Charged Higgs Bosons (H^{\pm} and $H^{\pm\pm}$), Searches for

CONTENTS:

 H^{\pm} (Charged Higgs) Mass Limits Mass limits for $H^{\pm\pm}$ (doubly-charged Higgs boson) - Limits for $H^{\pm\pm}$ with $T_3 = \pm 1$

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

— H^{\pm} (Charged Higgs) MASS LIMITS —

Unless otherwise stated, the limits below assume $B(H^+ \rightarrow \tau^+ \nu) + B(H^+ \rightarrow c \overline{s}) = 1$, 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have conclusively ruled out the existence of a charged Higgs in the region $m_{H^+} \lesssim 45$ GeV, and are meanwhile superseded by the searches in higher energy e^+e^- collisions at LEP. Results that are by now obsolete are therefore not included in this compilation, and can be found in a 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
> 80	95	¹ LEP	13	LEP	$e^+e^- \rightarrow H^+H^-, E_{\rm cm} \leq$
> 76.3	95	² ABBIENDI	12	OPAL	$e^+e^- \rightarrow H^+H^-, E_{cm} \leq 209 \text{GeV}$
> 74.4	95	ABDALLAH	041	DLPH	$E_{\rm cm} \leq 209 \; {\rm GeV}$
> 76.5	95	ACHARD	03E	L3	$E_{\rm cm} \leq 209 \; {\rm GeV}$
> 79.3	95	HEISTER	0 2P	ALEP	$E_{\rm cm} \leq 209 \; {\rm GeV}$

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

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		³ AAD	14M	ATLS	$H^0_2 \rightarrow H^{\pm} W^{\mp} \rightarrow$		
					$H^0 W^{\pm} W^{\mp}, H^0 \rightarrow b\overline{b}$		
		⁴ AALTONEN		CDF			
		⁵ AAD			$t \rightarrow bH^+$		
		6 _{AAD}	13V	ATLS	$t \rightarrow bH^+$, lepton non- universality		
		⁷ AAD	12вн	ATLS			
		⁸ CHATRCHYAN					
		⁹ AALTONEN			$t \rightarrow bH^+, H^+ \rightarrow W^+ A^0$		
>316	95	¹⁰ DESCHAMPS	11P 10		Type II, flavor physics data		
>310	90	¹¹ AALTONEN			$t \rightarrow bH^+$		
		¹² ABAZOV		D0			
		¹³ ABAZOV			$t \rightarrow bH^+$ $t \rightarrow bH^+$		
		¹⁴ ABAZOV					
					$t \rightarrow bH^+$		
		¹⁵ ABAZOV	09 P				
	<u>-</u>	¹⁶ ABULENCIA		CDF			
> 92.0	95	ABBIENDI	04		B(au u) = 1		
> 76.7	95	¹⁷ ABDALLAH		DLPH			
		¹⁸ ABBIENDI	03		$ au ightarrow \mu \overline{ u} u$, $e \overline{ u} u$		
		¹⁹ ABAZOV		D0	$t \rightarrow b H^+, H \rightarrow \tau \nu$		
		²⁰ BORZUMATI		RVUE			
		²¹ ABBIENDI			$B \rightarrow \tau \nu_{\tau} X$		
		²² BARATE			$B \rightarrow \tau \nu_{\tau}$		
>315	99	²³ GAMBINO	01		$b ightarrow s \gamma$		
	~-	²⁴ AFFOLDER	001		$t \rightarrow bH^+, H \rightarrow \tau \nu$		
> 59.5	95	ABBIENDI	99E		$E_{\rm cm} \leq 183 \; {\rm GeV}$		
		²⁵ ABBOTT	99E				
		²⁶ ACKERSTAFF					
		²⁷ ACCIARRI	97F		$B \rightarrow \tau \nu_{\tau}$		
		²⁸ AMMAR			$\tau \rightarrow \mu \nu \nu$		
		²⁹ COARASA	97		$B \rightarrow \tau \nu_{\tau} X$		
		³⁰ GUCHAIT	97		$t \rightarrow bH^+, H \rightarrow \tau \nu$		
		³¹ MANGANO	97	RVUE	$B_{u(c)} \rightarrow \tau \nu_{\tau}$		
		³² STAHL	97		$ au ightarrow \mu u u$		
>244	95	³³ ALAM	95		$b ightarrow s \gamma$		
		³⁴ BUSKULIC	95	ALEP	$b \rightarrow \tau \nu_{\tau} X$		
1					1		

