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Review of prospects for $H^{\pm}$ in SUSY models in view of ATLAS and CMS results

Oscar Stål[*]
The Oskar Klein Centre, Department of Physics
Stockholm University, SE-106 91 Stockholm, Sweden
E-mail: `oscar.stal@fysik.su.se`

We review the prospects for charged Higgs bosons in supersymmetric (SUSY) models in light of the recent results from ATLAS and CMS. In particular, we discuss the charged Higgs phenomenology in the minimal supersymmetric standard model (MSSM) for the regions of parameter space that are compatible with the discovery of a Higgs-like (neutral) particle around a mass $M_H \simeq 125$ GeV and current exclusion bounds from other LHC searches.

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[*] Speaker.

1. Introduction

The charged Higgs boson has a special role in Higgs sectors beyond the Standard Model (SM), since as a charged fundamental scalar it has no SM counterpart. The question of a standard or extended Higgs sectors has of course become even more interesting by now in light of the recent discovery of a Higgs like state with mass $M_H \sim 125$ GeV by ATLAS [1] and CMS [2].

The Higgs sector of the minimal supersymmetric standard model (MSSM) consists of two complex Higgs doublets. Following electroweak symmetry breaking, the three Goldstone modes are eaten by the gauge bosons, and there remains three neutral states and one charged pair in the spectrum. In the CP-conserving case, these are classified as two CP-even scalars (h, H, with $m_h < m_H$), one CP-odd scalar (A), and the charged Higgs boson ($H^{\pm}$). The MSSM Higgs sector is fully specified, at tree-level, by only two parameters. These can be taken, e.g., as the charged Higgs mass, $M_{H^{\pm}}$, and the ratio of the vacuum expectation values of the two doublets, $\tan\beta$. Tree-level mass relations then fix the remaining Higgs masses according to

$$M_A^2 = M_{H^{\pm}}^2 - M_W^2 \tag{1.1}$$

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2) - 4M_A^2 M_Z^2 \cos 2\beta}\right]. \tag{1.2}$$

Going beyond the minimal model, these relations can receive (important) modifications. This could, for example, assist in rising the tree-level value for M_h (which is low in the MSSM compared to the observed mass of the Higgs-like boson), or modify the relation Eq. (1.1).

It is known since a long time that the MSSM Higgs mass relations may acquire substantial corrections at higher orders; in particular the leading one-loop (1L) correction to M_h^2 scales as m_t^4 [3], and may be written schematically as

$$(\delta M_h^2)^{\mathrm{1L}} \sim \frac{m_t^4}{v_u^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]. \tag{1.3}$$

Here M_S is a common mass scale for the scalar tops (stops), and $X_t = A_t - \mu\cot\beta$ is the corresponding mixing in the stop sector induced by their trilinear stop coupling A_t and the Higgsino mass parameter μ. Due to the importance of higher-order corrections, the lightest Higgs mass in the MSSM is known up to (partial) two-loop accuracy, and the leading corrections even to three-loop order [4]. All taken together, the estimated theoretical uncertainty on M_h from unknown higher orders is estimated to be 1–2 GeV [4, 5]. In the decoupling limit ($M_A \gg M_Z$, $\tan\beta \gg 1$) this leads to an upper limit of $M_h \lesssim 135$ GeV for TeV-scale supersymmetry.

Higher-order corrections to Eq. (1.1) are also known, but are generically of much lower numerical relevance than those affecting M_h. State-of-the-art predictions for the MSSM Higgs sector are readily available for phenomenological studies using public software programs; see [6] for a review of codes relevant for charged Higgs phenomenology.

