

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 Note above on “Searches for Higgs Bosons.”

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from e^+e^- collisions at LEP at energies up to 202 GeV, and weaker limits obtained from other sources, have been superseded by the more recent data of LEP. They have been removed from this compilation, and are documented in previous editions 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
>114.1	95	¹ ABDALLAH	04 DLPH	$E_{\text{cm}} \leq 209$ GeV
>112.7	95	¹ ABBIENDI	03B OPAL	$E_{\text{cm}} \leq 209$ GeV
>114.4	95	^{1,2} HEISTER	03D LEP	$E_{\text{cm}} \leq 209$ GeV
>111.5	95	^{1,3} HEISTER	02 ALEP	$E_{\text{cm}} \leq 209$ GeV
>112.0	95	¹ ACHARD	01C L3	$E_{\text{cm}} \leq 209$ GeV

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

4	ABAZOV	07X	D0	$p\bar{p} \rightarrow H^0 Z X$
5	ABAZOV	06	D0	$p\bar{p} \rightarrow H^0 X, H^0 \rightarrow W W^*$
6	ABAZOV	06O	D0	$p\bar{p} \rightarrow H^0 W X, H^0 \rightarrow W W^*$
7	ABAZOV	06Q	D0	$p\bar{p} \rightarrow H^0 Z X$
8	ABAZOV	06Q	D0	$p\bar{p} \rightarrow H^0 W X$
9	ABULENCIA	06H	CDF	$p\bar{p} \rightarrow H^0 W X$
10	ABULENCIA,A	06A	CDF	$p\bar{p} \rightarrow H^0 X, H^0 \rightarrow W W^*$
11	ABAZOV	05F	D0	$p\bar{p} \rightarrow H^0 W X$
12	ACOSTA	05K	CDF	$p\bar{p} \rightarrow H^0 Z X$
13	ABE	98T	CDF	$p\bar{p} \rightarrow H^0 W X, H^0 Z X$

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

² Combination of the results of all LEP experiments.

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

⁴ ABAZOV 07X search for associated $H^0 Z$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV in the final state $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$; $H^0 \rightarrow b\bar{b}$. A limit $\sigma(ZH^0) \cdot \text{B}(H^0 \rightarrow b\bar{b}) < (4.4-3.1)$ pb (95%CL) is given for $m_{H^0} = 105-145$ GeV, which is more than 40 times larger than the expected Standard Model cross section.

- ⁵ ABAZOV 06 search for Higgs boson production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV with the decay chain $H^0 \rightarrow WW^* \rightarrow \ell^\pm \nu \ell'^\mp \bar{\nu}$. A limit $\sigma(H^0) \cdot \text{B}(H^0 \rightarrow WW^*) < (5.6-3.2)$ pb (95 %CL) is given for $m_{H^0} = 120-200$ GeV, which far exceeds the expected Standard Model cross section.
- ⁶ ABAZOV 06O search for associated $H^0 W$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV with the decay $H^0 \rightarrow WW^*$, in the final states $\ell^\pm \ell'^\mp \nu \nu' X$ where $\ell = e, \mu$. A limit $\sigma(H^0 W) \cdot \text{B}(H^0 \rightarrow WW^*) < (3.2-2.8)$ pb (95 %CL) is given for $m_{H^0} = 115-175$ GeV, which far exceeds the expected Standard Model cross section.
- ⁷ ABAZOV 06Q search for associated $H^0 Z$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV with $Z \rightarrow \nu\bar{\nu}$ and $H^0 \rightarrow b\bar{b}$. A limit $\sigma(H^0 Z) \cdot \text{B}(H^0 \rightarrow b\bar{b}) < (3.4-2.5)$ pb (95% CL) for $m_{H^0} = 105-135$ GeV is derived, which is more than one order of magnitude larger than the expected Standard Model cross section.
- ⁸ ABAZOV 06Q search for associated $H^0 W$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV with $W \rightarrow \ell\nu$ (ℓ missing) and $H^0 \rightarrow b\bar{b}$. A limit $\sigma(H^0 W) \cdot \text{B}(H^0 \rightarrow b\bar{b}) < (8.3-6.3)$ pb (95% CL) for $m_{H^0} = 105-135$ GeV is derived, which is more than one order of magnitude larger than the expected Standard Model cross section.
- ⁹ ABULENCIA 06H search for associated $H^0 W$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV in the final state $W \rightarrow e\nu, \mu\nu; H^0 \rightarrow b\bar{b}$. A limit $\sigma(WH^0) \cdot \text{B}(H^0 \rightarrow b\bar{b}) < (10-3)$ pb (95% CL) is given for $m_{H^0} = 110-150$ GeV, which is more than 50 times larger than the expected Standard Model cross section.
- ¹⁰ ABULENCIA, A 06A search for Higgs boson production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV with the decay chain $H^0 \rightarrow WW^* \rightarrow e^+ e^- \nu\bar{\nu}, e^\pm \mu^\mp \nu\bar{\nu}, \mu^+ \mu^- \nu\bar{\nu}$. A limit $\sigma(H^0) \cdot \text{B}(H^0 \rightarrow WW^*) < (3.2-5.2)$ pb (95% CL) is given for $m_{H^0} = 120-200$ GeV, which far exceeds the expected Standard Model cross section.
- ¹¹ ABAZOV 05F search for associated $H^0 W$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV in the final state $W \rightarrow e\nu, H^0 \rightarrow b\bar{b}$. A limit $\sigma(WH^0) \cdot \text{B}(H^0 \rightarrow b\bar{b}) < [9.0, 9.1, 12.2]$ pb (95 %CL) is given for $m_{H^0} = [115, 125, 135]$ GeV, which far exceeds the expected Standard Model cross section.
- ¹² ACOSTA 05K search for associated $H^0 Z$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.8$ TeV with $Z \rightarrow \ell\bar{\ell}, \nu\bar{\nu}$ and $H^0 \rightarrow b\bar{b}$. Combined with ABE 98T, a limit $\sigma(H^0 + W/Z) \cdot \text{B}(H^0 \rightarrow b\bar{b}) < (7.8-6.6)$ pb (95 %CL) for $m_{H^0} = 90-130$ GeV is derived, which is more than one order of magnitude larger than the expected Standard Model cross section.
- ¹³ ABE 98T search for associated $H^0 W$ and $H^0 Z$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with $W(Z) \rightarrow q\bar{q}^{(\prime)}$, $H^0 \rightarrow b\bar{b}$. The results are combined with the search in ABE 97W, resulting in the cross-section limit $\sigma(H^0 + W/Z) \cdot \text{B}(H^0 \rightarrow b\bar{b}) < (23-17)$ pb (95%CL) for $m_H = 70-140$ GeV. This limit is one to two orders of magnitude larger than the expected cross section in the Standard Model.

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."

VALUE (GeV)	DOCUMENT ID	TECN
129^{+74}_{-49}	¹⁴ LEP-SLC	06 RVUE

¹⁴ LEP-SLC 06 make Standard Model fits to Z parameters from LEP/SLC and m_t , m_W , and Γ_W measurements available in 2005 with $\Delta\alpha_{\text{had}}^{(5)}(m_Z) = 0.02758 \pm 0.00035$. The 95% CL limit is 285 GeV.