¹ LEP 13 give a limit that refers to the Type II scenario. The limit for $B(H^+ \rightarrow \tau \nu) = 1$ is 94 GeV (95% CL), and for $B(H^+ \rightarrow cs) = 1$ the region below 80.5 as well as the region 83–88 GeV is excluded (95% CL). LEP 13 also search for the decay mode $H^+ \rightarrow A^0 W^*$ with $A^0 \rightarrow b\overline{b}$, which is not negligible in Type I models. The limit in Type I models is 72.5 GeV (95% CL) if $m_{A^0} > 12$ GeV.

² ABBIENDI 12 also search for the decay mode $H^+ \rightarrow A^0 W^*$ with $A^0 \rightarrow b\overline{b}$. ³ AAD 14M search for the decay cascade $H_2^0 \rightarrow H^{\pm} W^{\mp} \rightarrow H^0 W^{\pm} W^{\mp}$, H^0 decaying to $b\overline{b}$ in 20.3 fb⁻¹ of pp collisions at $E_{\rm cm} = 8$ TeV. See their Table III for limits on cross section times branching ratio for $m_{H_2^0}^0 = 325$ -1025 GeV and $m_{H^+} = 225$ -925 GeV.

- ⁴ AALTONEN 14A measure B($t \rightarrow b \tau \nu$) = 0.096 ± 0.028 using 9 fb⁻¹ of $p\overline{p}$ collisions at $E_{\rm cm}$ = 1.96 TeV. For m_{H^+} = 80–140 GeV, this measured value is translated to a limit B($t \rightarrow bH^+$) < 0.059 at 95% CL assuming B($H^+ \rightarrow \tau^+ \nu$) = 1.
- ⁵ AAD 13AC search for $t\overline{t}$ production followed by $t \to bH^+$, $H^+ \to c\overline{s}$ (flavor unidentified) in 4.7 fb⁻¹ of pp collisions at $E_{\rm cm} = 7$ TeV. Upper limits on B($t \to bH^+$) between 0.05 and 0.01 (95%CL) are given for m_{H^+} =90–150 GeV and B($H^+ \to c\overline{s}$)=1.
- ⁶ AAD 13V search for $t\bar{t}$ production followed by $t \to bH^+$, $H^+ \to \tau^+ \nu$ through violation of lepton universality with 4.6 fb⁻¹ of pp collisions at $E_{\rm cm} = 7$ TeV. Upper limits on $B(t \to bH^+)$ between 0.032 and 0.044 (95% CL) are given for $m_{H^+} = 90$ -140 GeV and $B(H^+ \to \tau^+ \nu) = 1$. By combining with AAD 12BH, the limits improve to 0.008 to 0.034 for $m_{H^+} = 90$ -160 GeV. See their Fig. 7 for the excluded region in the $m_h^{\rm max}$ _ scenario of the MSSM.
- ⁷ AAD 12BH search for $t\bar{t}$ production followed by $t \rightarrow bH^+$, $H^+ \rightarrow \tau^+ \nu$ with 4.6 fb⁻¹ of pp collisions at $E_{\rm cm} = 7$ TeV. Upper limits on B($t \rightarrow bH^+$) between 0.01 and 0.05 (95% CL) are given for $m_{H^+} = 90$ -160 GeV and B($H^+ \rightarrow \tau^+ \nu$) = 1. See their Fig. 8 for the excluded region in the $m_h^{\rm max}$ scenario of the MSSM.
- ⁸ CHATRCHYAN 12AA search for $t\bar{t}$ production followed by $t \rightarrow bH^+$, $H^+ \rightarrow \tau^+ \nu$ with 2 fb⁻¹ of *pp* collisions at $E_{\rm cm} = 7$ TeV. Upper limits on B($t \rightarrow bH^+$) between 0.019 and 0.041 (95% CL) are given for $m_{H^+} = 80$ -160 GeV and B($H^+ \rightarrow \tau^+ \nu$)=1.
