ TeV. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. These results update ABREU 00G. Updates the results of ABREU 99I.

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," 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. Unless otherwise stated, two-loop radiative corrections have been included, where relevant, in the limits presented here.

Limits obtained at the Z pole have been made obsolete by more recent results from higher energy e^+e^- collision data at LEP. Together with other by now obsolete results, they have been omitted from this compilation, and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review. Unless otherwise stated, the following results assume no invisible H_1^0 or A^0 decays. Limits quoted for a given value of E_{cm} may include data from lower energies.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 83.8	95	[23,24] ACCIARRI	01C	L3	$E_{cm} \leq 202$ GeV, $\tan\beta > 0.8$
>100	95	[25] AFFOLDER	01D	CDF	$p\overline{p} \rightarrow b\overline{b}A^0$, $\tan\beta \gtrsim 55$
> 91.6	95	[23,26] BARATE	01C	ALEP	$E_{cm} \leq 202$ GeV, $\tan\beta > 0.5$
> 76.5	95	[27] ABBIENDI	00F	OPAL	$E_{cm} \leq 189$ GeV, $\tan\beta > 1$
> 78	95	[28] ABREU,P	00B	DLPH	$E_{cm} \leq 189$ GeV

[23] Search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$ and $b\overline{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H_1^0 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and $\mu = -200$ GeV are assumed, and two-loop radiative corrections incorporated. The limits hold for m_t=175 GeV and for stop mixing leading to the most conservative Higgs mass limit.

[24] Updates the results of ACCIARRI 99U.

[25] AFFOLDER 01D search for final states with 3 or more b-tagged jets. See Figs. 2 and 3 for Higgs mass limits as a function of tanβ, and for different stop mixing scenarios. Stronger limits are obtained at larger tanβ values.

[26] Updates the results of BARATE 00F.

[27] ABBIENDI 00F search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\overline{b}b\overline{b}$, $b\overline{b}\tau^+\tau^-$, and $A^0 A^0 A^0 \rightarrow b\overline{b}b\overline{b}b\overline{b}$, and $e^+e^- \rightarrow H_1^0 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 1.63 TeV and Higgsino mass parameter $\mu = -0.1$ TeV are assumed. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. Limits obtained from scans of the Supersymmetric parameter space can be found in the paper. Updates the results of ABBIENDI 99E.

[28] ABREU,P 00B 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 $e^+e^- \rightarrow H_1^0 Z$. Full two-loop radiative corrections are incorporated. A scan of the MSSM parameters space is performed, assuming $m_{A^0} > 20$ GeV, universal scalar mass m_0 and SU(2) gaugino mass in the range 0.2–1 TeV and Higgsino mass parameter $|\mu| < 0.5$ TeV. m_t=175 GeV is used. The cases of maximal and no-stop mixing are examined. These results update ABREU 00G. Updates the results of ABREU 99I.

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

This Section covers models which do not fit into either the Standard Model or its simplest minimal Supersymmetric extension (MSSM), leading to anomalous production rates, or nonstandard final states and branching ratios. In particular, this Section covers limits which may apply to generic two-Higgs-doublet models (2HDM), or to special regions of the MSSM parameter space where decays to invisible particles or to photon pairs are dominant (see the Note on 'Searches for Higgs Bosons' at the beginning of this Chapter). See the footnotes or the comment lines for details on the nature of the models to which the limits apply.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 1–44	95	[29] ABBIENDI	01E	OPAL	H_1^0, Type-II model
none 12–56	95	[29] ABBIENDI	01E	OPAL	A^0, Type-II model
$>$107	95	[30] ABREU	01F	DLPH	$H_1^0 \rightarrow \gamma\gamma$
$>$106.4	95	[31] BARATE	01C	ALEP	Invisible H^0
$>$ 89.2	95	[32] ACCIARRI	00M	L3	invisible H^0
		[33] ACCIARRI	00R	L3	$e^+e^- \rightarrow H^0\gamma$ and/or $H^0 \rightarrow \gamma\gamma$
		[34] ACCIARRI	00R	L3	$e^+e^- \rightarrow e^+e^- H^0$
$>$ 94.9	95	[35] ACCIARRI	00S	L3	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$

