

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

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- $H^\pm$  (Charged Higgs) Mass Limits
- Mass limits for  $H^{\pm\pm}$  (doubly-charged Higgs boson)
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  - Limits for  $H^{\pm\pm}$  with  $T_3 = 0$

## ————— $H^\pm$ (Charged Higgs) MASS LIMITS —————

Unless otherwise stated, the limits below assume  $B(H^+ \rightarrow \tau^+ \nu) + B(H^+ \rightarrow c \bar{s}) = 1$ , 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conclusively ruled out the existence of a charged Higgs in the region  $m_{H^\pm} \lesssim 45$  GeV, and are meanwhile superseded by the searches in higher energy  $e^+ e^-$  collisions at LEP.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
> <b>80</b>	95	<sup>1</sup> LEP	13	LEP $e^+ e^- \rightarrow H^+ H^-, E_{\text{cm}} \leq 209 \text{ GeV}$
> 76.3	95	<sup>2</sup> ABBIENDI	12	OPAL $e^+ e^- \rightarrow H^+ H^-, E_{\text{cm}} \leq 209 \text{ GeV}$
> 74.4	95	ABDALLAH	04I	DLPH $E_{\text{cm}} \leq 209 \text{ GeV}$
> 76.5	95	ACHARD	03E	L3 $E_{\text{cm}} \leq 209 \text{ GeV}$
> 79.3	95	HEISTER	02P	ALEP $E_{\text{cm}} \leq 209 \text{ GeV}$

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

<sup>3</sup> AAD	15AF ATLS	$t \rightarrow b H^+$
<sup>4</sup> AAD	15AF ATLS	$t H^\pm$
<sup>5</sup> AAD	15M ATLS	$H^\pm \rightarrow W^\pm Z$
<sup>6</sup> KHACHATRY...	15AX CMS	$t \rightarrow b H^+, H^+ \rightarrow \tau^+ \nu$

		7	KHACHATRY...15AX	CMS	$tH^+, H^+ \rightarrow t\bar{b}$
		8	KHACHATRY...15AX	CMS	$tH^\pm, H^\pm \rightarrow \tau^\pm\nu$
		9	KHACHATRY...15BF	CMS	$t \rightarrow bH^+, H^+ \rightarrow c\bar{s}$
		10	AAD	14M ATLS	$H_2^0 \rightarrow H^\pm W^\mp \rightarrow$ $H^0 W^\pm W^\mp, H^0 \rightarrow b\bar{b}$
		11	AALTONEN	14A CDF	$t \rightarrow b\tau\nu$
		12	AAD	13AC ATLS	$t \rightarrow bH^+$
		13	AAD	13V ATLS	$t \rightarrow bH^+$ , lepton non- universality
		14	AAD	12BH ATLS	$t \rightarrow bH^+$
		15	CHATRCHYAN	12AA CMS	$t \rightarrow bH^+$
		16	AALTONEN	11P CDF	$t \rightarrow bH^+, H^+ \rightarrow W^+ A^0$
>316	95	17	DESCHAMPS	10 RVUE	Type II, flavor physics data
		18	AALTONEN	09AJ CDF	$t \rightarrow bH^+$
		19	ABAZOV	09AC D0	$t \rightarrow bH^+$
		20	ABAZOV	09AG D0	$t \rightarrow bH^+$
		21	ABAZOV	09AI D0	$t \rightarrow bH^+$
		22	ABAZOV	09P D0	$H^+ \rightarrow t\bar{b}$
		23	ABULENCIA	06E CDF	$t \rightarrow bH^+$
> 92.0	95		ABBIENDI	04 OPAL	$B(\tau\nu) = 1$
> 76.7	95	24	ABDALLAH	04I DLPH	Type I
		25	ABBIENDI	03 OPAL	$\tau \rightarrow \mu\bar{\nu}\nu, e\bar{\nu}\nu$
		26	ABAZOV	02B D0	$t \rightarrow bH^+, H \rightarrow \tau\nu$
		27	BORZUMATI	02 RVUE	
		28	ABBIENDI	01Q OPAL	$B \rightarrow \tau\nu_\tau X$
		29	BARATE	01E ALEP	$B \rightarrow \tau\nu_\tau$
>315	99	30	GAMBINO	01 RVUE	$b \rightarrow s\gamma$
> 59.5	95	31	AFFOLDER	00I CDF	$t \rightarrow bH^+, H \rightarrow \tau\nu$
			ABBIENDI	99E OPAL	$E_{\text{cm}} \leq 183 \text{ GeV}$
		32	ABBOTT	99E D0	$t \rightarrow bH^+$
		33	ACKERSTAFF	99D OPAL	$\tau \rightarrow e\nu\nu, \mu\nu\nu$
		34	ACCIARRI	97F L3	$B \rightarrow \tau\nu_\tau$
		35	AMMAR	97B CLEO	$\tau \rightarrow \mu\nu\nu$
		36	COARASA	97 RVUE	$B \rightarrow \tau\nu_\tau X$
		37	GUCHAIT	97 RVUE	$t \rightarrow bH^+, H \rightarrow \tau\nu$
		38	MANGANO	97 RVUE	$B_{u(c)} \rightarrow \tau\nu_\tau$
		39	STAHL	97 RVUE	$\tau \rightarrow \mu\nu\nu$
>244	95	40	ALAM	95 CLE2	$b \rightarrow s\gamma$
		41	BUSKULIC	95 ALEP	$b \rightarrow \tau\nu_\tau X$