- ⁹ AALTONEN 11P search in 2.7 fb⁻¹ of $p\overline{p}$ collisions at $E_{\rm cm} = 1.96$ TeV for the decay chain $t \rightarrow bH^+$, $H^+ \rightarrow W^+A^0$, $A^0 \rightarrow \tau^+\tau^-$ with m_{A^0} between 4 and 9 GeV. See their Fig. 4 for limits on B($t \rightarrow bH^+$) for 90 $< m_{H^+} < 160$ GeV.
- ¹⁰ DESCHAMPS 10 make Type II two Higgs doublet model fits to weak leptonic and semileptonic decays, $b \rightarrow s\gamma$, B, B_s mixings, and $Z \rightarrow b\overline{b}$. The limit holds irrespective of tan β .
- ¹¹ AALTONEN 09AJ search for $t \rightarrow bH^+$, $H^+ \rightarrow c\overline{s}$ in $t\overline{t}$ events in 2.2 fb⁻¹ of $p\overline{p}$ collisions at $E_{\rm cm} = 1.96$ TeV. Upper limits on B($t \rightarrow bH^+$) between 0.08 and 0.32 (95% CL) are given for $m_{H^+} = 60$ –150 GeV and B($H^+ \rightarrow c\overline{s}$) = 1.
- ¹² ABAZOV 09AC search for $t \rightarrow bH^+$, $H^+ \rightarrow \tau^+ \nu$ in $t\bar{t}$ events in 0.9 fb⁻¹ of $p\bar{p}$ collisions at $E_{\rm cm} = 1.96$ TeV. Upper limits on B($t \rightarrow bH^+$) between 0.19 and 0.25 (95% CL) are given for $m_{H^+} = 80$ -155 GeV and B($H^+ \rightarrow \tau^+ \nu$) = 1. See their Fig. 4 for an excluded region in a MSSM scenario.
- ¹³ ABAZOV 09AG measure $t\bar{t}$ cross sections in final states with ℓ + jets ($\ell = e, \mu$), $\ell\ell$, and $\tau\ell$ in 1 fb⁻¹ of $p\bar{p}$ collisions at $E_{\rm cm} = 1.96$ TeV, which constrains possible $t \rightarrow bH^+$ branching fractions. Upper limits (95% CL) on B($t \rightarrow bH^+$) between 0.15 and 0.40 (0.48 and 0.57) are given for B($H^+ \rightarrow \tau^+ \nu$) = 1 (B($H^+ \rightarrow c\bar{s}$) = 1) for $m_{H^+} = 80-155$ GeV.
- ¹⁴ ABAZOV 09AI search for $t \to bH^+$ in $t\overline{t}$ events in 1 fb⁻¹ of $p\overline{p}$ collisions at $E_{\rm cm} = 1.96$ TeV. Final states with $\ell + {\rm jets}$ ($\ell = e, \mu$), $\ell\ell$, and $\tau\ell$ are examined. Upper limits on B($t \to bH^+$) (95% CL) between 0.15 and 0.19 (0.19 and 0.22) are given for B($H^+ \to \tau^+ \nu$) = 1 (B($H^+ \to c\overline{s}$) = 1) for $m_{H^+} = 80$ -155 GeV. For B($H^+ \to \tau^+ \nu$) = 1 also a simultaneous extraction of B($t \to bH^+$) and the $t\overline{t}$ cross section is performed, yielding a limit on B($t \to bH^+$) between 0.12 and 0.26 for $m_{H^+} = 80$ -155 GeV. See their Figs. 5–8 for excluded regions in several MSSM scenarios.
- ¹⁵ABAZOV 09P search for H^+ production by $q \overline{q}'$ annihilation followed by $H^+ \rightarrow t \overline{b}$ decay in 0.9 fb⁻¹ of $p \overline{p}$ collisions at $E_{\rm cm} = 1.96$ TeV. Cross section limits in several

two-doublet models are given for $m_{H^+} = 180-300$ GeV. A region with $20 \lesssim \tan\beta \lesssim$ 70 is excluded (95% CL) for 180 GeV $\lesssim m_{H^+} \lesssim$ 184 GeV in type-I models.

