

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from e^+e^- collisions at LEP at energies up to 202 GeV, and weaker limits obtained from other sources, have been superseded by the most recent data of LEP.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	01E D0	$p\bar{p} \rightarrow H^0 WX, H^0 ZX$
⁵ ABE	98T CDF	$p\bar{p} \rightarrow H^0 WX, H^0 ZX$

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 01E search for associated $H^0 W$ and $H^0 Z$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.8$ TeV. The limits of $\sigma(H^0 W) \times B(W \rightarrow e\nu) \times B(H^0 \rightarrow q\bar{q}) < 2.0$ pb (95%CL) and $\sigma(H^0 Z) \times B(Z \rightarrow e^+e^-) \times B(H^0 \rightarrow q\bar{q}) < 0.8$ pb (95%CL) are given for $m_H = 115$ GeV.

⁵ 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 $\sigma(H^0 + W/Z) \cdot B(H^0 \rightarrow b\bar{b}) < (23-17)$ 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."

Because of the high current interest, we mention here the following unpublished result (LEP 04,) although we do not include it in the Listings or Tables: $m_H = 114^{+69}_{-45}$ GeV. This is obtained from a fit to LEP, SLD, W mass, top mass, and neutrino scattering data available in the Summer of 2004, with $\Delta\alpha_{\text{had}}^{(5)}(m_Z) = 0.0276 \pm 0.0036$. The 95%CL limit is 260 GeV.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		⁶ CHANOWITZ 02	RVUE	
390^{+750}_{-280}		⁷ ABBIENDI 01A	OPAL	
		⁸ CHANOWITZ 99	RVUE	
<290	95	⁹ D'AGOSTINI 99	RVUE	
<211	95	¹⁰ FIELD 99	RVUE	
		¹¹ CHANOWITZ 98	RVUE	
170^{+150}_{-90}		¹² HAGIWARA 98B	RVUE	
141^{+140}_{-77}		¹³ DEBOER 97B	RVUE	
127^{+143}_{-71}		¹⁴ DEGRASSI 97	RVUE	$\sin^2\theta_W(\text{eff,lept})$
158^{+148}_{-84}		¹⁵ DITTMAIER 97	RVUE	
149^{+148}_{-82}		¹⁶ RENTON 97	RVUE	
145^{+164}_{-77}		¹⁷ ELLIS 96C	RVUE	
185^{+251}_{-134}		¹⁸ GURTU 96	RVUE	

⁶ CHANOWITZ 02 studies the impact for the prediction of the Higgs mass of two 3σ anomalies in the SM fits to electroweak data. It argues that the Higgs mass limit should not be trusted whether the anomalies originate from new physics or from systematic effects.

⁷ ABBIENDI 01A make Standard Model fits to OPAL's measurements of Z -lineshape parameters and lepton forward-backward asymmetries, using $m_t = 174.3 \pm 5.1$ GeV and $1/\alpha(m_Z) = 128.90 \pm 0.09$. The fit also yields $\alpha_s(m_Z) = 0.127 \pm 0.005$. If the external value of $\alpha_s(m_Z) = 0.1184 \pm 0.0031$ is added to the fit, the result changes to $m_{H0} = 190^{+335}_{-165}$ GeV.

⁸ CHANOWITZ 99 studies LEP/SLD data on 9 observables related $\sin^2\theta_{\text{eff}}^{\ell}$, 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.

⁹ 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 $E_{\text{cm}} = 183$ GeV. $\alpha(m_Z)$ given by DAVIER 98.

¹⁰ FIELD 99 studies the data on b asymmetries from $Z^0 \rightarrow b\bar{b}$ 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.

