

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

CONTENTS:

- H^\pm (charged Higgs) mass limits for $m_{H^+} < m(\text{top})$
- H^\pm (charged Higgs) mass limits for $m_{H^+} > m(\text{top})$
- $H^{\pm\pm}$ (doubly-charged Higgs boson) mass limits
 - Limits for $H^{\pm\pm}$ with $T_3 = \pm 1$
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———— H^\pm (charged Higgs) mass limits for $m_{H^+} < m(\text{top})$ ————

Unless otherwise stated, LEP limits 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.

Limits obtained at the LHC are given in the m_h^{mod-} benchmark scenario, see CARENA 13, and hold for all $\tan\beta$ values.

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have conclusively ruled out the existence of a charged Higgs in the region $m_{H^+} \lesssim 45$ GeV, and are meanwhile superseded by the searches in higher energy e^+e^- collisions at LEP.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
none 80–140	95	¹ AAD	15AF ATLS	$t \rightarrow bH^+$
none 90–155	95	² KHACHATRY...15AX	CMS	$t \rightarrow bH^+, H^+ \rightarrow \tau^+ \nu$
> 80	95	³ LEP	13 LEP	$e^+e^- \rightarrow H^+H^-, E_{cm} \leq 209\text{GeV}$
> 76.3	95	⁴ ABBIENDI	12 OPAL	$e^+e^- \rightarrow H^+H^-, E_{cm} \leq 209\text{GeV}$
> 74.4	95	ABDALLAH	04I DLPH	$E_{cm} \leq 209$ GeV
> 76.5	95	ACHARD	03E L3	$E_{cm} \leq 209$ GeV
> 79.3	95	HEISTER	02P ALEP	$E_{cm} \leq 209$ GeV

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

		5	TUMASYAN	22B	CMS	$H^\pm \rightarrow W^\pm \gamma$
		6	AAD	21V	ATLS	$\bar{t} b H^+, H^+ \rightarrow t \bar{b}$
		7	SIRUNYAN	21W	CMS	$H^+ \rightarrow W^+ Z$
		8	AAD	20W	ATLS	$H^+ \rightarrow t \bar{b}$
		9	SIRUNYAN	20AO	CMS	$H^+ \rightarrow t \bar{b}$
		10	SIRUNYAN	20AV	CMS	$H^+ \rightarrow t \bar{b}$
		11	SIRUNYAN	20BE	CMS	$t \rightarrow b H^+, H^+ \rightarrow c \bar{s}$
		12	SIRUNYAN	19AH	CMS	$H^+ \rightarrow \tau^+ \nu$
		13	SIRUNYAN	19BP	CMS	$H^+ \rightarrow W^+ Z$
		14	SIRUNYAN	19CC	CMS	$t \rightarrow b H^+, H^+ \rightarrow$ $W^+ A^0, A^0 \rightarrow \mu^+ \mu^-$
		15	SIRUNYAN	19CQ	CMS	$H^+ \rightarrow W^+ Z$
		16	AABOUD	18BW	ATLS	$\bar{t} b H^+$ or $t \rightarrow b H^+$, $H^+ \rightarrow \tau^+ \nu$
		17	AABOUD	18CD	ATLS	$\bar{t} b H^+, H^+ \rightarrow t \bar{b}$
		18	AABOUD	18CH	ATLS	$H^\pm \rightarrow W^\pm Z$
		19	HALLER	18	RVUE	$b \rightarrow s \gamma$
		20	SIRUNYAN	18DO	CMS	$t \rightarrow b H^+, H^+ \rightarrow c \bar{b}$
		21	MISIAK	17	RVUE	$b \rightarrow s(d) \gamma$
		22	SIRUNYAN	17AE	CMS	$H^\pm \rightarrow W^\pm Z$
		23	AABOUD	16A	ATLS	$t(b) H^+, H^+ \rightarrow \tau^+ \nu$
		24	AAD	16AJ	ATLS	$t(b) H^+, H^+ \rightarrow t \bar{b}$
		25	AAD	16AJ	ATLS	$q q \rightarrow H^+, H^+ \rightarrow t \bar{b}$
		26	AAD	15AF	ATLS	$t H^\pm$
		27	AAD	15M	ATLS	$H^\pm \rightarrow W^\pm Z$
		28	KHACHATRY...	15AX	CMS	$t H^+, H^+ \rightarrow t \bar{b}$
		29	KHACHATRY...	15AX	CMS	$t H^\pm, H^\pm \rightarrow \tau^\pm \nu$
		30	KHACHATRY...	15BF	CMS	$t \rightarrow b H^+, H^+ \rightarrow c \bar{s}$
		31	AAD	14M	ATLS	$H_2^0 \rightarrow H^\pm W^\mp \rightarrow$ $H^0 W^\pm W^\mp, H^0 \rightarrow b \bar{b}$
		32	AALTONEN	14A	CDF	$t \rightarrow b \tau \nu$
		33	AAD	13AC	ATLS	$t \rightarrow b H^+$
		34	AAD	13V	ATLS	$t \rightarrow b H^+$, lepton non- universality
		35	AAD	12BH	ATLS	$t \rightarrow b H^+$
		36	CHATRCHYAN	12AA	CMS	$t \rightarrow b H^+$
		37	AALTONEN	11P	CDF	$t \rightarrow b H^+, H^+ \rightarrow W^+ A^0$
>316	95	38	DESCHAMPS	10	RVUE	Type II, flavor physics data
		39	AALTONEN	09AJ	CDF	$t \rightarrow b H^+$
		40	ABAZOV	09AC	D0	$t \rightarrow b H^+$
		41	ABAZOV	09AG	D0	$t \rightarrow b H^+$
		42	ABAZOV	09AI	D0	$t \rightarrow b H^+$
		43	ABAZOV	09P	D0	$H^+ \rightarrow t \bar{b}$
		44	ABULENCIA	06E	CDF	$t \rightarrow b H^+$
> 92.0	95		ABBIENDI	04	OPAL	$B(\tau \nu) = 1$
> 76.7	95	45	ABDALLAH	04I	DLPH	Type I
		46	ABBIENDI	03	OPAL	$\tau \rightarrow \mu \bar{\nu} \nu, e \bar{\nu} \nu$
		47	ABAZOV	02B	D0	$t \rightarrow b H^+, H \rightarrow \tau \nu$