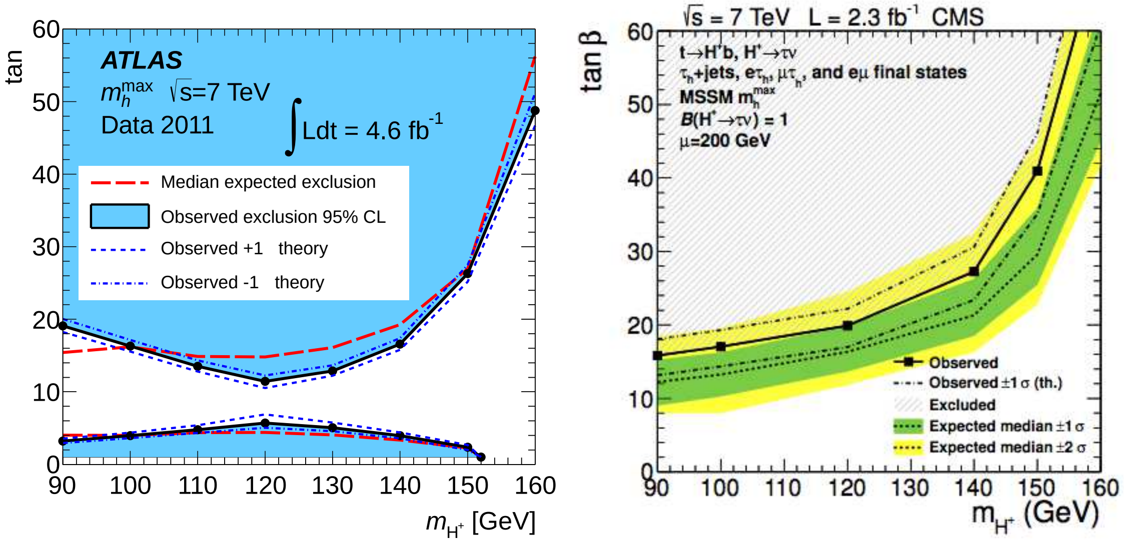

Figure 1: Direct limits on the MSSM $M_h^{\rm max}$ scenario from charged Higgs searches in the process $t \to bH^+$, $H^+ \to \tau^+\nu_\tau$ by ATLAS [7] (left) and CMS [8] (right).

2. MSSM charged Higgs after the light Higgs discovery

The searches for charged Higgs bosons at the LHC has so far been limited to the kinematical region below the top quark mass, $M_{H^\pm} < m_t - m_b$, where the charged Higgs could be produced in the decay $t \to bH^+$ ($\bar{t} \to \bar{b}H^-$). Except for the region at very low $\tan\beta$ (which is anyway disfavoured by LEP results), the MSSM charged Higgs decays in the channel $H^\pm \to \tau^\pm\nu_\tau$ with a branching fraction close to unity. Since an excess of τ events over the SM $t\bar{t}$ expectation has not been observed, ATLAS and CMS set upper limits [7, 8] on $\mathrm{BR}(t \to bH^+)$ over the mass range 90 GeV $< M_{H^\pm} <$ 160 GeV that are of order 1–5%, depending on the precise value of $M_{H^\pm}$.

To interpret the results from LHC Higgs searches, it is necessary to fix the MSSM soft-breaking parameters which have the highest impact on Higgs sector predictions, e.g. through their effects on the higher-order corrections to M_h. For charged Higgs physics, there are also important higher-order effects that act directly on the H^+tb vertex [9], known as Δ_b corrections. The impact of these corrections on the interpretation of experimental limits can be substantial [10], in particular for a light charged Higgs boson [11]. The MSSM scenario can be fixed either by choosing a motivated high-scale model for SUSY breaking (a top-down approach), or by investigating low-energy benchmarks that capture some essential phenomenological feature (bottom-up). For historical reasons, the experimental results from MSSM Higgs searches are usually presented in the so-called $M_h^{\rm max}$-scenario [12], which is an example of the latter approach. For a given value of $\tan\beta$, this scenario maximizes the size of the radiative corrections to M_h. Once the scenario is chosen, the predictions are fixed, and the limits (or measurements) can be presented in the plane of tree-level parameters ($M_{H^\pm}, \tan\beta$). An example of such a limit is shown in Fig. 1. As can be seen from this figure, the present results exclude a large region of low- and high values for $\tan\beta$ (and always with $M_{H^\pm} < m_t$). The $\tan\beta$ dependence can be understood from the fact that the H^+tb coupling has a minimum for $\tan\beta = \sqrt{m_t/m_b} \simeq 7$. With more data, it is expected that these searches will be able