MASS LIMITS FOR NEUTRAL HIGGS BOSONS IN SUPERSYMMETRIC MODELS

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H_1^0 and H_2^0 , where we define $m_{H_1^0} < m_{H_2^0}$], a pseudoscalar (A^0), and a charged Higgs pair (H^\pm). H_1^0 and H_2^0 are also called h and H in the literature. There are two free parameters in the theory which can be chosen to be m_{A^0} and $\tan\beta = v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets. Tree-level Higgs masses are constrained by the model to be $m_{H_1^0} \leq m_Z$, $m_{H_2^0} \geq m_Z$, $m_{A^0} \geq m_{H_1^0}$, and $m_{H^\pm} \geq m_W$. However, as described in the review on “Searches for Higgs Bosons” in this Volume these relations are violated by radiative corrections.

Unless otherwise noted, the experiments in e^+e^- collisions search for the processes $e^+e^- \rightarrow H_1^0 Z^0$ in the channels used for the Standard Model Higgs searches and $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$. Limits on the A^0 mass arise from these direct searches, as well as from the relations valid in the minimal supersymmetric model between m_{A^0} and $m_{H_1^0}$. As discussed in the review on “Searches for Higgs Bosons” in this Volume, these relations depend, via potentially large radiative corrections, on the mass of the t quark and on the supersymmetric parameters, in particular those of the stop sector. The limits are weaker for larger t and \bar{t} masses. To include the radiative corrections to the Higgs masses, unless otherwise stated, the listed papers use the two-loop results with $m_t = 175$ GeV, the universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and the Higgsino mass parameter $\mu = +200$ GeV or $\mu = -200$ GeV, and examine the two scenarios of no scalar top mixing and the m_h^{max} benchmark scenario (which gives rise to the most conservative upper bound on the mass of H_1^0 for given values of m_{A^0} and $\tan\beta$), see CARENA 99B and CARENA 03.

Limits in the low-mass region of H_1^0 , as well as other by now obsolete limits from different techniques, have been removed from this compilation, and can be found in earlier editions of this Review. Unless otherwise stated, the following results assume no invisible H_1^0 or A^0 decays.

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

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 92.8	95	15 SCHAEL	06B LEP	
> 84.5	95	16,17 ABBIENDI	04M OPAL	$E_{\text{cm}} \leq 209$ GeV
> 89.7	95	16,18 ABDALLAH	04 DLPH	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.4$
> 86.0	95	16,19 ACHARD	02H L3	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.4$
>100	95	20 AFFOLDER	01D CDF	$p\bar{p} \rightarrow b\bar{b}H_1^0$, $\tan\beta \gtrsim 55$

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

- 21 ABBIENDI 03G OPAL $H_1^0 \rightarrow A^0 A^0$
 > 89.8 95 16,22 HEISTER 02 ALEP $E_{\text{cm}} \leq 209 \text{ GeV}, \tan\beta > 0.5$
- 15 SCHAEL 06B make a combined analysis of the LEP data. The quoted limit is for the m_h^{max} scenario with $m_t = 174.3 \text{ GeV}$. In the CP -violating CPX scenario no lower bound on $m_{H_1^0}$ can be set at 95% CL. See paper for excluded regions in various scenarios. See Figs. 2–6 and Tabs. 14–21 for limits on $\sigma(ZH^0) \cdot \text{B}(H^0 \rightarrow b\bar{b}, \tau^+\tau^-)$ and $\sigma(H_1^0 H_2^0) \cdot \text{B}(H_1^0, H_2^0 \rightarrow b\bar{b}, \tau^+\tau^-)$.
- 16 Search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$, and $e^+e^- \rightarrow H_1^0 Z$. Universal scalar mass of 1 TeV, SU(2) gaugino mass of 200 GeV, and $\mu = -200 \text{ GeV}$ are assumed, and two-loop radiative corrections incorporated. The limits hold for $m_t = 175 \text{ GeV}$, and for the m_h^{max} scenario.
- 17 ABBIENDI 04M exclude $0.7 < \tan\beta < 1.9$, assuming $m_t = 174.3 \text{ GeV}$. Limits for other MSSM benchmark scenarios, as well as for CP violating cases, are also given.
- 18 This limit applies also in the no-mixing scenario. Furthermore, ABDALLAH 04 excludes the range $0.54 < \tan\beta < 2.36$. The limit improves in the region $\tan\beta < 6$ (see Fig. 28). Limits for $\mu = 1 \text{ TeV}$ are given in Fig. 30.
- 19 ACHARD 02H also search for the final state $H_1^0 Z \rightarrow 2A^0 q\bar{q}, A^0 \rightarrow q\bar{q}$. In addition, the MSSM parameter set in the “large- μ ” and “no-mixing” scenarios are examined.
- 20 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.
- 21 ABBIENDI 03G search for $e^+e^- \rightarrow H_1^0 Z$ followed by $H_1^0 \rightarrow A^0 A^0, A^0 \rightarrow c\bar{c}, gg,$ or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H_1^0} = 45\text{--}85 \text{ GeV}$ and $m_{A^0} = 2\text{--}9.5 \text{ GeV}$ is excluded at 95% CL.
- 22 HEISTER 02 excludes the range $0.7 < \tan\beta < 2.3$. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

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

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 93.4	95	23 SCHAEL	06B LEP	
> 85.0	95	24,25 ABBIENDI	04M OPAL	$E_{\text{cm}} \leq 209 \text{ GeV}$
> 90.4	95	24,26 ABDALLAH	04 DLPH	$E_{\text{cm}} \leq 209 \text{ GeV}, \tan\beta > 0.4$
> 86.5	95	24,27 ACHARD	02H L3	$E_{\text{cm}} \leq 209 \text{ GeV}, \tan\beta > 0.4$
> 90.1	95	24,28 HEISTER	02 ALEP	$E_{\text{cm}} \leq 209 \text{ GeV}, \tan\beta > 0.5$
>100	95	29 AFFOLDER	01D CDF	$p\bar{p} \rightarrow b\bar{b}A^0, \tan\beta \gtrsim 55$

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

30 ABAZOV	06J D0	$p\bar{p} \rightarrow H^0 X, H^0 \rightarrow \tau^+\tau^-$
31 ABULENCIA	06 CDF	$p\bar{p} \rightarrow H_{1,2}^0/A^0 + X$
32 ABAZOV	05T D0	$p\bar{p} \rightarrow b\bar{b}H_{1,2}^0/A^0 + X$
33 ACOSTA	05Q CDF	$p\bar{p} \rightarrow H_{1,2}^0/A^0 + X$
34 ABBIENDI	03G OPAL	$H_1^0 \rightarrow A^0 A^0$
35 AKEROYD	02 RVUE	