- ¹¹ CHANOWITZ 98 fits LEP and SLD Z-decay-asymmetry data (as reported in ABBA-NEO 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.
- ¹² 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.
- ¹³ 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.
- ¹⁴ DEGRASSI 97 is a two-loop calculation of M_W and $\sin^2\theta_{\text{eff}}^{\text{lept}}$ as a function of m_H , using $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23165(24)$ as reported in ALCARAZ 96, $m_t = 175 \pm 6$ GeV, and $1/\alpha(m_Z) = 128.90 \pm 0.09$.
- ¹⁵ DITTMAYER 97 fit to m_W and LEP/SLC data as reported in ALCARAZ 96, with $m_t = 175 \pm 6$ GeV, $1/\alpha(m_Z) = 128.89 \pm 0.09$. Exclusion of the SLD data gives $m_H = 261^{+224}_{-128}$ GeV. Taking only the data on m_t , m_W , $\sin^2\theta_{\text{eff}}^{\text{lept}}$, and Γ_Z^{lept} , 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).
- ¹⁶ RENTON 97 fit to LEP and SLD data (as reported in ALCARAZ 96), as well as m_W and m_t from $p\bar{p}$, and low-energy νN data available in early 1997. $1/\alpha(m_Z) = 128.90 \pm 0.09$ is used.
- ¹⁷ 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.
- ¹⁸ 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 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 Supersymmetry 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 minireview on Supersymmetry, in this volume, these relations depend on the masses of the t quark and \tilde{t} squark. The limits are weaker for larger t and \tilde{t} masses, while they increase with the inclusion of two-loop radiative corrections. 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, and examine the two scenarios of no scalar top mixing and 'maximal' stop mixing (which maximizes the effect of the radiative correction).

The mass region $m_{H_1^0} \lesssim 45$ 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 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
> 84.5	95	19,20 ABBIENDI	04M OPAL	$E_{\text{cm}} \leq 209$ GeV
> 89.7	95	19,21 ABDALLAH	04 DLPH	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.4$
> 86.0	95	19,22 ACHARD	02H L3	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.4$
> 89.8	95	19,23 HEISTER	02 ALEP	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.5$
>100	95	24 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. • • •

25 ABBIENDI 03G OPAL $H_1^0 \rightarrow A^0 A^0$

¹⁹ 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 so-called "m_h-max scenario" (CARENA 99B).

²⁰ 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.

²¹ 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.

²² 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.

²³ HEISTER 02 excludes the range $0.7 < \tan\beta < 2.3$. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

²⁴ 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.

²⁵ ABBIENDI 03G search for $e^+e^- \rightarrow H_1^0 Z$ followed by $H_1^0 \rightarrow A^0 A^0$, $A^0 \rightarrow c\bar{c}$, $g g$, or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H_1^0} = 45$ -85 GeV and $m_{A^0} = 2$ -9.5 GeV is excluded at 95% CL.

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

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 85.0	95	26,27 ABBIENDI	04M OPAL	$E_{\text{cm}} \leq 209$ GeV
> 90.4	95	26,28 ABDALLAH	04 DLPH	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.4$
> 86.5	95	26,29 ACHARD	02H L3	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.4$
> 90.1	95	26,30 HEISTER	02 ALEP	$E_{\text{cm}} \leq 209$ GeV, $\tan\beta > 0.5$
>100	95	31 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. • • •

32 ABBIENDI	03G OPAL	$H_1^0 \rightarrow A^0 A^0$
33 AKEROYD	02 RVUE	

²⁶ 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 so-called “ m_h -max scenario” (CARENA 99B).

²⁷ 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.

²⁸ 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.

²⁹ 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.

³⁰ HEISTER 02 excludes the range $0.7 < \tan\beta < 2.3$. A wider range is excluded with different stop mixing assumptions. Updates BARATE 01C.

³¹ 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.

³² ABBIENDI 03G search for $e^+e^- \rightarrow H_1^0 Z$ followed by $H_1^0 \rightarrow A^0 A^0$, $A^0 \rightarrow c\bar{c}$, $g g$, or $\tau^+\tau^-$. In the no-mixing scenario, the region $m_{H_1^0} = 45$ -85 GeV and $m_{A^0} = 2$ -9.5 GeV is excluded at 95% CL.