- ¹⁶ ABULENCIA 06E search for associated H^0 W production in $p\overline{p}$ collisions at $E_{\rm cm} = 1.96$ TeV. A fit is made for $t\overline{t}$ 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 $H^+ \rightarrow \tau^+ \nu$, $c\overline{s}$, $t^*\overline{b}$, or $W^+ H^0$. Within the MSSM the search is sensitive to the region $\tan\beta < 1$ or > 30 in the mass range $m_{H^+} = 80-160$ GeV. See Fig. 2 for the excluded region in a certain MSSM scenario.
- ¹⁷ 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.
- 18 ABBIENDI 03 give a limit m_{H^+} > 1.28tan β GeV (95%CL) in Type II two-doublet models.
- ¹⁹ ABAZOV 02B search for a charged Higgs boson in top decays with $H^+ \rightarrow \tau^+ \nu$ at $E_{\rm cm}$ =1.8 TeV. For m_{H^+} =75 GeV, the region tan β > 32.0 is excluded at 95%CL. The excluded mass region extends to over 140 GeV for tan β values above 100.
- ²⁰ BORZUMATI 02 point out that the decay modes such as $b\overline{b}W$, A^0W , and supersymmetric ones can have substantial branching fractions in the mass range explored at LEP II and Tevatron.
- ²¹ABBIENDI 01Q give a limit $\tan\beta/m_{H^+} < 0.53 \text{ GeV}^{-1}$ (95%CL) in Type II two-doublet as models.
- ²² 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).
- ²³ GAMBINO 01 use the world average data in the summer of 2001 B($b \rightarrow s\gamma$)= (3.23 ± 0.42) × 10⁻⁴. The limit applies for Type-II two-doublet models.
- ²⁴ AFFOLDER 001 search for a charged Higgs boson in top decays with $H^+ \rightarrow \tau^+ \nu$ in $p\overline{p}$ collisions at $E_{\rm cm}$ =1.8 TeV. The excluded mass region extends to over 120 GeV for tan β 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.
- ²⁵ ABBOTT 99E search for a charged Higgs boson in top decays in $p\overline{p}$ collisions at $E_{\rm cm}$ =1.8 TeV, by comparing the observed $t\overline{t}$ cross section (extracted from the data assuming the dominant decay $t \rightarrow bW^+$) with theoretical expectation. The search is sensitive to regions of the domains $\tan\beta \lesssim 1$, 50 $< m_{H^+}$ (GeV) $\lesssim 120$ and $\tan\beta \gtrsim 40$, 50 $< m_{H^+}$
- (GeV) \lesssim 160. See Fig. 3 for the details of the excluded region.
- ²⁶ ACKERSTAFF 99D measure the Michel parameters ρ , ξ , η , and $\xi\delta$ in leptonic τ decays from $Z \rightarrow \tau \tau$. Assuming $e \mu$ 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.
- ²⁷ 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.
- ²⁸ 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).
- ²⁹COARASA 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.
- ³⁰ 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.
- ³¹ 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.