- 23 SCHAEEL 06B make a combined analysis of the LEP data. The quoted limit is for the m_h^{\max} scenario with $m_t = 174.3$ GeV. In the CP -violating CPX scenario no lower bound on $m_{H_1^0}$ can be set at 95% CL. See paper for excluded regions in various scenarios. See Figs. 2–6 and Tabs. 14–21 for limits on $\sigma(ZH^0) \cdot B(H^0 \rightarrow b\bar{b}, \tau^+\tau^-)$ and $\sigma(H_1^0 H_2^0) \cdot B(H_1^0, H_2^0 \rightarrow b\bar{b}, \tau^+\tau^-)$.
- 24 Search for $e^+e^- \rightarrow H_1^0 A^0$ in the final states $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$, 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 the m_h^{\max} scenario.
- 25 ABBIENDI 04M exclude $0.7 < \tan\beta < 1.9$, assuming $m_t = 174.3$ GeV. Limits for other MSSM benchmark scenarios, as well as for CP violating cases, are also given.
- 26 This limit applies also in the no-mixing scenario. Furthermore, ABDALLAH 04 excludes the range $0.54 < \tan\beta < 2.36$. The limit improves in the region $\tan\beta < 6$ (see Fig. 28). Limits for $\mu = 1$ TeV are given in Fig. 30.
- 27 ACHARD 02H also search for the final state $H_1^0 Z \rightarrow 2A^0 q\bar{q}$, $A^0 \rightarrow q\bar{q}$. In addition, the MSSM parameter set in the “large- μ ” and “no-mixing” scenarios are examined.
- 28 HEISTER 02 excludes the range $0.7 < \tan\beta < 2.3$. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.
- 29 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.
- 30 ABAZOV 06J search for Higgs boson production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV with the decay $H_{1,2}^0, A^0 \rightarrow \tau^+\tau^-$. See their Fig. 3 for the region in the MSSM parameter space excluded by this analysis and the results of ABAZOV 05T.
- 31 ABULENCIA 06 search for $H_{1,2}^0/A^0$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV with $H_{1,2}^0/A^0 \rightarrow \tau^+\tau^-$. A region with $\tan\beta > 40$ (100) is excluded for $m_{A^0} = 90$ (170) GeV.
- 32 ABAZOV 05T search for $H_{1,2}^0/A^0$ production in association with bottom quarks in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV, with the $b\bar{b}$ decay mode. See their Fig. 5 for the excluded parameter regions in the m_h^{\max} and no-mixing scenarios for $\mu = -200$ GeV.
- 33 ACOSTA 05Q search for $H_{1,2}^0/A^0$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.8$ TeV with $H_{1,2}^0/A^0 \rightarrow \tau^+\tau^-$. At $m_{A^0} = 100$ GeV, the obtained cross section upper limit is above theoretical expectation.
- 34 ABBIENDI 03G search for $e^+e^- \rightarrow H_1^0 Z$ followed by $H_1^0 \rightarrow A^0 A^0, A^0 \rightarrow c\bar{c}, gg$, or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H_1^0} = 45\text{--}85$ GeV and $m_{A^0} = 2\text{--}9.5$ GeV is excluded at 95% CL.
- 35 AKEROYD 02 examine the possibility of a light A^0 with $\tan\beta < 1$. Electroweak measurements are found to be inconsistent with such a scenario.

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. ● ● ●				
>105.8	95	36 ABBIENDI	07 OPAL	invisible H^0 , large width
		37 SCHAEAL	07 ALEP	$e^+e^- \rightarrow H^0 Z, H^0 \rightarrow$ $W W^*$
none 1–55	95	38 ABBIENDI	05A OPAL	H_1^0 , Type II model
none 3–63	95	38 ABBIENDI	05A OPAL	A^0 , Type II model
>110.6	95	39 ABDALLAH	05D DLPH	$H^0 \rightarrow 2$ jets
>112.3	95	40 ACHARD	05 L3	invisible H^0
>104	95	41 ABBIENDI	04K OPAL	$H^0 \rightarrow 2$ jets
		42 ABDALLAH	04 DLPH	$H^0 V V$ couplings
>112.1	95	40 ABDALLAH	04B DLPH	Invisible H^0
>104.1	95	43,44 ABDALLAH	04L DLPH	$e^+e^- \rightarrow H^0 Z, H^0 \rightarrow \gamma\gamma$
		45 ABDALLAH	04O DLPH	$Z \rightarrow f\bar{f}H$
		46 ABDALLAH	04O DLPH	$e^+e^- \rightarrow H^0 Z, H^0 A^0$
>110.3	95	47 ACHARD	04B L3	$H^0 \rightarrow 2$ jets
		48 ACHARD	04F L3	Anomalous coupling
		49 ABBIENDI	03F OPAL	$e^+e^- \rightarrow H^0 Z, H^0 \rightarrow$ any
		50 ABBIENDI	03G OPAL	$H_1^0 \rightarrow A^0 A^0$
>107	95	51 ACHARD	03C L3	$H^0 \rightarrow W W^*, Z Z^*, \gamma\gamma$
		52 ABBIENDI	02D OPAL	$e^+e^- \rightarrow b\bar{b}H$
>105.5	95	43,53 ABBIENDI	02F OPAL	$H_1^0 \rightarrow \gamma\gamma$
>105.4	95	54 ACHARD	02C L3	$H_1^0 \rightarrow \gamma\gamma$
>114.1	95	40 HEISTER	02 ALEP	Invisible $H^0, E_{\text{cm}} \leq 209$ GeV
>105.4	95	43,55 HEISTER	02L ALEP	$H_1^0 \rightarrow \gamma\gamma$
>109.1	95	56 HEISTER	02M ALEP	$H^0 \rightarrow 2$ jets or $\tau^+\tau^-$
none 1–44	95	57 ABBIENDI	01E OPAL	H_1^0 , Type-II model
none 12–56	95	57 ABBIENDI	01E OPAL	A^0 , Type-II model
> 98	95	58 AFFOLDER	01H CDF	$p\bar{p} \rightarrow H^0 W/Z, H^0 \rightarrow \gamma\gamma$
>106.4	95	40 BARATE	01C ALEP	Invisible $H^0, E_{\text{cm}} \leq 202$ GeV
> 89.2	95	59 ACCIARRI	00M L3	Invisible H^0
		60 ACCIARRI	00R L3	$e^+e^- \rightarrow H^0 \gamma$ and/or $H^0 \rightarrow$ $\gamma\gamma$
> 94.9	95	61 ACCIARRI	00R L3	$e^+e^- \rightarrow e^+e^- H^0$
>100.7	95	62 ACCIARRI	00S L3	$e^+e^- \rightarrow H^0 Z, H^0 \rightarrow \gamma\gamma$
> 68.0	95	63 BARATE	00L ALEP	$e^+e^- \rightarrow H^0 Z, H^0 \rightarrow \gamma\gamma$
> 96.2	95	64 ABBIENDI	99E OPAL	$\tan\beta > 1$
> 78.5	95	65 ABBIENDI	99O OPAL	$e^+e^- \rightarrow H^0 Z, H^0 \rightarrow \gamma\gamma$
		66 ABBOTT	99B D0	$p\bar{p} \rightarrow H^0 W/Z, H^0 \rightarrow \gamma\gamma$
		67 ABREU	99P DLPH	$e^+e^- \rightarrow H^0 \gamma$ and/or $H^0 \rightarrow$ $\gamma\gamma$
		68 GONZALEZ-G..	98B RVUE	Anomalous coupling
		69 KRAWCZYK	97 RVUE	$(g-2)_\mu$
		70 ALEXANDER	96H OPAL	$Z \rightarrow H^0 \gamma$
		71 ABREU	95H DLPH	$Z \rightarrow H^0 Z^*, H^0 A^0$
		72 PICH	92 RVUE	Very light Higgs