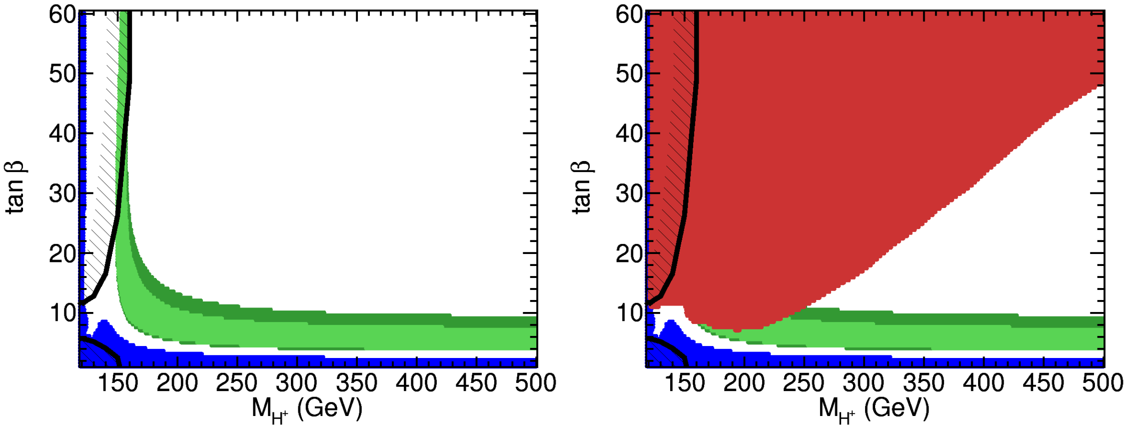

Figure 2: Charged Higgs limits in the $M_h^{\max}$-scenario by ATLAS [7] (black contours) and an indication of the region favoured by the Higgs mass corresponding to the LHC discovery: $M_h = 125.7 \pm 2.6$ GeV (green). Left: exclusion bounds from searches for neutral Higgs bosons by LEP (blue); right: exclusion limits from neutral Higgs searches at LEP (blue) and from neutral MSSM Higgs searches the LHC (red).

to exclude the whole mass range with $M_{H^{\pm}} < m_t$, which . This would also be a useful constraint on SUSY models with weaker correlation of $M_{H^{\pm}}$ to the mass of a neutral Higgs than in the MSSM.

Since the choice of scenario fixes the full Higgs spectrum, the direct limits from charged Higgs searches can be overlaid with the results from neutral MSSM Higgs searches at LEP [13] and the LHC [14, 15]. Due to the large degree of correlation between M_A and $M_{H^{\pm}}$ (for $M_A > m_t$ the two states become nearly mass degenerate, cf. Eq. (1.1)), the negative LHC searches for the CP-odd Higgs A using the decay $A \to \tau^+\tau^-$ [14, 15] also has a strong impact on the allowed parameter region. Furthermore, it is interesting to investigate what region of the MSSM parameter space is compatible with the observation of a Higgs-like particle around $M_H = 125$ GeV (some of the early papers discussing this are [16, 17]). In the MSSM, the LHC signal can be interpreted either as the light or the heavy CP-even scalar.[1] It turns out that the latter possibility is not realized in any experimentally allowed region of the $M_h^{\max}$ scenario, so we shall leave the heavy Higgs interpretation for now and return to this interpretation below. If the lightest MSSM Higgs boson is to be consistent with the new state observed at the LHC, a reasonable range for its mass is assumed to be

$$M_h = 125.7 \pm 2.6 \text{ GeV}, \tag{2.1}$$

where the uncertainty has been obtained by adding linearly a 2 GeV MSSM theory uncertainty to an experimental uncertainty of 0.6 GeV (combining ATLAS and CMS measurements).[2] The numerical results, shown in Fig. 2, are obtained using Higgs sector predictions from FeynHiggs [18]. The exclusion limits from LEP (blue), and from the LHC (red), are evaluated with Higgs-Bounds (v. 3.8.0) [19] (see also [20] for more recent developments). The green region in Fig. 2

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[1] That it would be the CP-odd scalar is clearly disfavoured by the fact that the observed state seems to have SM-like couplings to vector bosons.

[2] Given the latest developments with the slightly different observed masses in the $\gamma\gamma$ and ZZ channels, this might actually underestimate the current experimental uncertainty. Strictly speaking, there is an additional assumption here that this situation will eventually resolve.