³³ 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
>104	95	34 ABBIENDI	04K OPAL	$H^0 \rightarrow 2$ jets
		35 ABDALLAH	04 DLPH	$H^0 V V$ couplings
>112.1	95	36 ABDALLAH	04B DLPH	Invisible H^0
>104.1	95	37,38 ABDALLAH	04L DLPH	$e^+e^- \rightarrow H^0 Z$, $H^0 \rightarrow \gamma\gamma$
		39 ABDALLAH	04O DLPH	$Z \rightarrow f\bar{f}H$

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

³⁴ ABBIENDI 04K search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying to two jets of any flavor including $g g$. The limit is for SM production cross section with $B(H^0 \rightarrow jj) = 1$.

³⁵ 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.

³⁶ Search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying invisibly. The limit assumes SM production cross section and $B(H^0 \rightarrow \text{invisible}) = 1$.

³⁷ 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 $E_{\text{cm}} \leq 209 \text{ GeV}$. 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 .

³⁸ Updates ABREU 01F.

³⁹ 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.

⁴⁰ 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 $E_{\text{cm}} = 189\text{--}208 \text{ GeV}$. See paper for limits on couplings.

⁴¹ ACHARD 04B search for $e^+e^- \rightarrow H^0 Z$ with H^0 decaying to $b\bar{b}, c\bar{c}$, or $g g$. The limit is for SM production cross section with $B(H^0 \rightarrow jj) = 1$.

- 42 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^0Z 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.
- 43 ABBIENDI 03F search for $H^0 \rightarrow$ anything in $e^+e^- \rightarrow H^0Z$, 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.
- 44 ABBIENDI 03G search for $e^+e^- \rightarrow H_1^0Z$ followed by $H_1^0 \rightarrow A^0A^0$, $A^0 \rightarrow c\bar{c}$, 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.
- 45 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.
- 46 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.
- 47 For $B(H^0 \rightarrow \gamma\gamma) = 1$, $m_{H^0} > 117$ GeV is obtained.
- 48 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.
- 49 For $B(H^0 \rightarrow \gamma\gamma) = 1$, $m_{H^0} > 113.1$ GeV is obtained.
- 50 HEISTER 02M search for $e^+e^- \rightarrow H^0Z$, assuming that H^0 decays to $q\bar{q}$, gg , or $\tau^+\tau^-$ only. The limit assumes SM production cross section.
- 51 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.
- 52 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 $B(H^0 \rightarrow \gamma\gamma) < 1$.
- 53 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.
- 54 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.
- 55 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.
- 56 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).
- 57 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).
- 58 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 $m_H - m_A$ plane. Updates the results of ACKERSTAFF 98S.
- 59 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.
- 60 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 $\sigma(H^0 + Z/W) \cdot B(H^0 \rightarrow \gamma\gamma) = 0.80-0.34$ pb are obtained in the mass range $m_{H^0} = 65-150$ GeV.
- 61 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.
- 62 GONZALEZ-GARCIA 98B use $D\bar{O}$ 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.
- 63 KRAWCZYK 97 analyse the muon anomalous magnetic moment in a two-doublet Higgs model (with type II Yukawa couplings) assuming no $H_1^0 Z Z$ 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.
- 64 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.
- 65 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.
- 66 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.

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
> 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. ● ● ●				
> 92.0	95	ABBIENDI	04 OPAL	$B(\tau\nu) = 1$
> 76.7	95	67 ABDALLAH	04I DLPH	Type I
		68 ABBIENDI	03 OPAL	$\tau \rightarrow \mu\bar{\nu}\nu, e\bar{\nu}\nu$
		69 ABAZOV	02B D0	$t \rightarrow bH^+, H \rightarrow \tau\nu$
		70 BORZUMATI	02 RVUE	
		71 ABBIENDI	01Q OPAL	$B \rightarrow \tau\nu_\tau X$
		72 BARATE	01E ALEP	$B \rightarrow \tau\nu_\tau$
>315	99	73 GAMBINO	01 RVUE	$b \rightarrow s\gamma$
		74 AFFOLDER	00I CDF	$t \rightarrow bH^+, H \rightarrow \tau\nu$
> 59.5	95	ABBIENDI	99E OPAL	$E_{\text{cm}} \leq 183$ GeV
		75 ABBOTT	99E D0	$t \rightarrow bH^+$
		76 ACKERSTAFF	99D OPAL	$\tau \rightarrow e\nu\nu, \mu\nu\nu$
		77 ACCIARRI	97F L3	$B \rightarrow \tau\nu_\tau$
		78 AMMAR	97B CLEO	$\tau \rightarrow \mu\nu\nu$
		79 COARASA	97 RVUE	$B \rightarrow \tau\nu_\tau X$
		80 GUCHAIT	97 RVUE	$t \rightarrow bH^+, H \rightarrow \tau\nu$
		81 MANGANO	97 RVUE	$B_{u(c)} \rightarrow \tau\nu_\tau$
		82 STAHL	97 RVUE	$\tau \rightarrow \mu\nu\nu$
>244	95	83 ALAM	95 CLE2	$b \rightarrow s\gamma$
		84 BUSKULIC	95 ALEP	$b \rightarrow \tau\nu_\tau X$