- 36 ABBIENDI 07 search for $e^+e^- \rightarrow H^0 Z$ with $Z \rightarrow q\bar{q}$ and H^0 decaying to invisible final states. The H^0 width is varied between 1 GeV and 3 TeV. A limit $\sigma \cdot B(H^0 \rightarrow \text{invisible}) < (0.07\text{--}0.57)$ pb (95%CL) is obtained at $E_{\text{cm}} = 206$ GeV for $m_{H^0} = 60\text{--}114$ GeV.
- 37 SCHAEEL 07 search for Higgs bosons in association with a fermion pair and decaying to WW^* . The limit is from this search and HEISTER 02L for a H^0 with SM production cross section and $B(H^0 \rightarrow f\bar{f}) = 0$ for all fermions f .
- 38 ABBIENDI 05A search for $e^+e^- \rightarrow H_1^0 A^0$ in general Type-II two-doublet models, with decays $H_1^0, A^0 \rightarrow q\bar{q}, gg, \tau^+\tau^-$, and $H_1^0 \rightarrow A^0 A^0$.
- 39 ABDALLAH 05D search for $e^+e^- \rightarrow H^0 Z$ and $H^0 A^0$ with H^0, A^0 decaying to two jets of any flavor including gg . The limit is for SM $H^0 Z$ production cross section with $B(H^0 \rightarrow jj) = 1$.
- 40 Search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying invisibly. The limit assumes SM production cross section and $B(H^0 \rightarrow \text{invisible}) = 1$.
- 41 ABBIENDI 04K search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying to two jets of any flavor including gg . The limit is for SM production cross section with $B(H^0 \rightarrow jj) = 1$.
- 42 ABDALLAH 04 consider the full combined LEP and LEP2 datasets to set limits on the Higgs coupling to W or Z bosons, assuming SM decays of the Higgs. Results in Fig. 26.
- 43 Search for associated production of a $\gamma\gamma$ resonance with a Z boson, followed by $Z \rightarrow q\bar{q}, \ell^+\ell^-$, or $\nu\bar{\nu}$, at $E_{\text{cm}} \leq 209$ GeV. The limit is for a H^0 with SM production cross section and $B(H^0 \rightarrow f\bar{f})=0$ for all fermions f .
- 44 Updates ABREU 01F.
- 45 ABDALLAH 04O search for $Z \rightarrow b\bar{b}H^0, b\bar{b}A^0, \tau^+\tau^-H^0$ and $\tau^+\tau^-A^0$ in the final states $4b, b\bar{b}\tau^+\tau^-$, and 4τ . See paper for limits on Yukawa couplings.
- 46 ABDALLAH 04O search for $e^+e^- \rightarrow H^0 Z$ and $H^0 A^0$, with H^0, A^0 decaying to $b\bar{b}, \tau^+\tau^-$, or $H^0 \rightarrow A^0 A^0$ at $E_{\text{cm}} = 189\text{--}208$ GeV. See paper for limits on couplings.
- 47 ACHARD 04B search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying to $b\bar{b}, c\bar{c}$, or gg . The limit is for SM production cross section with $B(H^0 \rightarrow jj) = 1$.
- 48 ACHARD 04F search for H^0 with anomalous coupling to gauge boson pairs in the processes $e^+e^- \rightarrow H^0\gamma, e^+e^-H^0, H^0 Z$ with decays $H^0 \rightarrow f\bar{f}, \gamma\gamma, Z\gamma$, and W^*W at $E_{\text{cm}} = 189\text{--}209$ GeV. See paper for limits.
- 49 ABBIENDI 03F search for $H^0 \rightarrow \text{anything}$ in $e^+e^- \rightarrow H^0 Z$, using the recoil mass spectrum of $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$. In addition, it searched for $Z \rightarrow \nu\bar{\nu}$ and $H^0 \rightarrow e^+e^-$ or photons. Scenarios with large width or continuum H^0 mass distribution are considered. See their Figs. 11–14 for the results.
- 50 ABBIENDI 03G search for $e^+e^- \rightarrow H_1^0 Z$ followed by $H_1^0 \rightarrow A^0 A^0, A^0 \rightarrow c\bar{c}, gg$, or $\tau^+\tau^-$ in the region $m_{H_1^0} = 45\text{--}86$ GeV and $m_{A^0} = 2\text{--}11$ GeV. See their Fig. 7 for the limits.
- 51 ACHARD 03C search for $e^+e^- \rightarrow ZH^0$ followed by $H^0 \rightarrow WW^*$ or ZZ^* at $E_{\text{cm}} = 200\text{--}209$ GeV and combine with the ACHARD 02C result. The limit is for a H^0 with SM production cross section and $B(H^0 \rightarrow f\bar{f}) = 0$ for all f . For $B(H^0 \rightarrow WW^*) + B(H^0 \rightarrow ZZ^*) = 1$, $m_{H^0} > 108.1$ GeV is obtained. See fig. 6 for the limits under different BR assumptions.
- 52 ABBIENDI 02D search for $Z \rightarrow b\bar{b}H_1^0$ and $b\bar{b}A^0$ with $H_1^0/A^0 \rightarrow \tau^+\tau^-$, in the range $4 < m_H < 12$ GeV. See their Fig. 8 for limits on the Yukawa coupling.
- 53 For $B(H^0 \rightarrow \gamma\gamma)=1$, $m_{H^0} > 117$ GeV is obtained.
- 54 ACHARD 02C search for associated production of a $\gamma\gamma$ resonance with a Z boson, followed by $Z \rightarrow q\bar{q}, \ell^+\ell^-$, or $\nu\bar{\nu}$, at $E_{\text{cm}} \leq 209$ GeV. The limit is for a H^0 with SM production cross section and $B(H^0 \rightarrow f\bar{f})=0$ for all fermions f . For $B(H^0 \rightarrow \gamma\gamma)=1$, $m_{H^0} > 114$ GeV is obtained.