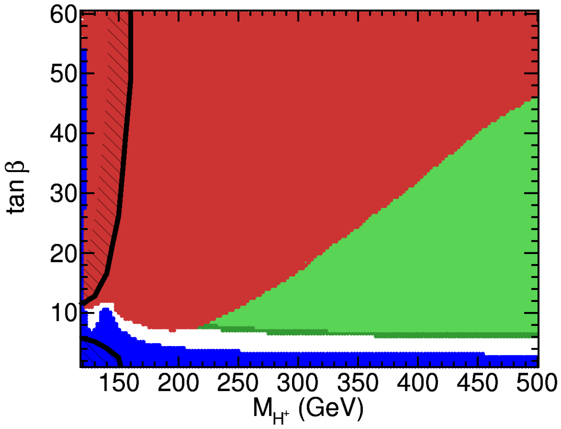

Figure 3: A modified scenario with $X_t = -2$ TeV, showing limits from ATLAS direct charged Higgs searches [7] (black contours), exclusion bounds from searches for neutral Higgs bosons by LEP (blue) and the LHC (red), and the mass region favoured by the LHC discovery, assuming $M_h = 125.7 \pm 2.6$ GeV (green).

illustrates where the lightest Higgs mass is in the correct range, as given by Eq. (2.1). The darker green corresponds to using the central value $m_t = 173.2$ GeV, whereas the brighter green includes a variation of m_t within $\pm 1\sigma$. For comparison, the ATLAS limits from direct $H^{\pm}$ searches [7] are indicated as black contours.[3] As can be seen from the right panel of Fig. 2, LHC searches are already quite constraining on the $(M_{H^{\pm}}, \tan\beta)$ parameter space in this scenario; mainly a result of CMS limit for $A \to \tau^+\tau^+$ [15].[4] Since the $M_h^{\max}$-scenario produces the highest possible value for the radiative contributions to M_h (for a fixed SUSY-breaking mass scale), and since M_h is an increasing function of the tree-level parameters, the lower edge of the green band in Fig. 2 represents scenario-independent lower limits on these parameters. Numerically, this corresponds to

$$M_{H^{\pm}} > 161 \text{ GeV} \qquad \tan\beta > 4.$$

A consequence is that, if the LHC discovery is interpreted as the lightest MSSM Higgs boson, top quark decays to a charged Higgs boson is practically ruled out by experiment. Note that this conclusion is arrived at from the mass measurement alone; taking also the measured rates in different channels (which have larger uncertainty at this point) into account in a global analysis, the favoured region is obtained for $M_{H^{\pm}} \gtrsim 200$ GeV or higher [22].

The appearance of the region in Fig. 2 with a favoured value for M_h might be discouraging for heavy charged Higgs searches (recall that the cross section has a minimum around $\tan\beta \simeq 7$). This is however somewhat misleading, since the upper edge of the green band cannot be taken as a general constraint. By changing the MSSM scenario, it is possible to allow for the correct M_h all the way up to the LHC exclusion (given by the red region). This is illustrated in Fig. 3, which shows a similar exclusion plot for the case with $X_t = -2$ TeV (as opposed to $X_t = +2$ TeV for $M_h^{\max}$).

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[3] Only the limit from ATLAS is shown here, but as can be seen from Fig. 1 the CMS results are very similar.

[4] In this channel the CMS limit has slightly higher statistical sensitivity for exclusion than the corresponding ATLAS results. There also exist a recent update of this limit [21] (not shown here), which excludes even lower $\tan\beta$ values.