67 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.

68 ABBIENDI 03 give a limit $m_{H^+} > 1.28\tan\beta$ GeV (95%CL) in Type II two-doublet models.

69 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.

70 BORZUMATI 02 point out that the decay modes such as $b\bar{b}W, A^0W$, and supersymmetric ones can have substantial branching fractions in the mass range explored at LEP II and Tevatron.

71 ABBIENDI 01Q give a limit $\tan\beta/m_{H^+} < 0.53$ GeV⁻¹ (95%CL) in Type II two-doublet models.

72 BARATE 01E give a limit $\tan\beta/m_{H^+} < 0.40$ GeV⁻¹ (90%CL) in Type II two-doublet models. An independent measurement of $B \rightarrow \tau\nu_\tau X$ gives $\tan\beta/m_{H^+} < 0.49$ GeV⁻¹ (90%CL).

- ⁷³ 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.
- ⁷⁴ 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.
- ⁷⁵ 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.
- ⁷⁶ 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 $m_{H^+} > 0.97 \tan\beta$ GeV (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.
- ⁷⁷ 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.
- ⁷⁸ 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).
- ⁷⁹ 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.
- ⁸⁰ 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.
- ⁸¹ 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.
- ⁸² 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.
- ⁸³ 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.
- ⁸⁴ 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	85 ABAZOV	04E D0	$\mu\mu$

>136	95	86 ACOSTA	04G CDF	$\mu\mu$	
> 98.1	95	87 ABDALLAH	03 DLPH	$\tau\tau$	
> 99.0	95	88 ABBIENDI	02C OPAL	$\tau\tau$	
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●					
		89 ABBIENDI	03Q OPAL	$E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$	
		90 GORDEEV	97 SPEC	muonium conversion	
		91 ASAKA	95 THEO		
> 45.6	95	92 ACTON	92M OPAL		
> 30.4	95	93 ACTON	92M OPAL		
none 6.5–36.6	95	94 SWARTZ	90 MRK2		
85 ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.					
86 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 $g_{\ell\ell'} \gtrsim 10^{-5}$.					
87 ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+\tau^+$, or decaying outside the detector.					
88 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 $g(H\ell\ell) \gtrsim 10^{-7}$.					
89 ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^+e^- \rightarrow e^{\pm}e^{\pm}H^{\mp\mp}$, 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).					
90 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.					
91 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.					
92 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.					
93 ACTON 92M from $\Delta\Gamma_Z < 40$ MeV.					
94 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	95 ABAZOV	04E D0	$\mu\mu$
>113	95	96 ACOSTA	04G CDF	$\mu\mu$
> 97.3	95	97 ABDALLAH	03 DLPH	$\tau\tau$
> 97.3	95	98 ACHARD	03F L3	$\tau\tau$
> 98.5	95	99 ABBIENDI	02C OPAL	$\tau\tau$