- 55 For $B(H^0 \rightarrow \gamma\gamma)=1$, $m_{H^0} > 113.1$ GeV is obtained.
- 56 HEISTER 02M search for $e^+e^- \rightarrow H^0 Z$, assuming that H^0 decays to $q\bar{q}$, gg , or $\tau^+\tau^-$ only. The limit assumes SM production cross section.
- 57 ABBIENDI 01E search for neutral Higgs bosons in general Type-II two-doublet models, at $E_{\text{cm}} \leq 189$ GeV. In addition to usual final states, the decays $H_1^0, A^0 \rightarrow q\bar{q}, gg$ are searched for. See their Figs. 15,16 for excluded regions.
- 58 AFFOLDER 01H search for associated production of a $\gamma\gamma$ resonance and a W or Z (tagged by two jets, an isolated lepton, or missing E_T). The limit assumes Standard Model values for the production cross section and for the couplings of the H^0 to W and Z bosons. See their Fig. 11 for limits with $B(H^0 \rightarrow \gamma\gamma) < 1$.
- 59 ACCIARRI 00M search for $e^+e^- \rightarrow ZH^0$ with H^0 decaying invisibly at $E_{\text{cm}}=183\text{--}189$ GeV. The limit assumes SM production cross section and $B(H^0 \rightarrow \text{invisible})=1$. See their Fig. 6 for limits for smaller branching ratios.
- 60 ACCIARRI 00R search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\bar{b}, Z\gamma$, 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.
- 61 ACCIARRI 00R search for the two-photon type processes $e^+e^- \rightarrow e^+e^-H^0$ with $H^0 \rightarrow b\bar{b}$ or $\gamma\gamma$. See their Fig. 4 for limits on $\Gamma(H^0 \rightarrow \gamma\gamma) \cdot B(H^0 \rightarrow \gamma\gamma \text{ or } b\bar{b})$ for $m_{H^0}=70\text{--}170$ GeV.
- 62 ACCIARRI 00S search for associated production of a $\gamma\gamma$ resonance with a $q\bar{q}, \nu\bar{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at $E_{\text{cm}}=189$ GeV. The limit is for a H^0 with SM production cross section and $B(H^0 \rightarrow f\bar{f})=0$ 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 $B(H \rightarrow \gamma\gamma) \cdot \sigma(e^+e^- \rightarrow Hf\bar{f})/\sigma(e^+e^- \rightarrow Hf\bar{f})$ (SM).
- 63 BARATE 00L search for associated production of a $\gamma\gamma$ resonance with a $q\bar{q}, \nu\bar{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at $E_{\text{cm}}=88\text{--}202$ GeV. The limit is for a H^0 with SM production cross section and $B(H^0 \rightarrow f\bar{f})=0$ 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 $B(H \rightarrow \gamma\gamma) \cdot \sigma(e^+e^- \rightarrow Hf\bar{f})/\sigma(e^+e^- \rightarrow Hf\bar{f})$ (SM).
- 64 ABBIENDI 99E search for $e^+e^- \rightarrow H^0 A^0$ and $H^0 Z$ at $E_{\text{cm}}=183$ 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 $m_H\text{--}m_A$ plane. Updates the results of ACKERSTAFF 98S.
- 65 ABBIENDI 990 search for associated production of a $\gamma\gamma$ resonance with a $q\bar{q}, \nu\bar{\nu}$, or $\ell^+\ell^-$ pair in e^+e^- collisions at 189 GeV. The limit is for a H^0 with SM production cross section and $B(H^0 \rightarrow f\bar{f})=0$, for all fermions f . See their Fig. 4 for limits on $\sigma(e^+e^- \rightarrow H^0 Z^0) \times B(H^0 \rightarrow \gamma\gamma) \times B(X^0 \rightarrow f\bar{f})$ for various masses. Updates the results of ACKERSTAFF 98Y.
- 66 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 $\sigma(H^0 + Z/W) \cdot B(H^0 \rightarrow \gamma\gamma) = 0.80\text{--}0.34$ pb are obtained in the mass range $m_{H^0} = 65\text{--}150$ GeV.
- 67 ABREU 99P search for $e^+e^- \rightarrow H^0\gamma$ with $H^0 \rightarrow b\bar{b}$ or $\gamma\gamma$, and $e^+e^- \rightarrow H^0 q\bar{q}$ with $H^0 \rightarrow \gamma\gamma$. See their Fig. 4 for limits on $\sigma \times B$. Explicit limits within an effective interaction framework are also given.
- 68 GONZALEZ-GARCIA 98B use $D\bar{D}$ limit for $\gamma\gamma$ events with missing E_T in $p\bar{p}$ collisions (ABBOTT 98) to constrain possible ZH or WH production followed by unconventional $H \rightarrow \gamma\gamma$ decay which is induced by higher-dimensional operators. See their Figs. 1 and 2 for limits on the anomalous couplings.
- 69 KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no $H_1^0 ZZ$ coupling and obtain $m_{H_1^0} \gtrsim$

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

⁷⁰ ALEXANDER 96H give $B(Z \rightarrow H^0 \gamma) \times B(H^0 \rightarrow q\bar{q}) < 1-4 \times 10^{-5}$ (95%CL) and $B(Z \rightarrow H^0 \gamma) \times B(H^0 \rightarrow b\bar{b}) < 0.7-2 \times 10^{-5}$ (95%CL) in the range $20 < m_{H^0} < 80$ GeV.

⁷¹ 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.

⁷² 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 π^\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 $B(H^+ \rightarrow \tau^+ \nu) + B(H^+ \rightarrow c\bar{s}) = 1$, and hold for all values of $B(H^+ \rightarrow \tau^+ \nu_\tau)$, and assume H^+ weak isospin of $T_3 = +1/2$. In the following, $\tan\beta$ 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 $m_{H^\pm} \lesssim 45$ 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 previous Edition (The European Physical Journal **C15** 1 (2000)) 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.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 74.4	95	ABDALLAH	04I DLPH	$E_{\text{cm}} \leq 209$ GeV
> 76.5	95	ACHARD	03E L3	$E_{\text{cm}} \leq 209$ GeV
> 79.3	95	HEISTER	02P ALEP	$E_{\text{cm}} \leq 209$ GeV
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		⁷³ ABULENCIA	06E CDF	$t \rightarrow bH^+$
> 92.0	95	ABBIENDI	04 OPAL	$B(\tau\nu) = 1$
> 76.7	95	⁷⁴ ABDALLAH	04I DLPH	Type I
		⁷⁵ ABBIENDI	03 OPAL	$\tau \rightarrow \mu\bar{\nu}\nu, e\bar{\nu}\nu$
		⁷⁶ ABAZOV	02B D0	$t \rightarrow bH^+, H \rightarrow \tau\nu$
		⁷⁷ BORZUMATI	02 RVUE	
		⁷⁸ ABBIENDI	01Q OPAL	$B \rightarrow \tau\nu_\tau X$
		⁷⁹ BARATE	01E ALEP	$B \rightarrow \tau\nu_\tau$
>315	99	⁸⁰ GAMBINO	01 RVUE	$b \rightarrow s\gamma$
		⁸¹ AFFOLDER	00I CDF	$t \rightarrow bH^+, H \rightarrow \tau\nu$
> 59.5	95	ABBIENDI	99E OPAL	$E_{\text{cm}} \leq 183$ GeV