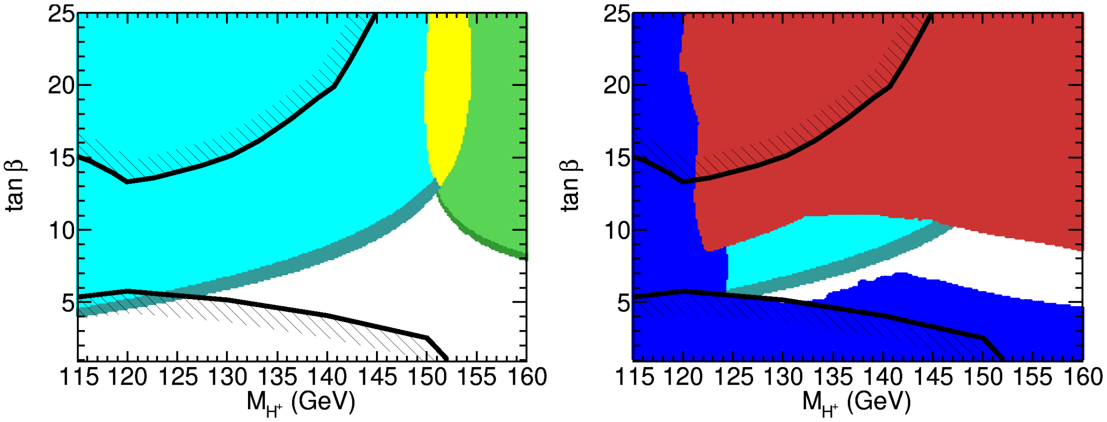

Figure 4: Parameter space of a "heavy Higgs" scenario (parameters defined in the text) with ATLAS direct charged Higgs searches [7] (black contours), exclusion bounds from searches for neutral Higgs bosons by LEP (blue) and the LHC (red). The mass region favoured by the LHC discovery is shown for $M_h = 125.7 \pm 2.6$ GeV (green), $M_H = 125.7 \pm 2.6$ GeV (cyan), or both CP-even Higgs masses in this range (yellow).

3. A heavy Higgs scenario gives a light charged Higgs

Let us now turn to an alternative scenario that can be realized in the MSSM, or more generally in other supersymmetric models with extended Higgs sectors: the possibility that the LHC discovery does *not* correspond to the lightest CP-even Higgs boson in the spectrum, but perhaps to a heavier state. Following the discovery of a signal, studies have demonstrated this as a viable scenario in the MSSM [16, 22, 23] and the NMSSM [24].

In the MSSM, the signal at 125.7 GeV would then correspond to the heavy of the two CP-even Higgs bosons, H, which in addition should have (reasonably) SM-like couplings to be in agreement with the observations. It is at least necessary that the rates into vector bosons and $\gamma\gamma$ final states are not significantly suppressed with respect to the SM, since these are the channels in which the signal is detected. A suppression of the $H \to \tau^+\tau^-$ and/or $H \to b\bar{b}$ modes is less constrained, and may in fact be beneficial since this could explain an enhancement of the BR$(H \to \gamma\gamma)$. To achieve $M_H \sim 125.7$ GeV in the MSSM it is necessary to be in a region of parameter space that admits strong mixing between the two Higgs doublets. This can be achieved for comparably large values of $|\mu|$ and $|X_t|$. In Fig. 4 we show the $(M_{H^{\pm}}, \tan\beta)$ plane for an example scenario where the soft scalar masses $M_{\rm SUSY} = 1000$ GeV, $\mu = 1000$ GeV, and $X_t = 2300$ GeV. The different colours used in the left plot show where a Higgs mass corresponding to the LHC signal is attained, with M_H in the right range (cyan), M_h (green), and even a region where both CP-even Higgs masses are in the favoured range (yellow).

Since we are at low $M_{H^{\pm}}$, most of this region is already excluded by experimental searches, as shown in Fig. 4 (right). As already mentioned, there exist more recent CMS results on $H/A \to \tau^+\tau^-$ [21] than those which were used for the limits in Fig. 4 (from HiggsBounds 3.8.0). The newest limits, which are only published for the $M_h^{\rm max}$ scenario,[5] exclude $\tan\beta \gtrsim 5.5$ in this mass range.

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[5] This is very unfortunate, since it makes the usefulness of these results very restrictive. We urge the experimental collaborations to always publish model-independent limits on $\sigma \times$ BR from all searches (following the proposal of [25]). When necessary to obtain a model-independent result, acceptances for all signal topologies should also be provided.