<sup>1</sup> 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  $m_{A^0} > 12 \text{ GeV}$ .

<sup>2</sup> ABBIENDI 12 also search for the decay mode  $H^+ \rightarrow A^0 W^*$  with  $A^0 \rightarrow b\bar{b}$ .

- <sup>3</sup> AAD 15AF search for  $t\bar{t}$  production followed by  $t \rightarrow bH^+$ ,  $H^+ \rightarrow \tau^+\nu$  in  $19.5 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 8 \text{ TeV}$ . Upper limits on  $B(t \rightarrow bH^+) B(H^+ \rightarrow \tau\nu)$  between  $2.3 \times 10^{-3}$  and  $1.3 \times 10^{-2}$  (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.
- <sup>4</sup> AAD 15AF search for  $tH^\pm$  associated production followed by  $H^\pm \rightarrow \tau^\pm\nu$  in  $19.5 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 8 \text{ TeV}$ . Upper limits on  $\sigma(tH^\pm) B(H^+ \rightarrow \tau\nu)$  between 760 and  $4.5 \text{ fb}$  (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.
- <sup>5</sup> 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  $20.3 \text{ fb}^{-1}$  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.
- <sup>6</sup> KHACHATRYAN 15AX search for  $t\bar{t}$  production followed by  $t \rightarrow bH^+$ ,  $H^+ \rightarrow \tau^+\nu$  in  $19.7 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 8 \text{ TeV}$ . Upper limits on  $B(t \rightarrow bH^+) B(H^+ \rightarrow \tau\nu)$  between  $1.2 \times 10^{-2}$  and  $1.5 \times 10^{-3}$  (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.
- <sup>7</sup> KHACHATRYAN 15AX search for  $tH^\pm$  associated production followed by  $H^\pm \rightarrow t\bar{b}$  in  $19.7 \text{ fb}^{-1}$  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.
- <sup>8</sup> KHACHATRYAN 15AX search for  $tH^\pm$  associated production followed by  $H^\pm \rightarrow \tau^\pm\nu$  in  $19.7 \text{ fb}^{-1}$  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.
- <sup>9</sup> KHACHATRYAN 15BF search for  $t\bar{t}$  production followed by  $t \rightarrow bH^+$ ,  $H^+ \rightarrow c\bar{s}$  in  $19.7 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 8 \text{ TeV}$ . Upper limits on  $B(t \rightarrow bH^+) B(H^+ \rightarrow c\bar{s})$  between  $1.2 \times 10^{-2}$  and  $6.5 \times 10^{-2}$  (95% CL) are given for  $m_{H^+} = 90\text{--}160 \text{ GeV}$ .
- <sup>10</sup> 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  $20.3 \text{ fb}^{-1}$  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  $m_{H^+} = 225\text{--}925 \text{ GeV}$ .
- <sup>11</sup> AALTONEN 14A measure  $B(t \rightarrow b\tau\nu) = 0.096 \pm 0.028$  using  $9 \text{ fb}^{-1}$  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  $B(H^+ \rightarrow \tau^+\nu) = 1$ .
- <sup>12</sup> AAD 13AC search for  $t\bar{t}$  production followed by  $t \rightarrow bH^+$ ,  $H^+ \rightarrow c\bar{s}$  (flavor unidentified) in  $4.7 \text{ fb}^{-1}$  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  $B(H^+ \rightarrow c\bar{s}) = 1$ .
- <sup>13</sup> AAD 13V search for  $t\bar{t}$  production followed by  $t \rightarrow bH^+$ ,  $H^+ \rightarrow \tau^+\nu$  through violation of lepton universality with  $4.6 \text{ fb}^{-1}$  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  $m_h^{\text{max}}$  scenario of the MSSM.
- <sup>14</sup> AAD 12BH search for  $t\bar{t}$  production followed by  $t \rightarrow bH^+$ ,  $H^+ \rightarrow \tau^+\nu$  with  $4.6 \text{ fb}^{-1}$  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  $m_h^{\text{max}}$  scenario of the MSSM.