		82	ABBOTT	99E	D0	$t \rightarrow bH^+$
		83	ACKERSTAFF	99D	OPAL	$\tau \rightarrow e\nu\nu, \mu\nu\nu$
		84	ACCIARRI	97F	L3	$B \rightarrow \tau\nu_\tau$
		85	AMMAR	97B	CLEO	$\tau \rightarrow \mu\nu\nu$
		86	COARASA	97	RVUE	$B \rightarrow \tau\nu_\tau X$
		87	GUCHAIT	97	RVUE	$t \rightarrow bH^+, H \rightarrow \tau\nu$
		88	MANGANO	97	RVUE	$B_{u(c)} \rightarrow \tau\nu_\tau$
		89	STAHL	97	RVUE	$\tau \rightarrow \mu\nu\nu$
>244	95	90	ALAM	95	CLE2	$b \rightarrow s\gamma$
		91	BUSKULIC	95	ALEP	$b \rightarrow \tau\nu_\tau X$

- 73 ABULENCIA 06E search for associated $H^0 W$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96$ TeV. A fit is made for $t\bar{t}$ production processes in dilepton, lepton + jets, and lepton + τ final states, with the decays $t \rightarrow W^+ b$ and $t \rightarrow H^+ b$ followed by $H^+ \rightarrow \tau^+ \nu$, $c\bar{s}$, $t^* \bar{b}$, or $W^+ H^0$. Within the MSSM the search is sensitive to the region $\tan\beta < 1$ or > 30 in the mass range $m_{H^+} = 80\text{--}160$ GeV. See Fig. 2 for the excluded region in a certain MSSM scenario.
- 74 ABDALLAH 04I search for $e^+ e^- \rightarrow H^+ H^-$ with H^\pm decaying to $\tau\nu$, cs , or $W^* A^0$ in Type-I two-Higgs-doublet models.
- 75 ABBIENDI 03 give a limit $m_{H^+} > 1.28 \tan\beta$ GeV (95%CL) in Type II two-doublet models.
- 76 ABAZOV 02B search for a charged Higgs boson in top decays with $H^+ \rightarrow \tau^+ \nu$ at $E_{\text{cm}}=1.8$ TeV. For $m_{H^+}=75$ GeV, the region $\tan\beta > 32.0$ is excluded at 95%CL. The excluded mass region extends to over 140 GeV for $\tan\beta$ values above 100.
- 77 BORZUMATI 02 point out that the decay modes such as $b\bar{b}W$, $A^0 W$, and supersymmetric ones can have substantial branching fractions in the mass range explored at LEP II and Tevatron.
- 78 ABBIENDI 01Q give a limit $\tan\beta/m_{H^+} < 0.53 \text{ GeV}^{-1}$ (95%CL) in Type II two-doublet models.
- 79 BARATE 01E give a limit $\tan\beta/m_{H^+} < 0.40 \text{ GeV}^{-1}$ (90% CL) in Type II two-doublet models. An independent measurement of $B \rightarrow \tau\nu_\tau X$ gives $\tan\beta/m_{H^+} < 0.49 \text{ GeV}^{-1}$ (90% CL).
- 80 GAMBINO 01 use the world average data in the summer of 2001 $B(b \rightarrow s\gamma) = (3.23 \pm 0.42) \times 10^{-4}$. The limit applies for Type-II two-doublet models.
- 81 AFFOLDER 00I search for a charged Higgs boson in top decays with $H^+ \rightarrow \tau^+ \nu$ in $p\bar{p}$ collisions at $E_{\text{cm}}=1.8$ TeV. The excluded mass region extends to over 120 GeV for $\tan\beta$ 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.
- 82 ABBOTT 99E search for a charged Higgs boson in top decays in $p\bar{p}$ collisions at $E_{\text{cm}}=1.8$ TeV, by comparing the observed $t\bar{t}$ 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 $\tan\beta \lesssim 1$, $50 < m_{H^+}(\text{GeV}) \lesssim 120$ and $\tan\beta \gtrsim 40$, $50 < m_{H^+}(\text{GeV}) \lesssim 160$. See Fig. 3 for the details of the excluded region.
- 83 ACKERSTAFF 99D measure the Michel parameters ρ , ξ , η , and $\xi\delta$ in leptonic τ decays from $Z \rightarrow \tau\tau$. Assuming $e\text{-}\mu$ universality, the limit $m_{H^+} > 0.97 \tan\beta$ GeV (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.
- 84 ACCIARRI 97F give a limit $m_{H^+} > 2.6 \tan\beta$ GeV (90% CL) from their limit on the exclusive $B \rightarrow \tau\nu_\tau$ branching ratio.
- 85 AMMAR 97B measure the Michel parameter ρ from $\tau \rightarrow e\nu\nu$ decays and assumes 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 $m_{H^+} > 0.97 \tan\beta$ GeV (90% CL).

- ⁸⁶ COARASA 97 reanalyzed the constraint on the $(m_{H^{\pm}}, \tan\beta)$ 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.
- ⁸⁷ GUCHAIT 97 studies the constraints on m_{H^+} set by Tevatron data on $\ell\tau$ final states in $t\bar{t} \rightarrow (Wb)(Hb)$, $W \rightarrow \ell\nu$, $H \rightarrow \tau\nu_{\tau}$. See Fig. 2 for the excluded region.
- ⁸⁸ 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.
- ⁸⁹ STAHL 97 fit τ lifetime, leptonic branching ratios, and the Michel parameters and derive limit $m_{H^+} > 1.5 \tan\beta$ GeV (90% CL) for a two-doublet model. See also STAHL 94.
- ⁹⁰ 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.
- ⁹¹ BUSKULIC 95 give a limit $m_{H^+} > 1.9 \tan\beta$ 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) ————

This section covers searches for a doubly-charged Higgs boson with couplings to lepton pairs. Its weak isospin T_3 is thus restricted to two possibilities depending on lepton chiralities: $T_3(H^{\pm\pm}) = \pm 1$, with the coupling $g_{\ell\ell}$ to $\ell_L^- \ell_L'^-$ and $\ell_R^+ \ell_R'^+$ (“left-handed”) and $T_3(H^{\pm\pm}) = 0$, with the coupling to $\ell_R^- \ell_R'^-$ and $\ell_L^+ \ell_L'^+$ (“right-handed”). These Higgs bosons appear in some left-right symmetric models based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$. These two cases are listed separately in the following. Unless noted, one of the lepton flavor combinations is assumed to be dominant in the decay.

LIMITS for $H^{\pm\pm}$ with $T_3 = \pm 1$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
>118.4	95	92 ABAZOV	04E D0	$\mu\mu$
>136	95	93 ACOSTA	04G CDF	$\mu\mu$
> 98.1	95	94 ABDALLAH	03 DLPH	$\tau\tau$
> 99.0	95	95 ABBIENDI	02C OPAL	$\tau\tau$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		96 AKTAS	06A H1	single $H^{\pm\pm}$
>133	95	97 ACOSTA	05L CDF	stable
		98 ABBIENDI	03Q OPAL	$E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$
		99 GORDEEV	97 SPEC	muonium conversion
		100 ASAKA	95 THEO	
> 45.6	95	101 ACTON	92M OPAL	
> 30.4	95	102 ACTON	92M OPAL	
none 6.5–36.6	95	103 SWARTZ	90 MRK2	

- ⁹² ABAZOV 04E search for $H^{++} H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm} \mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.
- ⁹³ ACOSTA 04G search for $H^{++} H^{--}$ pair production in $p\bar{p}$ collisions with muon and electron final states. The limit holds for $\mu\mu$. For ee and $e\mu$ modes, the limits are 133 and 115 GeV, respectively. The limits are valid for $g_{\ell\ell'} \gtrsim 10^{-5}$.
- ⁹⁴ ABDALLAH 03 search for $H^{++} H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+ \tau^+$, or decaying outside the detector.

