[59] BELTRAMI 86 measured the wavelengths of the $3d_{5/2}$–$2p_{3/2}$ X-ray transitions in muonic ^{24}Mg and ^{28}Si and found the deviation from QED $\delta\lambda/\lambda = (-0.2 \pm 3.1)\times 10^{-6}$. The listed limit uses $\eta_{HNN} = 0.23$. The experiment excludes $m_{H^0} \lesssim 1$ MeV by more than 3 s.d.

[60] FREEDMAN 84 is ANL experiment with dynamitron proton bombarding tritium to form He*. $\eta_{HNN} = 0.30$ is used to derive the limit . They also reanalyze KOHLER 74 He* data to find no mass region is excluded by that data. See also footnote for MUKHOPADHYAY 84 below.

[61] MUKHOPADHYAY 84 examine KOHLER 74 He* and C* data. Claim that no mass region can be excluded by 74 He* data since He* decay width to proton is large [B(He* $\rightarrow$ H^0He) = 3.4×10^{-11} is very small]. Above limit is from KOHLER 74 O* decay data.

[62] HOFFMAN 83 looked for e^+e^- peak from Higgs produced in $\pi^- p \rightarrow H^0 n$ at 300 MeV/c. Set CL = 90% limit $d\sigma/dt$ B(e^+e^-) $< 3.5 \times 10^{-32}$ cm^2/GeV^2 for 140 $< m_{H^0} <$160 MeV, which does not exclude H^0 with the standard one-doublet-model couplings.

[63] BARBIERI 75 studied Higgs boson exchange effect in neutron-lead scattering data of ALEKSANDROV 66 and found limit $(g^2_{H^0 nn}/4\pi)\,(m_{H^0}/\text{MeV})^{-4} \lesssim 3.4 \times 10^{-11}$ for $m_{H^0} \gtrsim 1$ MeV. This gives the listed limit for $\eta_{HNN} = 0.2$ and 10 MeV for $\eta_{HNN} = 0.56$. Lighter mass region $m_{H^0} \lesssim 1$ MeV would be incompatible with the measured angular distribution.

From Other Techniques

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 0.001–0.072	95	[64] BARABASH	92	BDMP	$\eta' \rightarrow \eta H^0$
none 0.0012–0.052	90	DAVIER	89	BDMP	$e^- Z \rightarrow e H^0 Z$ ($H^0 \rightarrow e^+e^-$)
none 0.010–0.10	90	[65] EGLI	89	CNTR	$\pi^+ \rightarrow e^+ \nu H^0$ ($H^0 \rightarrow e^+e^-$)
		[66] LINDNER	89	THEO	Vacuum stability
none 0.015–0.04	90	[67] YEPES	89	RVUE	$\pi^{\pm} \rightarrow e^{\pm} \nu H^0$ ($H^0 \rightarrow e^+e^-$)
		[68] DZHELYADIN	81		$\eta' \rightarrow \eta H^0$ ($H^0 \rightarrow \mu^+\mu^-$)
		[69] WITTEN	81	COSM	
		[69] GUTH	80	COSM	
		[69] SHER	80	COSM	

[64] BARABASH 92 is a beam dump experiment that searched for $H^0 \rightarrow e^+e^-$ and $\gamma\gamma$ produced via the decays $\pi \rightarrow e\nu_e H^0$, $K \rightarrow e\nu_e H^0$, $K \rightarrow \pi H^0$, and $\eta' \rightarrow \eta H^0$. The last process gives the best limit if the theoretical calculation by RUSKOV 87 is used.

[65] EGLI 89 give a limit for B($\pi^+ \rightarrow e^+ \nu H^0$)·B($H^0 \rightarrow e^+e^-$) ranging from 10^{-9} to 10^{-11} for the mass range 10–110 MeV. The theoretical prediction they use is too large by a factor of 162/49 (see DAWSON 89, DAWSON 90, and CHENG 89). The lower limit given above is reevaluated by us.

[66] LINDNER 89 require vacuum stability and numerically solve the renormalization equations to two-loop order. If m_{top} = 100, 110, 120 GeV, then $m_{\text{Higgs}} >$ 20, 34, 50 GeV. However, it is possible that the vacuum is not stable but is very long-lived.

[67] YEPES 89 reanalyzed a BNL beam-dump experiment (JACQUES 80) which looked for electron pairs in 7 foot BC downstream from the dump and found none.

[68] DZHELYADIN 81 obtained B($\eta' \rightarrow \eta\mu^+\mu^-$) $< 1.5 \times 10^{-5}$ (CL = 90%), and argued that it excludes H^0 with the standard one-doublet-model couplings in $\mu^+\mu^-$ channel for m_{H^0} = 0.25–0.409 GeV. However, the number 0.409 is not well-determined due to theoretical uncertainties in B($H^0 \rightarrow \mu^+\mu^-$).