- 15 CHATRCHYAN 12AA search for  $t\bar{t}$  production followed by  $t \rightarrow bH^+$ ,  $H^+ \rightarrow \tau^+\nu$  with  $2 \text{ fb}^{-1}$  of  $p\bar{p}$  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  $B(H^+ \rightarrow \tau^+\nu)=1$ .
- 16 AALTONEN 11P search in  $2.7 \text{ fb}^{-1}$  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  $90 < m_{H^+} < 160 \text{ GeV}$ .
- 17 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  $\tan\beta$ .
- 18 AALTONEN 09AJ search for  $t \rightarrow bH^+$ ,  $H^+ \rightarrow c\bar{s}$  in  $t\bar{t}$  events in  $2.2 \text{ fb}^{-1}$  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  $B(H^+ \rightarrow c\bar{s}) = 1$ .
- 19 ABAZOV 09AC search for  $t \rightarrow bH^+$ ,  $H^+ \rightarrow \tau^+\nu$  in  $t\bar{t}$  events in  $0.9 \text{ fb}^{-1}$  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.
- 20 ABAZOV 09AG measure  $t\bar{t}$  cross sections in final states with  $\ell + \text{jets}$  ( $\ell = e, \mu$ ),  $\ell\ell$ , and  $\tau\ell$  in  $1 \text{ fb}^{-1}$  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  $m_{H^+} = 80\text{--}155 \text{ GeV}$ .
- 21 ABAZOV 09AI search for  $t \rightarrow bH^+$  in  $t\bar{t}$  events in  $1 \text{ fb}^{-1}$  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.
- 22 ABAZOV 09P search for  $H^+$  production by  $q\bar{q}'$  annihilation followed by  $H^+ \rightarrow t\bar{b}$  decay in  $0.9 \text{ fb}^{-1}$  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.
- 23 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 +  $\tau$  final states, with the decays  $t \rightarrow W^+ b$  and  $t \rightarrow H^+ b$  followed by  $H^+ \rightarrow \tau^+\nu$ ,  $c\bar{s}$ ,  $t^*\bar{b}$ , or  $W^+ H^0$ . Within the MSSM the search is sensitive to the region  $\tan\beta < 1$  or  $> 30$  in the mass range  $m_{H^+} = 80\text{--}160 \text{ GeV}$ . See Fig. 2 for the excluded region in a certain MSSM scenario.
- 24 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.
- 25 ABBIENDI 03 give a limit  $m_{H^+} > 1.28\tan\beta \text{ GeV}$  (95%CL) in Type II two-doublet models.
- 26 ABAZOV 02B search for a charged Higgs boson in top decays with  $H^+ \rightarrow \tau^+\nu$  at  $E_{\text{cm}}=1.8 \text{ TeV}$ . For  $m_{H^+}=75 \text{ GeV}$ , 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.
- 27 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.