		48	BORZUMATI	02	RVUE	
		49	ABBIENDI	01Q	OPAL	$B \rightarrow \tau \nu_{\tau} X$
		50	BARATE	01E	ALEP	$B \rightarrow \tau \nu_{\tau}$
>315	99	51	GAMBINO	01	RVUE	$b \rightarrow s \gamma$
		52	AFFOLDER	00I	CDF	$t \rightarrow b H^+, H \rightarrow \tau \nu$
> 59.5	95		ABBIENDI	99E	OPAL	$E_{\text{cm}} \leq 183 \text{ GeV}$
		53	ABBOTT	99E	D0	$t \rightarrow b H^+$
		54	ACKERSTAFF	99D	OPAL	$\tau \rightarrow e \nu \nu, \mu \nu \nu$
		55	ACCIARRI	97F	L3	$B \rightarrow \tau \nu_{\tau}$
		56	AMMAR	97B	CLEO	$\tau \rightarrow \mu \nu \nu$
		57	COARASA	97	RVUE	$B \rightarrow \tau \nu_{\tau} X$
		58	GUCHAIT	97	RVUE	$t \rightarrow b H^+, H \rightarrow \tau \nu$
		59	MANGANO	97	RVUE	$B_{u(c)} \rightarrow \tau \nu_{\tau}$
		60	STAHL	97	RVUE	$\tau \rightarrow \mu \nu \nu$
>244	95	61	ALAM	95	CLE2	$b \rightarrow s \gamma$
		62	BUSKULIC	95	ALEP	$b \rightarrow \tau \nu_{\tau} X$

¹ AAD 15AF search for $t\bar{t}$ production followed by $t \rightarrow b H^+, H^+ \rightarrow \tau^+ \nu$ in 19.5 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. Upper limits on $B(t \rightarrow b H^+) B(H^+ \rightarrow \tau \nu)$ between 2.3×10^{-3} and 1.3×10^{-2} (95% CL) are given for $m_{H^+} = 80\text{--}160 \text{ GeV}$. See their Fig. 8 for the excluded regions in different benchmark scenarios of the MSSM. The region $m_{H^+} < 140 \text{ GeV}$ is excluded for $\tan\beta > 1$ in the considered scenarios.

² KHACHATRYAN 15AX search for $t\bar{t}$ production followed by $t \rightarrow b H^+, H^+ \rightarrow \tau^+ \nu$ in 19.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. Upper limits on $B(t \rightarrow b H^+) B(H^+ \rightarrow \tau \nu)$ between 1.2×10^{-2} and 1.5×10^{-3} (95% CL) are given for $m_{H^+} = 80\text{--}160 \text{ GeV}$. See their Fig. 11 for the excluded regions in different benchmark scenarios of the MSSM. The region $m_{H^+} < 155 \text{ GeV}$ is excluded for $\tan\beta > 1$ in the considered scenarios.

³ 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 $A^0 \rightarrow b\bar{b}$, which is not negligible in Type I models. The limit in Type I models is 72.5 GeV (95% CL) if $m_{A^0} > 12 \text{ GeV}$.

⁴ ABBIENDI 12 also search for the decay mode $H^+ \rightarrow A^0 W^*$ with $A^0 \rightarrow b\bar{b}$.

⁵ TUMASYAN 22B search for production of scalar resonance decaying to $W^{\pm} \gamma \rightarrow qq\gamma$ in 137 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 5 for limits on cross section times branching ratio for the mass range 0.7–6.0 TeV, assuming narrow width or $\Gamma/M = 0.05$.

⁶ AAD 21V search for $\bar{t}bH^+$ associated production followed by $H^+ \rightarrow t\bar{b}$ in 139 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 6 for upper limits on cross section times branching ratio for $m_{H^+} = 0.2\text{--}2 \text{ TeV}$. See also their Fig. 7 for the excluded region in the parameter space of the hMSSM and the following MSSM benchmark scenarios: $M_h^{125}, M_h^{125}(\tilde{\chi}), M_h^{125}(\tilde{\tau}), M_h^{125}(\text{alignment}), M_{h_1}^{125}(\text{CPV})$.

⁷ SIRUNYAN 21W search for vector boson fusion production of H^+ decaying to $H^+ \rightarrow W^+ Z \rightarrow \ell^+ \nu \ell^+ \ell^-$ in 137 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 8 for limits on cross section times branching ratio for $m_{H^+} = 0.2\text{--}3.0 \text{ TeV}$, and also for limits on the fraction of the triplet vev contribution to the W mass in the Georgi-Machacek model.

⁸ AAD 20W search for dijet resonances in events with isolated leptons using 139 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. As a byproduct, $H^+ \rightarrow t\bar{b}$ produced in association with $\bar{t}b$ is searched for. Limits on the product of cross section times branching ratio for $m_{H^+} = 0.6\text{--}2 \text{ TeV}$ are given in their Fig. 5(c).