- 95 ABBIENDI 02C searches for pair production of $H^{++}H^{--}$, with $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ ($\ell, \ell' = e, \mu, \tau$). The limit holds for $\ell = \ell' = \tau$, and becomes stronger for other combinations of leptonic final states. To ensure the decay within the detector, the limit only applies for $g(H\ell\ell) \gtrsim 10^{-7}$.
- 96 AKTAS 06A search for single $H^{\pm\pm}$ production in ep collisions at HERA. Assuming that H^{++} only couples to $e^+\mu^+$ with $g_{e\mu} = 0.3$ (electromagnetic strength), a limit $m_{H^{++}} > 141$ GeV (95% CL) is derived. For the case where H^{++} couples to $e\tau$ only the limit is 112 GeV.
- 97 ACOSTA 05L search for $H^{++}H^{--}$ pair production in $p\bar{p}$ collisions. The limit is valid for $g_{\ell\ell} < 10^{-8}$ so that the Higgs decays outside the detector.
- 98 ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^+e^- \rightarrow e^{\mp}e^{\mp}H^{\pm\pm}$, and via t -channel exchange in $e^+e^- \rightarrow e^+e^-$. In the direct case, and assuming $B(H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}) = 1$, a 95% CL limit on $h_{ee} < 0.071$ is set for $m_{H^{\pm\pm}} < 160$ GeV (see Fig. 6). In the second case, indirect limits on h_{ee} are set for $m_{H^{\pm\pm}} < 2$ TeV (see Fig. 8).
- 99 GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\bar{M}}/G_F < 0.14$ (90% CL), where $G_{M\bar{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}} > 210$ GeV if the Yukawa couplings 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.
- 100 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.
- 101 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.
- 102 ACTON 92M from $\Delta\Gamma_Z < 40$ MeV.
- 103 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.

LIMITS for $H^{\pm\pm}$ with $T_3 = 0$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
> 98.2	95	104 ABAZOV	04E D0	$\mu\mu$
>113	95	105 ACOSTA	04G CDF	$\mu\mu$
> 97.3	95	106 ABDALLAH	03 DLPH	$\tau\tau$
> 97.3	95	107 ACHARD	03F L3	$\tau\tau$
> 98.5	95	108 ABBIENDI	02C OPAL	$\tau\tau$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		109 AKTAS	06A H1	single $H^{\pm\pm}$
>109	95	110 ACOSTA	05L CDF	stable
		111 ABBIENDI	03Q OPAL	$E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$
		112 GORDEEV	97 SPEC	muonium conversion
> 45.6	95	113 ACTON	92M OPAL	
> 25.5	95	114 ACTON	92M OPAL	
none 7.3–34.3	95	115 SWARTZ	90 MRK2	

- 104 ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.
- 105 ACOSTA 04G search for $H^{++}H^{--}$ pair production in $p\bar{p}$ collisions with muon and electron final states. The limit holds for $\mu\mu$.
- 106 ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+\tau^+$, or decaying outside the detector.
- 107 ACHARD 03F search for $e^+e^- \rightarrow H^{++}H^{--}$ with $H^{\pm\pm} \rightarrow \ell^{\pm}\ell'^{\pm}$. The limit holds for $\ell = \ell' = \tau$, and slightly different limits apply for other flavor combinations. The limit is valid for $g_{\ell\ell'} \gtrsim 10^{-7}$.
- 108 ABBIENDI 02C searches for pair production of $H^{++}H^{--}$, with $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ ($\ell, \ell' = e, \mu, \tau$). the limit holds for $\ell = \ell' = \tau$, and becomes stronger for other combinations of leptonic final states. To ensure the decay within the detector, the limit only applies for $g(H\ell\ell) \gtrsim 10^{-7}$.
- 109 AKTAS 06A search for single $H^{\pm\pm}$ production in ep collisions at HERA. Assuming that H^{++} only couples to $e^+\mu^+$ with $g_{e\mu} = 0.3$ (electromagnetic strength), a limit $m_{H^{++}} > 141$ GeV (95% CL) is derived. For the case where H^{++} couples to $e\tau$ only the limit is 112 GeV.
- 110 ACOSTA 05L search for $H^{++}H^{--}$ pair production in $p\bar{p}$ collisions. The limit is valid for $g_{\ell\ell'} < 10^{-8}$ so that the Higgs decays outside the detector.
- 111 ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^+e^- \rightarrow e^{\mp}e^{\mp}H^{\pm\pm}$, and via t -channel exchange in $e^+e^- \rightarrow e^+e^-$. In the direct case, and assuming $B(H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}) = 1$, a 95% CL limit on $h_{ee} < 0.071$ is set for $m_{H^{\pm\pm}} < 160$ GeV (see Fig. 6). In the second case, indirect limits on h_{ee} are set for $m_{H^{\pm\pm}} < 2$ TeV (see Fig. 8).
- 112 GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\bar{M}}/G_F < 0.14$ (90% CL), where $G_{M\bar{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}} > 210$ GeV if the Yukawa couplings 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.
- 113 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.
- 114 ACTON 92M from $\Delta\Gamma_Z < 40$ MeV.
- 115 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.

H^0 and H^{\pm} REFERENCES

ABAZOV	07X	PL B655 209	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABBIENDI	07	EPJ C49 457	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
SCHAEF	07	EPJ C49 439	S. Schael <i>et al.</i>	(ALEPH Collab.)
ABAZOV	06	PRL 96 011801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	06J	PRL 97 121802	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	06O	PRL 97 151804	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	06Q	PRL 97 161803	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABULENCIA	06	PRL 96 011802	A. Abulencia <i>et al.</i>	(CDF Collab.)
ABULENCIA	06E	PRL 96 042003	A. Abulencia <i>et al.</i>	(CDF Collab.)
ABULENCIA	06H	PRL 96 081803	A. Abulencia <i>et al.</i>	(CDF Collab.)
ABULENCIA,A	06A	PRL 97 081802	A. Abulencia <i>et al.</i>	(CDF Collab.)
AKTAS	06A	PL B638 432	A. Aktas <i>et al.</i>	(H1 Collab.)
LEP-SLC	06	PRPL 427 257	ALEPH, DELPHI, L3, OPAL, SLD and working groups	
SCHAEF	06B	EPJ C47 547	S. Schael <i>et al.</i>	(LEP Collabs.)
ABAZOV	05F	PRL 94 091802	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	05T	PRL 95 151801	V.M. Abazov <i>et al.</i>	(D0 Collab.)