- <sup>28</sup> ABBIENDI 01Q give a limit  $\tan\beta/m_{H^+} < 0.53 \text{ GeV}^{-1}$  (95%CL) in Type II two-doublet models.
- <sup>29</sup> 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).
- <sup>30</sup> 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.
- <sup>31</sup> AFFOLDER 00I search for a charged Higgs boson in top decays with  $H^+ \rightarrow \tau^+ \nu$  in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8 \text{ TeV}$ . 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.
- <sup>32</sup> ABBOTT 99E search for a charged Higgs boson in top decays in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8 \text{ TeV}$ , 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.
- <sup>33</sup> ACKERSTAFF 99D measure the Michel parameters  $\rho$ ,  $\xi$ ,  $\eta$ , and  $\xi\delta$  in leptonic  $\tau$  decays from  $Z \rightarrow \tau\tau$ . Assuming  $e$ - $\mu$  universality, the limit  $m_{H^+} > 0.97 \tan\beta \text{ GeV}$  (95%CL) is obtained for two-doublet models in which only one doublet couples to leptons.
- <sup>34</sup> ACCIARRI 97F give a limit  $m_{H^+} > 2.6 \tan\beta \text{ GeV}$  (90% CL) from their limit on the exclusive  $B \rightarrow \tau\nu_\tau$  branching ratio.
- <sup>35</sup> AMMAR 97B measure the Michel parameter  $\rho$  from  $\tau \rightarrow e\nu\nu$  decays and assumes  $e/\mu$  universality to extract the Michel  $\eta$  parameter from  $\tau \rightarrow \mu\nu\nu$  decays. The measurement is translated to a lower limit on  $m_{H^+}$  in a two-doublet model  $m_{H^+} > 0.97 \tan\beta \text{ GeV}$  (90% CL).
- <sup>36</sup> 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.
- <sup>37</sup> 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.
- <sup>38</sup> 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.
- <sup>39</sup> STAHL 97 fit  $\tau$  lifetime, leptonic branching ratios, and the Michel parameters and derive limit  $m_{H^+} > 1.5 \tan\beta \text{ GeV}$  (90% CL) for a two-doublet model. See also STAHL 94.
- <sup>40</sup> 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  $m_{H^+} > [244 + 63/(\tan\beta)^{1.3}] \text{ GeV}$  in the Type II two-doublet model. Light supersymmetric particles can invalidate this bound.
- <sup>41</sup> BUSKULIC 95 give a limit  $m_{H^+} > 1.9 \tan\beta \text{ GeV}$  (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  $T_3 = \pm 1$**