- 9 SIRUNYAN 20AO search for $H^+ \rightarrow t\bar{b}$ produced in association with $t(b)$ in all jet final states in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 6 for limits on the product of cross section times branching ratio for $m_{H^+} = 0.2\text{--}3 \text{ TeV}$. Limits for s -channel production are also given for $m_{H^+} = 0.8\text{--}3 \text{ TeV}$. See also Fig. 7 for the corresponding limits in scenarios in the minimal supersymmetric standard model. Cross section limits from combined results with SIRUNYAN 20AV are given in Fig. 8.
- 10 SIRUNYAN 20AV search for $H^+ \rightarrow t\bar{b}$ produced in association with $t(b)$ in final states with one or two leptons, in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 5 for limits on the product of cross section times branching ratio for $m_{H^+} = 0.2\text{--}3 \text{ TeV}$, and their Fig. 6 for the corresponding limits in scenarios in the minimal supersymmetric standard model.
- 11 SIRUNYAN 20BE search for $t \rightarrow bH^+$ followed by the decay $H^+ \rightarrow c\bar{s}$ in pair produced top quark events using 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. Limits on the branching ratio in the range $1.68\text{--}0.25\%$ (95%CL) are given for $m_{H^+} = 80\text{--}160 \text{ GeV}$, see their Fig. 4.
- 12 SIRUNYAN 19AH search for H^+ in the decay of a pair-produced t quark, or in associated tbH^+ or nonresonant $b\bar{b}H^+W^-$ production, followed by $H^+ \rightarrow \tau^+\nu$, in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. Upper limits on cross section times branching ratio between 6 pb and 5 fb (95% CL) are given for $m_{H^+} = 80\text{--}3000 \text{ GeV}$ (including the non-resonant production near the top quark mass), see their Fig. 6 (left). See their Fig. 6 (right) for the excluded regions in the $m_h^{\text{mod-}}$ scenario of the MSSM.
- 13 SIRUNYAN 19BP search for vector boson fusion production of H^+ decaying to $H^+ \rightarrow W^+Z \rightarrow \ell^+\nu\ell^+\ell^-$ in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 7 for limits on cross section times branching ratio for $m_{H^+} = 0.3\text{--}2.0 \text{ TeV}$, and also for limits on the fraction of the triplet vev contribution to the W mass in the Georgi-Machacek model.
- 14 SIRUNYAN 19CC search for $t \rightarrow bH^+$ from pair produced top quarks, with the decay chain $H^+ \rightarrow W^+A^0, A^0 \rightarrow \mu^+\mu^-$ in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 2 for limits on the product of branching ratios for $m_{A^0} = 15\text{--}75 \text{ GeV}$.
- 15 SIRUNYAN 19CQ search for vector boson fusion production of H^+ decaying to $H^+ \rightarrow W^+Z \rightarrow \ell^+\nu q\bar{q}$ or $q\bar{q}\ell^+\ell^-$ in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 5 for limits on cross section times branching ratio for $m_{H^+} = 0.6\text{--}2.0 \text{ TeV}$, and also for limits on the triplet vacuum expectation value fraction in the Georgi-Machacek model.
- 16 AABOUD 18BW search for $\bar{t}bH^+$ associated production or the decay $t \rightarrow bH^+$, followed by $H^+ \rightarrow \tau^+\nu$, in 36.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 8(a) for upper limits on cross section times branching ratio for $m_{H^+} = 90\text{--}2000 \text{ GeV}$, and Fig. 8(b) for limits on $B(t \rightarrow bH^+) B(H^+ \rightarrow \tau^+\nu)$ for $m_{H^+} = 90\text{--}160 \text{ GeV}$. See also their Fig. 9 for the excluded region in the hMSSM parameter space.
- 17 AABOUD 18CD search for $\bar{t}bH^+$ associated production followed by $H^+ \rightarrow t\bar{b}$ in 36.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 8 for upper limits on cross section times branching ratio for $m_{H^+} = 0.2\text{--}2 \text{ TeV}$. See also their Fig. 9 for the excluded region in the parameter space of the $m_h^{\text{mod-}}$ and hMSSM scenarios of the MSSM. The theory predictions overlaid to the experimental limits to determine the excluded m_{H^+} range are shown without their respective uncertainty band.
- 18 AABOUD 18CH search for vector boson fusion production of H^\pm decaying to $H^\pm \rightarrow W^\pm Z \rightarrow \ell^\pm\nu\ell^+\ell^-$ in 36.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 7 for limits on cross section times branching ratio for $m_{H^\pm} = 0.2\text{--}0.9 \text{ TeV}$, and also for limits on the triplet vacuum expectation value fraction in the Georgi-Machacek model.
- 19 HALLER 18 give 95% CL lower limits on m_{H^+} of 590 GeV in type II two Higgs doublet model from combined data (including an unpublished BELLE result) for $B(b \rightarrow s\gamma)$.