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

- | | | | | | | |
|--------|----------|-----|----------|--------|------|---|
| | | 100 | ABBIENDI | 03Q | OPAL | $E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$ |
| | | 101 | GORDEEV | 97 | SPEC | muonium conversion |
| > 45.6 | 95 | 102 | ACTON | 92M | OPAL | |
| > 25.5 | 95 | 103 | ACTON | 92M | OPAL | |
| none | 7.3–34.3 | 95 | 104 | SWARTZ | 90 | MRK2 |
- 95 ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.
- 96 ACOSTA 04G search for $H^{++}H^{--}$ pair production in $p\bar{p}$ collisions with muon and electron final states. The limit holds for $\mu\mu$.
- 97 ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+\tau^+$, or decaying outside the detector.
- 98 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 $g_{\ell\ell'} \gtrsim 10^{-7}$.
- 99 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 $g(H\ell\ell) \gtrsim 10^{-7}$.
- 100 ABBIENDI 03Q searches for single $H^{\pm\pm}$ via direct production in $e^+e^- \rightarrow e^{\pm}e^{\pm}H^{\mp\mp}$, 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).
- 101 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.
- 102 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.
- 103 ACTON 92M from $\Delta\Gamma_Z < 40$ MeV.
- 104 SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (any flavor). The limits are valid for the Higgs-lepton coupling $g(H\ell\ell) \gtrsim 7.4 \times 10^{-7}/[m_{H^{\pm\pm}}/\text{GeV}]^{1/2}$. The limits improve somewhat for ee and $\mu\mu$ decay modes.

H^0 and H^{\pm} REFERENCES

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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.)
LEP	04	LEPEWWG/2004-01, CERN-PH-EP/2004-069		(LEP Collabs.)
ALEPH, DELPHI, L3, OPAL, the LEP EWWG, and the SLD HFEW				
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.)
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	
CHANOWITZ	02	PR D66 073002	M.S. Chanowitz	
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.)
ABAZOV	01E	PRL 87 231801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABBIENDI	01A	EPJ C19 587	G. Abbiendi <i>et al.</i>	(OPAL 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. Acciari <i>et al.</i>	(L3 Collab.)
ACCIARRI	00R	PL B489 102	M. Acciari <i>et al.</i>	(L3 Collab.)
ACCIARRI	00S	PL B489 115	M. Acciari <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.)
FIELD	00	PR D61 013010	J.H. Field	
LEP	00B	CERN-EP-2000-055	LEP Collabs.	
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. Carena <i>et al.</i>	
CERN-TH/99-374				
CHANOWITZ	99	PR D59 073005	M.S. Chanowitz	
D'AGOSTINI	99	EPJ C10 663	G. D'Agostini, G. Degrassi	
FIELD	99	MPL A14 1815	J.H. Field	
LEP	99	CERN-EP/99-015	LEP Collabs. (ALEPH, DELPHI, L3, OPAL, LEP EWWG+)	
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.)
CHANOWITZ	98	PRL 80 2521	M. Chanowitz	
DAVIER	98	PL B435 427	M. Davier, A. Hoecker	
GONZALEZ-G...	98B	PR D57 7045	M.C. Gonzalez-Garcia, S.M. Lietti, S.F. Novaes	
HAGIWARA	98B	EPJ C2 95	K. Hagiwara, D. Haidt, S. Matsumoto	
PDG	98	EPJ C3 1	C. Caso <i>et al.</i>	
ABBANELO	97	CERN-PPE/97-154	D. Abbaneo <i>et al.</i>	
ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, and the LEP Electroweak Working Group.				
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. Acciari <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	
DEBOER	97B	ZPHY C75 627	W. de Boer <i>et al.</i>	

DEGRASSI	97	PL B394 188	G. Degrassi, P. Gambino, A. Sirlin	(MPIM, NYU)
DITTMAYER	97	PL B391 420	S. Dittmaier, D. Schildknecht	(BIEL)
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	
RENTON	97	IJMP A12 4109	P.B. Renton	
STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ALCARAZ	96	CERN-PPE/96-183	J. Alcaraz <i>et al.</i>	
		The ALEPH, DELPHI, L3, OPAL, and SLD	Collaborations and the LEP Electroweak Working Group	
ALEXANDER	96H	ZPHY C71 1	G. Alexander <i>et al.</i>	(OPAL Collab.)
ELLIS	96C	PL B389 321	J. Ellis, G.L. Fogli, E. Lisi	(CERN, BARI)
GURTU	96	PL B385 415	A. Gurtu	(TATA)
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.)