- ³² 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.
- ³³ALAM 95 measure the inclusive $b \rightarrow s\gamma$ branching ratio at $\Upsilon(4S)$ and give B($b \rightarrow s\gamma$)< 4.2 × 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.
- ³⁴ 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 $SU(2)_L \times SU(2)_R \times U(1)$, the type-II seesaw model, and the Zee-Babu model. The 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 $T_3 = \pm$	LIMITS	for	$H^{\pm\pm}$	with	Ta	=	±1
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	with 73 =	
VALUE (GeV)	CL%	DOCUMENT ID TECN COMMENT
>398	95	¹ AAD 12CQ ATLS $\mu\mu$
>375	95	1 AAD 12CQ ATLS $e \mu$
>409	95	¹ AAD 12CQ ATLS <i>e e</i>
>169	95	² CHATRCHYAN 12AU CMS $ au au$
>300	95	2 CHATRCHYAN 12AU CMS μau
>293	95	2 CHATRCHYAN 12AU CMS $e au$
>395	95	² CHATRCHYAN 12AU CMS $\mu\mu$
>391	95	2 CHATRCHYAN 12AU CMS $e \mu$
>382	95	² CHATRCHYAN 12AU CMS <i>e e</i>
> 98.1	95	³ ABDALLAH 03 DLPH $ au au$
> 99.0	95	⁴ ABBIENDI 02C OPAL $ au au$
• • • We do not us	se the followin	g data for averages, fits, limits, etc. • • •
		⁵ KANEMURA 14 RVUE $W^{(*)\pm}W^{(*)\pm}$
>330	95	⁶ AAD 13Y ATLS $\mu\mu$
>237	95	⁶ AAD 13Y ATLS $\mu \tau$
>355	95	⁷ AAD 12AY ATLS $\mu\mu$
>128	95	⁸ ABAZOV 12A D0 $\tau \tau$
>144	95	⁸ ABAZOV 12A D0 μau
>245	95	⁹ AALTONEN 11AF CDF $\mu\mu$
>210	95	⁹ AALTONEN 11AF CDF $e\mu$
>225	95	⁹ AALTONEN 11AF CDF ee
>114	95	10 AALTONEN 08AA CDF $e au$
>112	95	10 AALTONEN 08AA CDF μau
>168	95	¹¹ ABAZOV 08V D0 $\mu\mu$
		¹² AKTAS 06A H1 single $H^{\pm\pm}$

>133 >118.4	95 95	¹³ ACOSTA ¹⁴ ABAZOV ¹⁵ ABBIENDI	05l 04e 03q	CDF D0 OPAL	stable $\mu\mu$ $E_{cm} \leq 209$ GeV, single $\mu^{\pm\pm}$
		¹⁶ GORDEEV ¹⁷ ASAKA	97 95	SPEC THEO	muonium conversion
> 45.6	95	¹⁸ ACTON		OPAL	
> 45.0	95		9211	OFAL	
> 30.4	95	¹⁹ ACTON	92M	OPAL	
none 6.5–36.6	95	²⁰ SWARTZ	90	MRK2	

¹AAD 12CQ search for $H^{++}H^{--}$ production with 4.7 fb⁻¹ of pp collisions at $E_{cm} =$ 7 TeV. The limit assumes 100% branching ratio to the specified final state. See their Table 1 for limits assuming smaller branching ratios.

- ²CHATRCHYAN 12AU search for $H^{++}H^{--}$ production with 4.9 fb⁻¹ of pp collisions at $E_{\rm cm}=7$ TeV. The limit assumes 100% branching ratio to the specified final state. See their Table 6 for limits including associated $H^{++}H^{-}$ production or assuming different scenarios.
- ³ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow$ $\tau^+ \tau^+$, or decaying outside the detector.
- ⁴ABBIENDI 02C searches for pair production of $H^{++}H^{--}$, with $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (ℓ,ℓ' $= e, \mu, \tau$). 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 $g(H\ell\ell) \gtrsim 10^{-7}$.
- ⁵ KANEMURA 14 examine the case where H^{++} decays preferentially to $W^{(*)}W^{(*)}$ and estimate that a lower mass limit of \sim 60 GeV can be derived from the same-sign dilepton data of AAD 12CY.
- ⁶AAD 13Y search for $H^{++}H^{--}$ production in a generic search of events with three charged leptons in 4.6 fb⁻¹ of pp collisions at $E_{\rm cm} = 7$ TeV. The limit assumes 100% branching ratio to the specified final state.
- ⁷ AAD 12AY search for $H^{++}H^{--}$ production with 1.6 fb⁻¹ of pp collisions at $E_{\rm cm} =$ 7 TeV. The limit assumes 100% branching ratio to the specified final state. ⁸ ABAZOV 12A search for $H^{++}H^{--}$ production in 7.0 fb⁻¹ of $p\overline{p}$ collisions at $E_{\rm cm} =$
- 1.96 TeV.
- ⁹AALTONEN 11AF search for $H^{++}H^{--}$ production in 6.1 fb⁻¹ of $p\overline{p}$ collisions at E_{cm} = 1.96 TeV.
- ¹⁰ AALTONEN 08AA search for $H^{++}H^{--}$ production in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV. The limit assumes 100% branching ratio to the specified final state.
- ¹¹ABAZOV 08V search for $H^{++}H^{--}$ production in $p\overline{p}$ collisions at E_{cm} = 1.96 TeV. The limit is for B($H \rightarrow \mu\mu$) = 1. The limit is updated in ABAZOV 12A.
- 12 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. ¹³ ACOSTA 05L search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions. The limit is valid for $g_{\ell\,\ell\prime}~<~10^{-8}$ so that the Higgs decays outside the detector.
- ¹⁴ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.
- ¹⁵ 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 ${\sf B}(H^{\pm\pm} o \ \ell^\pm \ \ell^\pm) =$ 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 $m_{\mu\pm\pm}$ < 2 TeV (see Fig. 8).