- ²⁰ SIRUNYAN 18DO search for $t\bar{t}$ production followed by $t \rightarrow bH^+$, $H^+ \rightarrow c\bar{b}$ in 19.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. See their Fig. 3 for upper limits on $B(t \rightarrow bH^+)$ for $m_{H^+} = 90\text{--}150 \text{ GeV}$ assuming that $B(H^+ \rightarrow c\bar{b}) = 1$ and $B(t \rightarrow bH^+) + B(t \rightarrow bW^+) = 1$.
- ²¹ MISIAK 17 give 95% CL lower limits on m_{H^+} between 570 and 800 GeV in type II two Higgs doublet model from combined data (including an unpublished BELLE result) for $B(b \rightarrow s(d)\gamma)$.
- ²² SIRUNYAN 17AE search for vector boson fusion production of H^\pm decaying to $H^\pm \rightarrow W^\pm Z \rightarrow \ell^\pm \nu \ell^+ \ell^-$ in 15.2 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 3 for limits on cross section times branching ratio for $m_{H^\pm} = 0.2\text{--}2.0 \text{ TeV}$, and also for limits on the triplet vacuum expectation value fraction in the Georgi-Machacek model.
- ²³ AABOUD 16A search for $t(b) H^\pm$ associated production followed by $H^+ \rightarrow \tau^+ \nu$ in 3.2 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. Upper limits on $\sigma(t(b) H^\pm) B(H^+ \rightarrow \tau\nu)$ between 1.9 pb and 15 fb (95% CL) are given for $m_{H^+} = 200\text{--}2000 \text{ GeV}$, see their Fig. 6. See their Fig. 7 for the excluded regions in the hMSSM scenario.
- ²⁴ AAD 16AJ search for $t(b) H^\pm$ associated production followed by $H^\pm \rightarrow tb$ in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. See their Fig. 6 for upper limits on $\sigma(t(b) H^\pm) B(H^+ \rightarrow tb)$ for $m_{H^+} = 200\text{--}600 \text{ GeV}$.
- ²⁵ AAD 16AJ search for H^\pm production from quark-antiquark annihilation, followed by $H^\pm \rightarrow tb$, in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. See their Fig. 10 for upper limits on $\sigma(H^\pm) B(H^+ \rightarrow tb)$ for $m_{H^+} = 400\text{--}3000 \text{ GeV}$.
- ²⁶ AAD 15AF search for tH^\pm associated production followed by $H^\pm \rightarrow \tau^\pm \nu$ in 19.5 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. Upper limits on $\sigma(tH^\pm) B(H^+ \rightarrow \tau\nu)$ between 760 and 4.5 fb (95% CL) are given for $m_{H^+} = 180\text{--}1000 \text{ GeV}$. See their Fig. 8 for the excluded regions in different benchmark scenarios of the MSSM.
- ²⁷ AAD 15M search for vector boson fusion production of H^\pm decaying to $H^\pm \rightarrow W^\pm Z \rightarrow q\bar{q}\ell^+\ell^-$ in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. See their Fig. 2 for limits on cross section times branching ratio for $m_{H^\pm} = 200\text{--}1000 \text{ GeV}$, and Fig. 3 for limits on the triplet vacuum expectation value fraction in the Georgi-Machacek model.
- ²⁸ KHACHATRYAN 15AX search for tH^\pm associated production followed by $H^\pm \rightarrow tb$ in 19.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. Upper limits on $\sigma(tH^\pm) B(H^+ \rightarrow t\bar{b})$ between 2.0 and 0.13 pb (95% CL) are given for $m_{H^+} = 180\text{--}600 \text{ GeV}$. See their Fig. 11 for the excluded regions in different benchmark scenarios of the MSSM.
- ²⁹ KHACHATRYAN 15AX search for tH^\pm associated production followed by $H^\pm \rightarrow \tau^\pm \nu$ in 19.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. Upper limits on $\sigma(tH^\pm) B(H^+ \rightarrow \tau\nu)$ between 380 and 25 fb (95% CL) are given for $m_{H^+} = 180\text{--}600 \text{ GeV}$. See their Fig. 11 for the excluded regions in different benchmark scenarios of the MSSM.
- ³⁰ KHACHATRYAN 15BF search for $t\bar{t}$ production followed by $t \rightarrow bH^+$, $H^+ \rightarrow c\bar{s}$ in 19.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. Upper limits on $B(t \rightarrow bH^+) B(H^+ \rightarrow c\bar{s})$ between 1.2×10^{-2} and 6.5×10^{-2} (95% CL) are given for $m_{H^+} = 90\text{--}160 \text{ GeV}$.
- ³¹ 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 $b\bar{b}$ in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. See their Table III for limits on cross section times branching ratio for $m_{H_2^0} = 325\text{--}1025 \text{ GeV}$ and $m_{H^+} = 225\text{--}925 \text{ GeV}$.
- ³² AALTONEN 14A measure $B(t \rightarrow b\tau\nu) = 0.096 \pm 0.028$ using 9 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. For $m_{H^+} = 80\text{--}140 \text{ GeV}$, this measured value is translated to a limit $B(t \rightarrow bH^+) < 0.059$ at 95% CL assuming $B(H^+ \rightarrow \tau^+\nu) = 1$.
- ³³ AAD 13AC search for $t\bar{t}$ production followed by $t \rightarrow bH^+$, $H^+ \rightarrow c\bar{s}$ (flavor unidentified) in 4.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 7 \text{ TeV}$. Upper limits on $B(t \rightarrow bH^+)$ between 0.05 and 0.01 (95%CL) are given for $m_{H^+} = 90\text{--}150 \text{ GeV}$ and $B(H^+ \rightarrow c\bar{s}) = 1$.