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;551</b>	95	1 AAD	15AG ATLS	$ee$
>468	95	1 AAD	15AG ATLS	$e\mu$
>516	95	1 AAD	15AG ATLS	$\mu\mu$
>400	95	2 AAD	15AP ATLS	$e\tau$
>400	95	2 AAD	15AP ATLS	$\mu\tau$
>169	95	3 CHATRCHYAN	12AU CMS	$\tau\tau$
>300	95	3 CHATRCHYAN	12AU CMS	$\mu\tau$
>293	95	3 CHATRCHYAN	12AU CMS	$e\tau$
>395	95	3 CHATRCHYAN	12AU CMS	$\mu\mu$
>391	95	3 CHATRCHYAN	12AU CMS	$e\mu$
>382	95	3 CHATRCHYAN	12AU CMS	$ee$
> 98.1	95	4 ABDALLAH	03 DLPH	$\tau\tau$
> 99.0	95	5 ABBIENDI	02C OPAL	$\tau\tau$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		6 KANEMURA	15 RVUE	$W^{(*)\pm} W^{(*)\pm}$
		7 KHACHATRY...	15D CMS	$W^\pm W^\pm$
		8 KANEMURA	14 RVUE	$W^{(*)\pm} W^{(*)\pm}$
>330	95	9 AAD	13Y ATLS	$\mu\mu$
>237	95	9 AAD	13Y ATLS	$\mu\tau$
>355	95	10 AAD	12AY ATLS	$\mu\mu$
>398	95	11 AAD	12CQ ATLS	$\mu\mu$
>375	95	11 AAD	12CQ ATLS	$e\mu$
>409	95	11 AAD	12CQ ATLS	$ee$
>128	95	12 ABAZOV	12A D0	$\tau\tau$
>144	95	12 ABAZOV	12A D0	$\mu\tau$
>245	95	13 AALTONEN	11AF CDF	$\mu\mu$
>210	95	13 AALTONEN	11AF CDF	$e\mu$
>225	95	13 AALTONEN	11AF CDF	$ee$
>114	95	14 AALTONEN	08AA CDF	$e\tau$
>112	95	14 AALTONEN	08AA CDF	$\mu\tau$
>168	95	15 ABAZOV	08V D0	$\mu\mu$
		16 AKTAS	06A H1	single $H^{\pm\pm}$
>133	95	17 ACOSTA	05L CDF	stable
>118.4	95	18 ABAZOV	04E D0	$\mu\mu$
		19 ABBIENDI	03Q OPAL	$E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$
		20 GORDEEV	97 SPEC	muonium conversion
		21 ASAKA	95 THEO	
> 45.6	95	22 ACTON	92M OPAL	
> 30.4	95	23 ACTON	92M OPAL	
none 6.5–36.6	95	24 SWARTZ	90 MRK2	

<sup>1</sup> AAD 15AG search for  $H^{++} H^{--}$  production in  $20.3 \text{ fb}^{-1}$  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.

- 2 AAD 15AP search for  $H^{++}H^{--}$  production in  $20.3 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 8 \text{ TeV}$ . The limit assumes 100% branching ratio to the specified final state.
- 3 CHATRCHYAN 12AU search for  $H^{++}H^{--}$  production with  $4.9 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 7 \text{ TeV}$ . The limit assumes 100% branching ratio to the specified final state. See their Table 6 for limits including associated  $H^{++}H^{-}$  production or assuming different scenarios.
- 4 ABDALLAH 03 search for  $H^{++}H^{--}$  pair production either followed by  $H^{++} \rightarrow \tau^+\tau^+$ , or decaying outside the detector.
- 5 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  $g(H\ell\ell) \gtrsim 10^{-7}$ .
- 6 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  $W^{(*)}W^{(*)}$ .
- 7 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  $19.4 \text{ fb}^{-1}$  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.
- 8 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.
- 9 AAD 13Y search for  $H^{++}H^{--}$  production in a generic search of events with three charged leptons in  $4.6 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 7 \text{ TeV}$ . The limit assumes 100% branching ratio to the specified final state.
- 10 AAD 12AY search for  $H^{++}H^{--}$  production with  $1.6 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 7 \text{ TeV}$ . The limit assumes 100% branching ratio to the specified final state.
- 11 AAD 12CQ search for  $H^{++}H^{--}$  production with  $4.7 \text{ fb}^{-1}$  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.
- 12 ABAZOV 12A search for  $H^{++}H^{--}$  production in  $7.0 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96 \text{ TeV}$ .
- 13 AALTONEN 11AF search for  $H^{++}H^{--}$  production in  $6.1 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96 \text{ TeV}$ .
- 14 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.
- 15 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.
- 16 AKTAS 06A search for single  $H^{\pm\pm}$  production in  $e\bar{p}$  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.
- 17 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.
- 18 ABAZOV 04E search for  $H^{++}H^{--}$  pair production in  $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$ . The limit is valid for  $g_{\mu\mu} \gtrsim 10^{-7}$ .
- 19 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).