- ¹⁶ GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\overline{M}}/G_{F} < 0.14$ (90% CL), where $G_{M\overline{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}} > 210$ GeV if the Yukawa couplings of H^{++} to *ee* and $\mu\mu$ are as large as the weak gauge coupling. For similar limits on muoniumantimuonium conversion, see the muon Particle Listings.
- ¹⁷ 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.
- ¹⁸ 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.
- ¹⁹ ACTON 92M from $\Delta\Gamma_7$ <40 MeV.
- ²⁰ SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (any flavor). The limits are valid for the Higgslepton 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.

VALUE (GeV)	<u>CL%</u>	DOCUMENT ID	TECN	COMMENT
>306	95	¹ AAD	12CQ ATLS	$\mu\mu$
>310	95	¹ AAD	12CQ ATLS	e μ
>322	95	¹ AAD	12CQ ATLS	ee
> 97.3	95	² ABDALLAH	03 DLPH	au au
> 97.3	95	³ ACHARD	03F L3	au au
> 98.5	95	⁴ ABBIENDI	02C OPAL	au au
$\bullet \bullet \bullet$ We do not use the	ne followi	ng data for averages	s, fits, limits,	etc. ● ● ●
>251	95	⁵ AAD	12AY ATLS	$\mu\mu$
>113	95	⁶ ABAZOV	12A D0	μau
>205	95	⁷ AALTONEN	11af CDF	$\mu\mu$
>190	95	⁷ AALTONEN	11af CDF	e μ
>205	95	⁷ AALTONEN	11af CDF	ee
>145	95	⁸ ABAZOV	08v D0	$\mu\mu$
		⁹ AKTAS	06A H1	single $\mathit{H}^{\pm\pm}$
>109	95	¹⁰ ACOSTA	05L CDF	stable
> 98.2	95	¹¹ ABAZOV	04E D0	$\mu\mu$
		¹² ABBIENDI	03Q OPAL	$E_{ m cm} \leq$ 209 GeV, single $H^{\pm\pm}$
		¹³ GORDEEV	97 SPEC	muonium conversion
> 45.6	95	¹⁴ ACTON	92м OPAL	
> 25.5	95	¹⁵ ACTON	92м OPAL	
none 7.3–34.3	95	¹⁶ SWARTZ	90 MRK2	
1			1	

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

¹AAD 12CQ search for $H^{++}H^{--}$ production with 4.7 fb⁻¹ of pp collisions at $E_{\rm cm} =$ 7 TeV. The limit assumes 100% branching ratio to the specified final state. See their Table 1 for limits assuming smaller branching ratios.

²ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+ \tau^+$, or decaying outside the detector.

³ACHARD 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 $g_{\ell \ell'} \gtrsim 10^{-7}$.

⁴ABBIENDI 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 $g(H\ell\ell) \gtrsim 10^{-7}$.