- ³⁴ AAD 13V search for $t\bar{t}$ production followed by $t \rightarrow bH^+$, $H^+ \rightarrow \tau^+\nu$ through violation of lepton universality with 4.6 fb^{-1} of pp collisions at $E_{\text{cm}} = 7 \text{ TeV}$. Upper limits on $B(t \rightarrow bH^+)$ between 0.032 and 0.044 (95% CL) are given for $m_{H^+} = 90\text{--}140 \text{ GeV}$ and $B(H^+ \rightarrow \tau^+\nu) = 1$. By combining with AAD 12BH, the limits improve to 0.008 to 0.034 for $m_{H^+} = 90\text{--}160 \text{ GeV}$. See their Fig. 7 for the excluded region in the m_h^{max} scenario of the MSSM.
- ³⁵ 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 $E_{\text{cm}} = 7 \text{ TeV}$. Upper limits on $B(t \rightarrow bH^+)$ between 0.01 and 0.05 (95% CL) are given for $m_{H^+} = 90\text{--}160 \text{ GeV}$ and $B(H^+ \rightarrow \tau^+\nu) = 1$. See their Fig. 8 for the excluded region in the m_h^{max} scenario of the MSSM.
- ³⁶ 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 $E_{\text{cm}} = 7 \text{ TeV}$. Upper limits on $B(t \rightarrow bH^+)$ between 0.019 and 0.041 (95% CL) are given for $m_{H^+} = 80\text{--}160 \text{ GeV}$ and $B(H^+ \rightarrow \tau^+\nu) = 1$.
- ³⁷ AALTONEN 11P search in 2.7 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$ 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 $90 < m_{H^+} < 160 \text{ GeV}$.
- ³⁸ 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 $Z \rightarrow b\bar{b}$. The limit holds irrespective of $\tan\beta$.
- ³⁹ AALTONEN 09AJ search for $t \rightarrow bH^+$, $H^+ \rightarrow c\bar{s}$ in $t\bar{t}$ events in 2.2 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. Upper limits on $B(t \rightarrow bH^+)$ between 0.08 and 0.32 (95% CL) are given for $m_{H^+} = 60\text{--}150 \text{ GeV}$ and $B(H^+ \rightarrow c\bar{s}) = 1$.
- ⁴⁰ 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 $E_{\text{cm}} = 1.96 \text{ TeV}$. Upper limits on $B(t \rightarrow bH^+)$ between 0.19 and 0.25 (95% CL) are given for $m_{H^+} = 80\text{--}155 \text{ GeV}$ and $B(H^+ \rightarrow \tau^+\nu) = 1$. See their Fig. 4 for an excluded region in a MSSM scenario.
- ⁴¹ ABAZOV 09AG measure $t\bar{t}$ cross sections in final states with $\ell + \text{jets}$ ($\ell = e, \mu$), $\ell\ell$, and $\tau\ell$ in 1 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$, 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 $m_{H^+} = 80\text{--}155 \text{ GeV}$.
- ⁴² ABAZOV 09AI search for $t \rightarrow bH^+$ in $t\bar{t}$ events in 1 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. Final states with $\ell + \text{jets}$ ($\ell = e, \mu$), $\ell\ell$, and $\tau\ell$ are examined. Upper limits on $B(t \rightarrow bH^+)$ (95% CL) between 0.15 and 0.19 (0.19 and 0.22) are given for $B(H^+ \rightarrow \tau^+\nu) = 1$ ($B(H^+ \rightarrow c\bar{s}) = 1$) for $m_{H^+} = 80\text{--}155 \text{ GeV}$. For $B(H^+ \rightarrow \tau^+\nu) = 1$ also a simultaneous extraction of $B(t \rightarrow bH^+)$ and the $t\bar{t}$ cross section is performed, yielding a limit on $B(t \rightarrow bH^+)$ between 0.12 and 0.26 for $m_{H^+} = 80\text{--}155 \text{ GeV}$. See their Figs. 5–8 for excluded regions in several MSSM scenarios.
- ⁴³ ABAZOV 09P search for H^+ production by $q\bar{q}'$ annihilation followed by $H^+ \rightarrow t\bar{b}$ decay in 0.9 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. Cross section limits in several two-doublet models are given for $m_{H^+} = 180\text{--}300 \text{ GeV}$. A region with $20 \lesssim \tan\beta \lesssim 70$ is excluded (95% CL) for $180 \text{ GeV} \lesssim m_{H^+} \lesssim 184 \text{ GeV}$ in type-I models.
- ⁴⁴ ABULENCIA 06E search for associated $H^0 W$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. 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 $m_{H^\pm} = 80\text{--}160$ GeV. See Fig. 2 for the excluded region in a certain MSSM scenario.
- 45 ABDALLAH 04I search for $e^+e^- \rightarrow H^+H^-$ with H^\pm decaying to $\tau\nu$, $c s$, or W^*A^0 in Type-I two-Higgs-doublet models.
- 46 ABBIENDI 03 give a limit $m_{H^\pm} > 1.28 \tan\beta$ GeV (95%CL) in Type II two-doublet models.
- 47 ABAZOV 02B search for a charged Higgs boson in top decays with $H^+ \rightarrow \tau^+\nu$ at $E_{\text{cm}}=1.8$ TeV. For $m_{H^\pm}=75$ 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.
- 48 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.
- 49 ABBIENDI 01Q give a limit $\tan\beta/m_{H^\pm} < 0.53$ GeV $^{-1}$ (95%CL) in Type II two-doublet models.
- 50 BARATE 01E give a limit $\tan\beta/m_{H^\pm} < 0.40$ GeV $^{-1}$ (90% CL) in Type II two-doublet models. An independent measurement of $B \rightarrow \tau\nu_\tau X$ gives $\tan\beta/m_{H^\pm} < 0.49$ GeV $^{-1}$ (90% CL).
- 51 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.
- 52 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^\pm} up to 160 GeV is excluded. Updates ABE 97L.
- 53 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 $\tan\beta \lesssim 1$, $50 < m_{H^\pm}(\text{GeV}) \lesssim 120$ and $\tan\beta \gtrsim 40$, $50 < m_{H^\pm}(\text{GeV}) \lesssim 160$. See Fig. 3 for the details of the excluded region.
- 54 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 $m_{H^\pm} > 0.97 \tan\beta$ GeV (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.
- 55 ACCIARRI 97F give a limit $m_{H^\pm} > 2.6 \tan\beta$ GeV (90% CL) from their limit on the exclusive $B \rightarrow \tau\nu_\tau$ branching ratio.
- 56 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^\pm} in a two-doublet model $m_{H^\pm} > 0.97 \tan\beta$ GeV (90% CL).
- 57 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.
- 58 GUCHAIT 97 studies the constraints on m_{H^\pm} 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.
- 59 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.
- 60 STAHL 97 fit τ lifetime, leptonic branching ratios, and the Michel parameters and derive limit $m_{H^\pm} > 1.5 \tan\beta$ GeV (90% CL) for a two-doublet model. See also STAHL 94.
- 61 ALAM 95 measure the inclusive $b \rightarrow s\gamma$ branching ratio at $\mathcal{T}(4S)$ and give $B(b \rightarrow s\gamma) < 4.2 \times 10^{-4}$ (95% CL), which translates to the limit $m_{H^\pm} > [244 + 63/(\tan\beta)^{1.3}]$ GeV in the Type II two-doublet model. Light supersymmetric particles can invalidate this bound.
- 62 BUSKULIC 95 give a limit $m_{H^\pm} > 1.9 \tan\beta$ GeV (90% CL) for Type-II models from $b \rightarrow \tau\nu_\tau X$ branching ratio, as proposed in GROSSMAN 94.