>100.7	95	36 BARATE	00L	ALEP	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
> 68.0	95	37 ABBIENDI	99E	OPAL	$\tan\beta > 1$
> 96.2	95	38 ABBIENDI	99O	OPAL	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
> 78.5	95	39 ABBOTT	99B	D0	$p\overline{p} \rightarrow H^0 W/Z$, $H^0 \rightarrow \gamma\gamma$
		40 ABREU	99P	DLPH	$e^+e^- \rightarrow H^0\gamma$ and/or $H^0 \rightarrow \gamma\gamma$
> 76.1	95	41 ABREU	99Q	DLPH	Invisible H^0
		42 GONZALEZ-G...	98B	RVUE	Anomalous coupling
		43 KRAWCZYK	97	RVUE	$(g-2)_\mu$
		44 ALEXANDER	96H	OPAL	$Z \rightarrow H^0\gamma$
		45 ABREU	95H	DLPH	$Z \rightarrow H^0 Z^*$, $H^0 A^0$
		46 PICH	92	RVUE	Very light Higgs

29 ABBIENDI 01E search for neutral Higgs bosons in general Type-II two-doublet models, at $E_{cm} \leq 189$ GeV. In addition to usual final states, the decays H^0_1, $A^0 \rightarrow q\overline{q}$, gg are searched for. See their Figs. 15,16 for excluded regions.

30 ABREU 01F search for neutral, fermiophobic Higgs bosons in Type-I two-doublet models, at $E_{cm} \leq 202$ GeV. The limit is from $e^+e^- \rightarrow H^0 Z$ with the SM cross section and B($H^0 \rightarrow \gamma\gamma$)=1. The process $e^+e^- \rightarrow H^0 A^0$ with $H^0 \rightarrow \gamma\gamma$ is also searched for in the modes $A^0 \rightarrow b\overline{b}$, $H^0 Z$ and long-lived A^0. See their Figs. 4–6 for the excluded regions.

31 BARATE 01C search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying invisibly at E_{cm}= 192–202 GeV. The limit assumes SM production cross section and B($H^0 \rightarrow$ invisible) = 1. See their Fig. 8 for limits on the ZZH^0 coupling vs. m_{H^0}. Updates the results of BARATE 99O.

32 ACCIARRI 00M search for $e^+e^- \rightarrow ZH^0$ with H^0 decaying invisibly at E_{cm}=183–189 GeV. The limit assumes SM production cross section and B($H^0 \rightarrow$ invisible)=1. See their Fig. 6 for limits for smaller branching ratios.

33 ACCIARRI 00R search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\overline{b}$, $Z\gamma$, or $\gamma\gamma$. See their Fig. 3 for limits on $\sigma\cdot$B. Explicit limits within an effective interaction framework are also given, for which the Standard Model Higgs search results are used in addition.

34 ACCIARRI 00R search for the two-photon type processes $e^+e^- \rightarrow e^+e^- H^0$ with $H^0 \rightarrow b\overline{b}$ or $\gamma\gamma$. See their Fig. 4 for limits on $\Gamma(H^0 \rightarrow \gamma\gamma)\cdot$B($H^0 \rightarrow \gamma\gamma$ or $b\overline{b}$) for m_{H^0}=70–170 GeV.

35 ACCIARRI 00S search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at E_{cm}= 189 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 98$ GeV is obtained. See their Fig. 5 for limits on B($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow Hf\overline{f})/\sigma(e^+e^- \rightarrow Hf\overline{f})$ (SM).