- ⁵ AAD 12AY search for $H^{++}H^{--}$ production with 1.6 fb⁻¹ of pp collisions at $E_{cm} =$ 7 TeV. The limit assumes 100% branching ratio to the specified final state.
- ⁶ABAZOV 12A search for $H^{++}H^{--}$ production in 7.0 fb⁻¹ of $p\overline{p}$ collisions at $E_{cm} =$ 1.96 TeV.
- ⁷AALTONEN 11AF search for $H^{++}H^{--}$ production in 6.1 fb⁻¹ of $p\overline{p}$ collisions at E_{cm} = 1.96 TeV.
- ⁸ABAZOV 08v search for $H^{++}H^{--}$ production in $p\overline{p}$ collisions at $E_{\rm cm}$ = 1.96 TeV. The limit is for B($H \rightarrow \mu\mu$) = 1. The limit is updated in ABAZOV 12A.
- ⁹AKTAS 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 au only the limit is 112 GeV.
- ¹⁰ ACOSTA 05L search for $H^{++}H^{--}$ pair production in $p\overline{p}$ collisions. The limit is valid for $g_{\ell\,\ell'}~<~10^{-8}$ so that the Higgs decays outside the detector.
- ¹¹ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.
- ¹²ABBIENDI 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 $e^+e^-
 ightarrow e^+e^-$. 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).
- 13 GORDEEV 97 search for muonium-antimuonium conversion and find $G_{M\overline{M}}/G_F < 0.14$ (90% CL), where $G_{M\overline{M}}$ is the lepton-flavor violating effective four-fermion coupling. This limit may be converted to $m_{H^{++}}$ > 210 GeV if the Yukawa couplings of H^{++} to ee and $\mu\mu$ are as large as the weak gauge coupling. For similar limits on muoniumantimuonium conversion, see the muon Particle Listings.
- ¹⁴ 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.
- $^{15}\,\text{ACTON}$ 92M from $\Delta\Gamma_{Z}$ <40 MeV.
- ¹⁶SWARTZ 90 assume $H^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ (any flavor). The limits are valid for the Higgslepton 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.

AAD	14M	PR D89 032002	G. Aad et al.	(ATLAS Col	llab.)
AALTONEN	14A	PR D89 091101	T. Aaltonen et al.	(CDF Col	llab.)
KANEMURA	14	PR D90 115018	S. Kanemura <i>et al.</i>		
AAD	13AC	EPJ C73 2465	G. Aad et al.	(ATLAS Col	llab.)
AAD	13V	JHEP 1303 076	G. Aad et al.	(ATLAS Col	llab.)
AAD	13Y	PR D87 052002	G. Aad et al.	(ATLAS Col	llab.)
LEP	13	EPJ C73 2463	LEP Collabs	(ALEPH, DELPHI, L3, OPAL,	LEP)
AAD	12AY	PR D85 032004	G. Aad et al.	(ATLAS Col	llab.)
AAD	12BH	JHEP 1206 039	G. Aad et al.	(ATLAS Col	llab.)
AAD	12CQ	EPJ C72 2244	G. Aad et al.	(ATLAS Col	llab.)
AAD	12CY	JHEP 1212 007	G. Aad et al.	(ATLAS Col	llab.)
ABAZOV	12A	PRL 108 021801	V.M. Abazov et al.	(D0 Col	llab.)
ABBIENDI	12	EPJ C72 2076	G. Abbiendi et al.	(OPAL Col	llab.)
CHATRCHYAN	12AA	JHEP 1207 143	S. Chatrchyan et al.	(CMS Col	llab.)
CHATRCHYAN	12AU	EPJ C72 2189	S. Chatrchyan et al.	CMS Col	llab.)
AALTONEN	11AF	PRL 107 181801	T. Aaltonen et al.	CDF Col	llab.)
AALTONEN	11P	PRL 107 031801	T. Aaltonen et al.	CDF Col	llab.)
DESCHAMPS	10	PR D82 073012	O. Deschamps et al.	(CLER, ORSAY, LA	APP)
AALTONEN	09AJ	PRL 103 101803	T. Aaltonen et al.	CDF Col	llab.)
ABAZOV	09AC	PR D80 051107	V.M. Abazov et al.	D0 Col	llab.)
ABAZOV	09AG	PR D80 071102	V.M. Abazov et al.	(D0 Col	llab.)
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