———— **H^\pm (charged Higgs) mass limits for $m_{H^\pm} > m(\text{top})$** ————

Limits obtained at the LHC are given in the m_h^{mod-} benchmark scenario, see CARENA 13, and depend on the $\tan\beta$ values.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 181	95	¹ AABOUD	18BWATLS	$\tan\beta = 10$
> 249	95	¹ AABOUD	18BWATLS	$\tan\beta = 20$
> 390	95	¹ AABOUD	18BWATLS	$\tan\beta = 30$
> 894	95	¹ AABOUD	18BWATLS	$\tan\beta = 40$
> 1017	95	¹ AABOUD	18BWATLS	$\tan\beta = 50$
> 1103	95	¹ AABOUD	18BWATLS	$\tan\beta = 60$

¹AABOUD 18BW search for $\bar{t}bH^+$ associated production in 36.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See also their Fig. 9 for the excluded region in the hMSSM parameter space.

———— **$H^{\pm\pm}$ (doubly-charged Higgs boson) mass limits** ————

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 $T_3 = \pm 1$

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>220	95	¹ AABOUD	19K ATLS	$W^\pm W^\pm$
>768	95	² AABOUD	18BC ATLS	ee
>846	95	² AABOUD	18BC ATLS	$\mu\mu$
>468	95	³ AAD	15AG ATLS	$e\mu$
>400	95	⁴ AAD	15AP ATLS	$e\tau$
>400	95	⁴ AAD	15AP ATLS	$\mu\tau$
>169	95	⁵ CHATRCHYAN	12AU CMS	$\tau\tau$
>300	95	⁵ CHATRCHYAN	12AU CMS	$\mu\tau$
>293	95	⁵ CHATRCHYAN	12AU CMS	$e\tau$
>395	95	⁵ CHATRCHYAN	12AU CMS	$\mu\mu$
>391	95	⁵ CHATRCHYAN	12AU CMS	$e\mu$
>382	95	⁵ CHATRCHYAN	12AU CMS	ee
> 98.1	95	⁶ ABDALLAH	03 DLPH	$\tau\tau$
> 99.0	95	⁷ ABBIENDI	02C OPAL	$\tau\tau$

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

>350	95	⁸ AAD	21U ATLS	$W^\pm W^\pm$
>230	95	⁹ AAD	21U ATLS	$H^{\pm\pm} H^\mp$ associated production, $H^{\pm\pm} \rightarrow W^\pm W^\pm$, $H^\pm \rightarrow W^\pm Z$
		¹⁰ SIRUNYAN	21W CMS	$W^\pm W^\pm$
		¹¹ SIRUNYAN	19CQ CMS	$W^\pm W^\pm$