36 BARATE 00L search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at E_{cm}= 88–202 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0 for all fermions f. For B($H^0 \rightarrow \gamma\gamma$)=1, $m_{H^0} > 109$ GeV is obtained. See their Fig. 3 for limits on B($H \rightarrow \gamma\gamma$)$\cdot\sigma(e^+e^- \rightarrow Hf\overline{f})/\sigma(e^+e^- \rightarrow Hf\overline{f})$ (SM).

37 ABBIENDI 99E search for $e^+e^- \rightarrow H^0 A^0$ 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. Updates the results of ACKERSTAFF 98S.

38 ABBIENDI 99O search for associated production of a $\gamma\gamma$ resonance with a $q\overline{q}$, $\nu\overline{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at 189 GeV. The limit is for a H^0 with SM production cross section and B($H^0 \rightarrow f\overline{f}$)=0, for all fermions f. See their Fig. 4 for limits on

$\sigma(e^+e^- \to H^0 Z^0)\times$B$(H^0 \to \gamma\gamma)\times$B$(X^0 \to f\overline{f})$ for various masses. Updates the results of ACKERSTAFF 98Y.

[39] 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.

[40] ABREU 99P search for $e^+e^- \to H^0\gamma$ with $H^0 \to b\overline{b}$ or $\gamma\gamma$, and $e^+e^- \to H^0 q\overline{q}$ with $H^0 \to \gamma\gamma$. See their Fig. 4 for limits on $\sigma\times$B. Explicit limits within an effective interaction framework are also given.

[41] ABREU 99Q search for $e^+e^- \to H^0 Z$ with H^0 decaying invisibly at $E_{\rm cm}$ between 161 and 183 GeV. The limit assumes SM production cross section, and holds for any B$(H^0 \to$ invisible). In the case of invisible decays in the MSSM, the excluded region of the (M_2, tanβ) plane overlaps the exclusion region from direct searches for charginos and neutralinos (ABREU 99E in the Supersymmetry Listings). See their Fig. 6(d) for limits on a Majoron model.

[42] GONZALEZ-GARCIA 98B use DØ limit for $\gamma\gamma$ events with missing E_T in $p\overline{p}$ collisions (ABBOTT 98) to constrain possible ZH or WH 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.

[43] 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.

[44] 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.

[45] 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 tanβ >1, the region $m_{H^0}+m_{A^0} \lesssim 87$ GeV, m_{H^0} <47 GeV is excluded at 95% CL.

[46] 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.

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

Unless otherwise stated, the limits below assume B$(H^+ \to \tau^+\nu)$+B$(H^+ \to c\overline{s})$=1, and hold for all values of B$(H^+ \to \tau^+\nu_\tau)$, and assume H^+ weak isospin of T_3=+1/2. In the following, tanβ is the ratio of the two vacuum expectation values in two-doublet models (2HDM).

The limits are also applicable to point-like technipions. For a discussion of techniparticles, see the Review of Dynamical Electroweak Symmetry Breaking in this Review.

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.

Searches in e^+e^- collisions at and above the Z pole have conclusively ruled out the existence of a charged Higgs in the region $m_{H^+} \lesssim 45$ GeV, and are now superseded by the most recent searches in higher energy e^+e^- collisions at LEP. Results by now obsolete are therefore not included in this compilation, and can be found in the 1998 Edition (The European Physical Journal **C3** 1 (1998)) of this Review.

In the following, and unless otherwise stated, results from the LEP experiments (ALEPH, DELPHI, L3, and OPAL) are assumed to derive from the study of the

$e^+e^- \rightarrow H^+H^-$ process. Limits from $b \rightarrow s\gamma$ decays are usually stronger in generic 2HDM models than in Supersymmetric models.