[69] Limits from cosmological considerations of SU(2)×U(1) symmetry-breaking phase transition occurring only after extreme supercooling, resulting in too high a ratio of entropy to baryon number. Limits apply to the standard one-doublet model H^0, with 'zero bare mass' whose physical mass is determined by the Coleman-Weinberg mechanism of dynamical symmetry breakdown. These limits depend on the mass of the top quark approximately according to $m_{H^0} > 10.4[1-4m_t{}^4/(2m_W^4+m_Z^4)]^{1/2}$ GeV when $m_t <$ 80 GeV. So for $m_t \approx$ 80 GeV, there is no limit. If $m_t >$ 80 GeV, then vacuum stability arguments may give bounds on m_H, see LINDNER 89 above.

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

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

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

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[70] BRAHMACH...	93	RVUE	
		[71] BUSKULIC	93I	ALEP	$Z \rightarrow H^0 Z^*$
>65	95	[72] BUSKULIC	93I	ALEP	Invisible H^0
		[73] LOPEZ-FERN...	93	RVUE	
		[74] ADRIANI	92G	L3	$Z \rightarrow H^0 Z^*$
		[75] PICH	92	RVUE	Very light Higgs
> 3.57	95	[76] ACTON	91	OPAL	$Z \rightarrow H^0 Z^*$
		[77] DECAMP	91F	ALEP	$Z \rightarrow H^0 \ell^+\ell^-$
		[78] DECAMP	91I	ALEP	Z decay
> 0.21	95	[79] AKRAWY	90P	OPAL	$Z \rightarrow H^0 Z^*$
		[80] DAVIER	89	BDMP	$e^- Z \rightarrow e H^0 Z$ ($H^0 \rightarrow e^+e^-$)
		[81] SNYDER	89	MRK2	$B \rightarrow H^0 X$ ($H^0 \rightarrow e^+e^-$)
none 0.6–6.2	90	[82] FRANZINI	87	CUSB	$\Upsilon(1S) \rightarrow \gamma H^0$, x=2
none 0.6–7.9	90	[82] FRANZINI	87	CUSB	$\Upsilon(1S) \rightarrow \gamma H^0$, x=4
none 3.7–5.6	90	[83] ALBRECHT	85J	ARG	$\Upsilon(1S) \rightarrow \gamma H^0$, x=2
none 3.7–8.2	90	[83] ALBRECHT	85J	ARG	$\Upsilon(1S) \rightarrow \gamma H^0$, x=4

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

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

[72] BUSKULIC 93I limit for H^0 with the standard coupling to Z but decaying to weakly interacting particles.

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

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

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

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

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

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

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

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

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

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

[83] ALBRECHT 85J found no mono-energetic photons in both $\Upsilon(1S)$ and $\Upsilon(2S)$ radiative decays in the range 0.5 GeV $< E(\gamma) <$4.0 GeV with typically BR< 0.01 for $\Upsilon(1S)$ and BR< 0.02 for $\Upsilon(2S)$ at 90% CL. These upper limits are 5–10 times the prediction of the standard Higgs-doublet model. The quoted 90% limit B($\Upsilon(1S) \rightarrow H^0\gamma$) $< 1.5 \times 10^{-3}$ at $E(\gamma)$ = 1.07 GeV contradicts previous Crystal Ball observation of $(4.7 \pm 1.1) \times 10^{-3}$; see their reference 3. Their figure 8a shows the upper limits of x^2 as a function of $E(\gamma)$ by assuming no QCD corrections. We used $m_{H^0} = m_\Upsilon\,(1-2E(\gamma)/m_\Upsilon)^{1/2}$.

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

The minimal supersymmetric model has two complex doublets of Higgs bosons. The resulting physical states are two scalars [H_1^0 and H_2^0, where we define $m_{H_1^0} < m_{H_2^0}$], a pseudoscalar (A^0), and a charged Higgs pair ($H^{\pm}$). 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 describe in the "Note on Supersymmetry," recent calculations of one-loop radiative corrections show that these relations may be violated. Many experimental analyses have not taken into account these corrections; footnotes indicate when these corrections are included. The results assume no invisible H^0 or A^0 decays.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>44	95	[84] BUSKULIC	93I	ALEP	$\tan\beta >1$
>29	95	[85] ABREU	92J	DLPH	any $\tan\beta$
>42	95	[86] ADRIANI	92G	L3	1<$\tan\beta$ <50
none 3–22	95	[87] AKRAWY	91C	OPAL	$\tan\beta >$ 0.5
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>34	95	[85] ABREU	92J	DLPH	$\tan\beta >$ 0.6
> 0.21	95	[88] ABREU	91B	DLPH	any $\tan\beta$
>28	95	[89] ABREU	91B	DLPH	any $\tan\beta$
none 3–38	95	[87] AKRAWY	91C	OPAL	$\tan\beta >$ 6
		[90] BLUEMLEIN	91	BDMP	$pN \rightarrow H_1^0$X ($H_1^0 \rightarrow e^+e^-$, 2γ)
>41	95	[91] DECAMP	91I	ALEP	$\tan\beta >$ 1
> 9	95	[92] ABREU	90E	DLPH	any $\tan\beta$
>13	95	[92] ABREU	90E	DLPH	$\tan\beta >$ 1