		12	SIRUNYAN	18CC CMS	$W^\pm W^\pm$
>551	95	3	AAD	15AG ATLS	$e e$
>516	95	3	AAD	15AG ATLS	$\mu\mu$
		13	KANEMURA	15 RVUE	$W^{(*)\pm} W^{(*)\pm}$
		14	KHACHATRY...	15D CMS	$W^\pm W^\pm$
		15	KANEMURA	14 RVUE	$W^{(*)\pm} W^{(*)\pm}$
>330	95	16	AAD	13Y ATLS	$\mu\mu$
>237	95	16	AAD	13Y ATLS	$\mu\tau$
>355	95	17	AAD	12AY ATLS	$\mu\mu$
>398	95	18	AAD	12CQ ATLS	$\mu\mu$
>375	95	18	AAD	12CQ ATLS	$e\mu$
>409	95	18	AAD	12CQ ATLS	$e e$
>128	95	19	ABAZOV	12A D0	$\tau\tau$
>144	95	19	ABAZOV	12A D0	$\mu\tau$
>245	95	20	AALTONEN	11AF CDF	$\mu\mu$
>210	95	20	AALTONEN	11AF CDF	$e\mu$
>225	95	20	AALTONEN	11AF CDF	$e e$
>114	95	21	AALTONEN	08AA CDF	$e\tau$
>112	95	21	AALTONEN	08AA CDF	$\mu\tau$
>168	95	22	ABAZOV	08V D0	$\mu\mu$
		23	AKTAS	06A H1	single $H^{\pm\pm}$
>133	95	24	ACOSTA	05L CDF	stable
>118.4	95	25	ABAZOV	04E D0	$\mu\mu$
		26	ABBIENDI	03Q OPAL	$E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$
		27	GORDEEV	97 SPEC	muonium conversion
		28	ASAKA	95 THEO	
> 45.6	95	29	ACTON	92M OPAL	
> 30.4	95	30	ACTON	92M OPAL	
none 6.5–36.6	95	31	SWARTZ	90 MRK2	

¹ AABOUD 19K search for pair production of $H^{++} H^{--}$ followed by the decay $H^{\pm\pm} \rightarrow W^\pm W^\pm$ in 36.1 fb^{-1} of pp collisions at $E_{\text{cm}} = 13$ TeV. The search is interpreted in a doublet-triplet extension of the scalar sector with a vev of 0.1 GeV, leading to $B(H^{\pm\pm} \rightarrow W^\pm W^\pm) = 1$. See their Fig. 5 for limits on the cross section for $m_{H^{++}}$ between 200 and 700 GeV.

² See their Figs. 11(b) and 13 for limits with smaller branching ratios.

³ AAD 15AG search for $H^{++} H^{--}$ production in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8$ TeV. The limit assumes 100% branching ratio to the specified final state. See their Fig. 5 for limits for arbitrary branching ratios.

⁴ AAD 15AP search for $H^{++} H^{--}$ production in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8$ TeV. The limit assumes 100% branching ratio to the specified final state.

⁵ CHATRCHYAN 12AU search for $H^{++} H^{--}$ production with 4.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 7$ 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.

⁶ ABDALLAH 03 search for $H^{++} H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+ \tau^+$, or decaying outside the detector.

⁷ 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 $g(H\ell\ell) \gtrsim 10^{-7}$.

- ⁸ AAD 21U search for pair production of $H^{++}H^{--}$ followed by the decay $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ in 139 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. The search is interpreted in a triplet extension of the SM Higgs sector with a triplet vev of 0.1 GeV, leading to $B(H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}) = 1$. See their Fig. 9(a) for limits on the cross section for $m_{H^{++}}$ between 200 and 600 GeV.
- ⁹ AAD 21U search for associated production of $H^{\pm\pm}H^{\mp}$ followed by the decays $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$, $H^{\pm} \rightarrow W^{\pm}Z$ in 139 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. $H^{\pm\pm}$ and H^{\pm} are assumed to be degenerate in mass within 5 GeV. The search is interpreted in a triplet extension of the SM Higgs sector with a triplet vev of 0.1 GeV, leading to $B(H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}) = 1$. See their Fig. 9(b) for limits on the cross section for $m_{H^{++}}$ between 200 and 600 GeV.
- ¹⁰ SIRUNYAN 21W search for vector boson fusion production of $H^{\pm\pm}$ decaying to $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu$ in 137 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 8 for limits on cross section times branching ratio for $m_{H^{++}} = 0.2\text{--}3.0 \text{ TeV}$.
- ¹¹ SIRUNYAN 19CQ search for $H^{\pm\pm}$ production by vector boson fusion followed by the decay $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm} \rightarrow qq\ell\nu$ in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 5 for limits on cross section times branching ratio for $m_{H^{\pm\pm}}$ between 0.6 and 2 TeV.
- ¹² SIRUNYAN 18CC search for $H^{\pm\pm}$ production by vector boson fusion followed by the decay $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ in 35.9 fb^{-1} of pp collisions at $E_{\text{cm}} = 13 \text{ TeV}$. See their Fig. 3 for limits on cross section times branching ratio for $m_{H^{\pm\pm}}$ between 200 and 1000 GeV.
- ¹³ KANEMURA 15 examine the case where H^{++} decays preferentially to $W^{(*)}W^{(*)}$ and estimate that a lower mass limit of $\sim 84 \text{ GeV}$ can be derived from the same-sign dilepton data of AAD 15AG if H^{++} decays with 100% branching ratio to $W^{(*)}W^{(*)}$.
- ¹⁴ KHACHATRYAN 15D search for $H^{\pm\pm}$ production by vector boson fusion followed by the decay $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ in 19.4 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. See their Fig. 4 for limits on cross section times branching ratio for $m_{H^{++}}$ between 160 and 800 GeV.
- ¹⁵ KANEMURA 14 examine the case where H^{++} decays preferentially to $W^{(*)}W^{(*)}$ and estimate that a lower mass limit of $\sim 60 \text{ GeV}$ can be derived from the same-sign dilepton data of AAD 12CY.
- ¹⁶ AAD 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 $E_{\text{cm}} = 7 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state.
- ¹⁷ AAD 12AY search for $H^{++}H^{--}$ production with 1.6 fb^{-1} of pp collisions at $E_{\text{cm}} = 7 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state.
- ¹⁸ AAD 12CQ search for $H^{++}H^{--}$ production with 4.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 7 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state. See their Table 1 for limits assuming smaller branching ratios.
- ¹⁹ ABAZOV 12A search for $H^{++}H^{--}$ production in 7.0 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$.
- ²⁰ AALTONEN 11AF search for $H^{++}H^{--}$ production in 6.1 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$.
- ²¹ AALTONEN 08AA search for $H^{++}H^{--}$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state.
- ²² ABAZOV 08V search for $H^{++}H^{--}$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. The limit is for $B(H \rightarrow \mu\mu) = 1$. The limit is updated in ABAZOV 12A.
- ²³ 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 $m_{H^{++}} > 141 \text{ GeV}$ (95% CL) is derived. For the case where H^{++} couples to $e\tau$ only the limit is 112 GeV.
- ²⁴ 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.