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

A recent combination (LEP 00B) of preliminary, unpublished results relative to data taken at LEP in the Summer of 1999 at energies up to 202 GeV gives the limit $m_{H_1^\pm} > 78.6$ GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> 69.0 (CL = 95%) OUR LIMIT					
> 67.4	95	[47] ACCIARRI	00W	L3	$E_{cm} \leq 202$ GeV
> 65.4	95	BARATE	00M	ALEP	$E_{cm} \leq 189$ GeV
> 59.5	95	ABBIENDI	99E	OPAL	$E_{cm} \leq 183$ GeV
> 56.3	95	ABREU	99R	DLPH	$E_{cm} \leq 183$ GeV
> 57.5	95	ACCIARRI	99B	L3	$E_{cm} \leq 183$ GeV
> 59	95	BARATE	99D	ALEP	$E_{cm} \leq 183$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 82.8	95	ABBIENDI	00G	OPAL	$E_{cm} \leq 189$ GeV, $B(\tau\nu) = 1$
		[48] AFFOLDER	00I	CDF	$t \rightarrow bH^+$, $H \rightarrow \tau\nu$
		[49] ABBOTT	99E	D0	$t \rightarrow bH^+$
		[50] ACKERSTAFF	99D	OPAL	$\tau \rightarrow e\nu\nu$, $\mu\nu\nu$
		[51] ACCIARRI	97F	L3	$B \rightarrow \tau\nu_\tau$
		[52] AMMAR	97B	CLEO	$\tau \rightarrow \mu\nu\nu$
		[53] COARASA	97	RVUE	$B \rightarrow \tau\nu_\tau X$
		[54] GUCHAIT	97	RVUE	$t \rightarrow bH^+$, $H \rightarrow \tau\nu$
		[55] MANGANO	97	RVUE	$B_{u(c)} \rightarrow \tau\nu_\tau$
		[56] STAHL	97	RVUE	$\tau \rightarrow \mu\nu\nu$
>244	95	[57] ALAM	95	CLE2	$b \rightarrow s\gamma$
		[58] BUSKULIC	95	ALEP	$b \rightarrow \tau\nu_\tau X$

[47] Updates the results of ACCIARRI 99P.

[48] AFFOLDER 00I search for a charged Higgs boson in top decays with $H^+ \rightarrow \tau^+\nu$ in $p\overline{p}$ collisions at E_{cm}=1.8 TeV. The excluded mass region extends to over 120 GeV for tanβ values above 100 and B($\tau\nu$)=1. If B($t \rightarrow bH^+$) $\gtrsim$ 0.6, m_{H^+} up to 160 GeV is excluded. Updates ABE 97L.

[49] ABBOTT 99E search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at E_{cm}=1.8 TeV, by comparing the observed $t\overline{t}$ cross section (extracted from the data assuming the dominant decay $t \rightarrow bW^+$) with theoretical expectation. The search is sensitive to regions of the domains tan$\beta \lesssim 1$, $50 < m_{H^+}$(GeV) $\lesssim 120$ and tan$\beta \gtrsim 40$, $50 < m_{H^+}$ (GeV) $\lesssim 160$. See Fig. 3 for the details of the excluded region.

[50] ACKERSTAFF 99D measure the Michel parameters ρ, ξ, η, and $\xi\delta$ in leptonic τ decays from $Z \rightarrow \tau\tau$. Assuming e-μ universality, the limit $m_{H^+} > 0.97$ tanβ GeV (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.

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

[52] AMMAR 97B measure the Michel parameter ρ from $\tau \rightarrow e\nu\nu$ decays and assmes e/μ universality to extract the Michel η parameter from $\tau \rightarrow \mu\nu\nu$ 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).

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

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

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

[56] 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.

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

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

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

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.6	95	[59] ACTON	92M	OPAL	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[60] GORDEEV	97	SPEC	muonium conversion
		[61] ASAKA	95	THEO	
>30.4	95	[62] ACTON	92M	OPAL	$T_3(H^{++})= +1$
>25.5	95	[62] ACTON	92M	OPAL	$T_3(H^{++})= 0$
none 6.5–36.6	95	[63] SWARTZ	90	MRK2	$T_3(H^{++}) = +1$
none 7.3–34.3	95	[63] SWARTZ	90	MRK2	$T_3(H^{++}) = 0$

[59] 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.

[60] 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.

[61] 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.

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

[63] 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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