- <sup>20</sup> 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.
- <sup>21</sup> 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.
- <sup>22</sup> 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.
- <sup>23</sup> ACTON 92M from  $\Delta\Gamma_Z < 40$  MeV.
- <sup>24</sup> 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
>374	95	1 AAD	15AG ATLS	$ee$
>402	95	1 AAD	15AG ATLS	$e\mu$
<b>&gt;438</b>	95	1 AAD	15AG ATLS	$\mu\mu$
>290	95	2 AAD	15AP ATLS	$e\tau$
>290	95	2 AAD	15AP ATLS	$\mu\tau$
> 97.3	95	3 ABDALLAH	03 DLPH	$\tau\tau$
> 97.3	95	4 ACHARD	03F L3	$\tau\tau$
> 98.5	95	5 ABBIENDI	02C OPAL	$\tau\tau$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>251	95	6 AAD	12AY ATLS	$\mu\mu$
>306	95	7 AAD	12CQ ATLS	$\mu\mu$
>310	95	7 AAD	12CQ ATLS	$e\mu$
>322	95	7 AAD	12CQ ATLS	$ee$
>113	95	8 ABAZOV	12A D0	$\mu\tau$
>205	95	9 AALTONEN	11AF CDF	$\mu\mu$
>190	95	9 AALTONEN	11AF CDF	$e\mu$
>205	95	9 AALTONEN	11AF CDF	$ee$
>145	95	10 ABAZOV	08V D0	$\mu\mu$
		11 AKTAS	06A H1	single $H^{\pm\pm}$
>109	95	12 ACOSTA	05L CDF	stable
> 98.2	95	13 ABAZOV	04E D0	$\mu\mu$
		14 ABBIENDI	03Q OPAL	$E_{\text{cm}} \leq 209$ GeV, single $H^{\pm\pm}$
		15 GORDEEV	97 SPEC	muonium conversion
> 45.6	95	16 ACTON	92M OPAL	
> 25.5	95	17 ACTON	92M OPAL	
none 7.3–34.3	95	18 SWARTZ	90 MRK2	

- <sup>1</sup> AAD 15AG search for  $H^{++}H^{--}$  production in  $20.3 \text{ fb}^{-1}$  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.
- <sup>2</sup> AAD 15AP search for  $H^{++}H^{--}$  production in  $20.3 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 8$  TeV. The limit assumes 100% branching ratio to the specified final state.
- <sup>3</sup> ABDALLAH 03 search for  $H^{++}H^{--}$  pair production either followed by  $H^{++} \rightarrow \tau^+\tau^+$ , or decaying outside the detector.

- 4 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  $g_{\ell\ell'} \gtrsim 10^{-7}$ .
- 5 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  $g(H\ell\ell) \gtrsim 10^{-7}$ .
- 6 AAD 12AY search for  $H^{++}H^{--}$  production with  $1.6 \text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{cm}} = 7 \text{ TeV}$ . The limit assumes 100% branching ratio to the specified final state.
- 7 AAD 12CQ search for  $H^{++}H^{--}$  production with  $4.7 \text{ fb}^{-1}$  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.
- 8 ABAZOV 12A search for  $H^{++}H^{--}$  production in  $7.0 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96 \text{ TeV}$ .
- 9 AALTONEN 11AF search for  $H^{++}H^{--}$  production in  $6.1 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96 \text{ TeV}$ .
- 10 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.
- 11 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  $112 \text{ GeV}$ .
- 12 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.
- 13 ABAZOV 04E search for  $H^{++}H^{--}$  pair production in  $H^{\pm\pm} \rightarrow \mu^\pm\mu^\pm$ . The limit is valid for  $g_{\mu\mu} \gtrsim 10^{-7}$ .
- 14 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).
- 15 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.
- 16 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.
- 17 ACTON 92M from  $\Delta\Gamma_Z < 40 \text{ MeV}$ .
- 18 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.
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