ABBIENDI	05A	EPJ C40 317	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABDALLAH	05D	EPJ C44 147	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ACHARD	05	PL B609 35	P. Achard <i>et al.</i>	(L3 Collab.)
ACOSTA	05K	PRL 95 051801	D. Acosta <i>et al.</i>	(CDF Collab.)
ACOSTA	05L	PRL 95 071801	D. Acosta <i>et al.</i>	(CDF Collab.)
ACOSTA	05Q	PR D72 072004	D. Acosta <i>et al.</i>	(CDF Collab.)
ABAZOV	04E	PRL 93 141801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABBIENDI	04	EPJ C32 453	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	04K	PL B597 11	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	04M	EPJ C37 49	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABDALLAH	04	EPJ C32 145	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ABDALLAH	04B	EPJ C32 475	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ABDALLAH	04I	EPJ C34 399	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ABDALLAH	04L	EPJ C35 313	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ABDALLAH	04O	EPJ C38 1	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ACHARD	04B	PL B583 14	P. Achard <i>et al.</i>	(L3 Collab.)
ACHARD	04F	PL B589 89	P. Achard <i>et al.</i>	(L3 Collab.)
ACOSTA	04G	PRL 93 221802	D. Acosta <i>et al.</i>	(CDF Collab.)
ABBIENDI	03	PL B551 35	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	03B	EPJ C26 479	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	03F	EPJ C27 311	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	03G	EPJ C27 483	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	03Q	PL B577 93	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABDALLAH	03	PL B552 127	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ACHARD	03C	PL B568 191	P. Achard <i>et al.</i>	(L3 Collab.)
ACHARD	03E	PL B575 208	P. Achard <i>et al.</i>	(L3 Collab.)
ACHARD	03F	PL B576 18	P. Achard <i>et al.</i>	(L3 Collab.)
CARENA	03	EPJ C26 601	M.S. Carena <i>et al.</i>	
HEISTER	03D	PL B565 61	A. Heister <i>et al.</i>	(ALEPH, DELPHI, L3+)
ALEPH, DELPHI, L3, OPAL, LEP Higgs Working Group				
ABAZOV	02B	PRL 88 151803	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABBIENDI	02C	PL B526 221	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	02D	EPJ C23 397	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	02F	PL B544 44	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ACHARD	02C	PL B534 28	P. Achard <i>et al.</i>	(L3 Collab.)
ACHARD	02H	PL B545 30	P. Achard <i>et al.</i>	(L3 Collab.)
AKERROYD	02	PR D66 037702	A.G. Akeroyd <i>et al.</i>	
BORZUMATI	02	PL B549 170	F.M. Borzumati, A. Djouadi	
HEISTER	02	PL B526 191	A. Heister <i>et al.</i>	(ALEPH Collab.)
HEISTER	02L	PL B544 16	A. Heister <i>et al.</i>	(ALEPH Collab.)
HEISTER	02M	PL B544 25	A. Heister <i>et al.</i>	(ALEPH Collab.)
HEISTER	02P	PL B543 1	A. Heister <i>et al.</i>	(ALEPH Collab.)
ABBIENDI	01E	EPJ C18 425	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	01Q	PL B520 1	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABREU	01F	PL B507 89	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACHARD	01C	PL B517 319	P. Achard <i>et al.</i>	(L3 Collab.)
AFFOLDER	01D	PRL 86 4472	T. Affolder <i>et al.</i>	(CDF Collab.)
AFFOLDER	01H	PR D64 092002	T. Affolder <i>et al.</i>	(CDF Collab.)
BARATE	01C	PL B499 53	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	01E	EPJ C19 213	R. Barate <i>et al.</i>	(ALEPH Collab.)
GAMBINO	01	NP B611 338	P. Gambino, M. Misiak	
ACCIARRI	00M	PL B485 85	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACCIARRI	00R	PL B489 102	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACCIARRI	00S	PL B489 115	M. Acciarri <i>et al.</i>	(L3 Collab.)
AFFOLDER	00I	PR D62 012004	T. Affolder <i>et al.</i>	(CDF Collab.)
BARATE	00L	PL B487 241	R. Barate <i>et al.</i>	(ALEPH Collab.)
PDG	00	EPJ C15 1	D.E. Groom <i>et al.</i>	
ABBIENDI	99E	EPJ C7 407	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	99O	PL B464 311	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	99B	PRL 82 2244	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	99E	PRL 82 4975	B. Abbott <i>et al.</i>	(D0 Collab.)
ABREU	99P	PL B458 431	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACKERSTAFF	99D	EPJ C8 3	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
CARENA	99B	hep-ph/9912223	M.S. Carena <i>et al.</i>	
CERN-TH/99-374				
ABBOTT	98	PRL 80 442	B. Abbott <i>et al.</i>	(D0 Collab.)
ABE	98T	PRL 81 5748	F. Abe <i>et al.</i>	(CDF Collab.)
ACKERSTAFF	98S	EPJ C5 19	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
ACKERSTAFF	98Y	PL B437 218	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
GONZALEZ-G...	98B	PR D57 7045	M.C. Gonzalez-Garcia, S.M. Lietti, S.F. Novaes	
PDG	98	EPJ C3 1	C. Caso <i>et al.</i>	

ABE	97L	PRL 79 357	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97W	PRL 79 3819	F. Abe <i>et al.</i>	(CDF Collab.)
ACCIARRI	97F	PL B396 327	M. Acciarri <i>et al.</i>	(L3 Collab.)
AMMAR	97B	PRL 78 4686	R. Ammar <i>et al.</i>	(CLEO Collab.)
COARASA	97	PL B406 337	J.A. Coarasa, R.A. Jimenez, J. Sola	
GORDEEV	97	PAN 60 1164	V.A. Gordeev <i>et al.</i>	(PNPI)
		Translated from YAF 60 1291.		
GUCHAIT	97	PR D55 7263	M. Guchait, D.P. Roy	(TATA)
KRAWCZYK	97	PR D55 6968	M. Krawczyk, J. Zochowski	(WARS)
MANGANO	97	PL B410 299	M. Mangano, S. Slabospitsky	
STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ALEXANDER	96H	ZPHY C71 1	G. Alexander <i>et al.</i>	(OPAL Collab.)
PDG	96	PR D54 1	R. M. Barnett <i>et al.</i>	
ABREU	95H	ZPHY C67 69	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ALAM	95	PRL 74 2885	M.S. Alam <i>et al.</i>	(CLEO Collab.)
ASAKA	95	PL B345 36	T. Asaka, K.I. Hikasa	(TOHOK)
BUSKULIC	95	PL B343 444	D. Buskulic <i>et al.</i>	(ALEPH Collab.)
GROSSMAN	95B	PL B357 630	Y. Grossman, H. Haber, Y. Nir	
GROSSMAN	94	PL B332 373	Y. Grossman, Z. Ligeti	
STAHL	94	PL B324 121	A. Stahl	(BONN)
ACTON	92M	PL B295 347	P.D. Acton <i>et al.</i>	(OPAL Collab.)
PICH	92	NP B388 31	A. Pich, J. Prades, P. Yepes	(CERN, CPPM)
SWARTZ	90	PRL 64 2877	M.L. Swartz <i>et al.</i>	(Mark II Collab.)