- ²⁵ ABAZOV 04E search for $H^{++} H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^{\pm} \mu^{\pm}$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.
- ²⁶ 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).
- ²⁷ 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.
- ²⁸ 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.
- ²⁹ 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.
- ³⁰ ACTON 92M from $\Delta\Gamma_Z < 40$ MeV.
- ³¹ 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 (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 58	95	1 AABOUD	18BC ATLS	ee
>723	95	1 AABOUD	18BC ATLS	$\mu\mu$
>402	95	2 AAD	15AG ATLS	$e\mu$
>290	95	3 AAD	15AP ATLS	$e\tau$
>290	95	3 AAD	15AP ATLS	$\mu\tau$
> 97.3	95	4 ABDALLAH	03 DLPH	$\tau\tau$
> 97.3	95	5 ACHARD	03F L3	$\tau\tau$
> 98.5	95	6 ABBIENDI	02C OPAL	$\tau\tau$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>374	95	2 AAD	15AG ATLS	ee
>438	95	2 AAD	15AG ATLS	$\mu\mu$
>251	95	7 AAD	12AY ATLS	$\mu\mu$
>306	95	8 AAD	12CQ ATLS	$\mu\mu$
>310	95	8 AAD	12CQ ATLS	$e\mu$
>322	95	8 AAD	12CQ ATLS	ee
>113	95	9 ABAZOV	12A D0	$\mu\tau$
>205	95	10 AALTONEN	11AF CDF	$\mu\mu$
>190	95	10 AALTONEN	11AF CDF	$e\mu$
>205	95	10 AALTONEN	11AF CDF	ee
>145	95	11 ABAZOV	08V D0	$\mu\mu$
		12 AKTAS	06A H1	single $H^{\pm\pm}$
>109	95	13 ACOSTA	05L CDF	stable
> 98.2	95	14 ABAZOV	04E D0	$\mu\mu$
		15 ABBIENDI	03Q OPAL	$E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$

		16	GORDEEV	97	SPEC	muonium conversion
> 45.6	95	17	ACTON	92M	OPAL	
> 25.5	95	18	ACTON	92M	OPAL	
none 7.3–34.3	95	19	SWARTZ	90	MRK2	

¹ See their Figs. 12(b) and 14 for limits with smaller branching ratios.

² AAD 15AG search for $H^{++}H^{--}$ production in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state. See their Fig. 5 for limits for arbitrary branching ratios.

³ AAD 15AP search for $H^{++}H^{--}$ production in 20.3 fb^{-1} of pp collisions at $E_{\text{cm}} = 8 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state.

⁴ ABDALLAH 03 search for $H^{++}H^{--}$ pair production either followed by $H^{++} \rightarrow \tau^+\tau^+$, or decaying outside the detector.

⁵ 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 $g_{\ell\ell'} \gtrsim 10^{-7}$.

⁶ 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 $g(H\ell\ell) \gtrsim 10^{-7}$.

⁷ AAD 12AY search for $H^{++}H^{--}$ production with 1.6 fb^{-1} of pp collisions at $E_{\text{cm}} = 7 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state.

⁸ AAD 12CQ search for $H^{++}H^{--}$ production with 4.7 fb^{-1} of pp collisions at $E_{\text{cm}} = 7 \text{ TeV}$. The limit assumes 100% branching ratio to the specified final state. See their Table 1 for limits assuming smaller branching ratios.

⁹ ABAZOV 12A search for $H^{++}H^{--}$ production in 7.0 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$.

¹⁰ AALTONEN 11AF search for $H^{++}H^{--}$ production in 6.1 fb^{-1} of $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$.

¹¹ ABAZOV 08V search for $H^{++}H^{--}$ production in $p\bar{p}$ collisions at $E_{\text{cm}} = 1.96 \text{ TeV}$. 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 $m_{H^{++}} > 141 \text{ GeV}$ (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 $p\bar{p}$ collisions. The limit is valid for $g_{\ell\ell'} < 10^{-8}$ so that the Higgs decays outside the detector.

¹⁴ ABAZOV 04E search for $H^{++}H^{--}$ pair production in $H^{\pm\pm} \rightarrow \mu^\pm\mu^\pm$. The limit is valid for $g_{\mu\mu} \gtrsim 10^{-7}$.

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 $B(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm) = 1$, a 95% CL limit on $h_{ee} < 0.071$ is set for $m_{H^{\pm\pm}} < 160 \text{ GeV}$ (see Fig. 6). In the second case, indirect limits on h_{ee} are set for $m_{H^{\pm\pm}} < 2 \text{ TeV}$ (see Fig. 8).

¹⁶ 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 $m_{H^{++}} > 210 \text{ GeV}$ 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.

¹⁷ 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.

¹⁸ ACTON 92M from $\Delta\Gamma_Z < 40$ MeV.

¹⁹ 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 $e e$ and $\mu\mu$ decay modes.

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