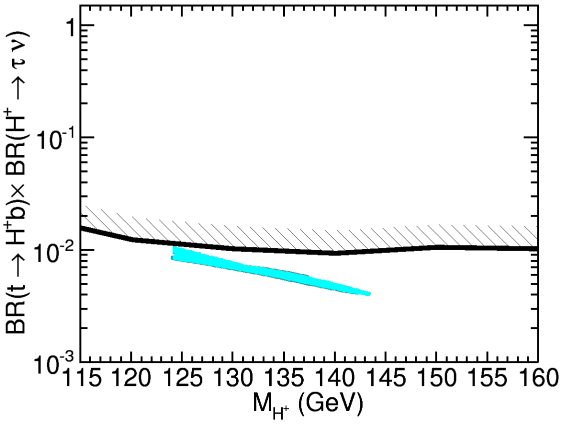

Figure 5: Predictions for $\mathrm{BR}(t \to bH^{+}) \times \mathrm{BR}(H^{+} \to \tau^{+}\nu_{\tau})$ in a scenario where the heavy MSSM Higgs boson corresponds to the LHC signal, $M_H = 125.7 \pm 2.6$ GeV (cyan points). The current ATLAS limit [7] is shown for comparison.

However, since the scenario with a heavy Higgs at 125.7 GeV is quite different from the $M_h^{\max}$ scenario (e.g. in terms of the value for μ which enters the Δ_b corrections), a naive application of this bound would certainly over-estimate the excluded region. A dedicated experimental analysis of this scenario is necessary to provide a reliable answer. That said, it is already quite clear that only a very small region (if anything) of the parameter space is still not excluded when the heavy MSSM Higgs is interpreted as the observed signal. Of interest to charged Higgs searches is that, in contrast to the light Higgs interpretation (discussed in Section 2), this region offers prospects for light charged Higgs bosons to play an interesting role.

As can be seen from Fig. 4, $M_{H^{\pm}}$ is required to be low (close to the observed signal mass). It is therefore a generic prediction in these scenarios that the $t \to bH^{+}$ channel should be open. Charged Higgs searches offer a clean handle on this scenario with a minimum of model-dependence, with the additional advantage over $\tau^{+}\tau^{-}$ searches (which combine the predictions from all the neutral MSSM Higgs bosons) that this is a search for a single particle. The current ATLAS limits from the searches for $t \to bH^{+}$, $H^{+} \to \tau^{+}\nu_{\tau}$ (properly adapted to this scenario) are shown in Fig. 4 (black contours). It can be seen that these limits are already very close to ruling this scenario out. This near-exclusion can be better quantified by looking directly at the predictions for $\mathrm{BR}(t \to bH^{+}) \times \mathrm{BR}(H^{+} \to \tau^{+}\nu_{\tau})$ for the unexcluded points with M_H in the correct mass range. This is shown in Fig. 5. The model predictions for the combined rate range from about 1% at low $M_{H^{\pm}}$ (which is very close to the current upper limit) to about 0.5% at higher $M_{H^{\pm}}$.[6]

As a final point on the heavy Higgs interpretation, we would like to stress the importance that charged Higgs searches in this mass range are pursued to lower values of $\mathrm{BR}(t \to bH^{+})$ even if this scenario is ruled out in the MSSM by searches in other channels. Only in this way is it possible to close any remaining “holes” in the exclusion of other theories (e.g. the NMSSM, and two-Higgs-doublet models without SUSY), where the correlations between the different Higgs masses are weaker.

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[6] It should be remembered here that this scenario is provided as an example. We expect the full range of predictions in the MSSM to vary over a somewhat larger range, but still within the same order of magnitude.

Conclusions and Outlook

Since the previous charged Higgs conference in 2010, ATLAS and CMS have contributed extraordinary progress on our knowledge of the Higgs sector, with the main highlight obviously the discovery of a Higgs-like object around a mass of 125.7 GeV. When interpreted in supersymmetric models, this discovery has immediate consequences for the allowed parameters of the model, and thereby on the resulting phenomenology.

In the MSSM, when the discovered state is interpreted as the lightest CP-even Higgs boson, the charged Higgs is necessarily heavy, $M_{H^\pm} \gtrsim 160\,\mathrm{GeV}$, meaning that it cannot be produced in the decay of top quarks. The attention should therefore turn to heavy charged Higgs searches, and the question is of course what results could be obtained with the already collected data. In the MSSM, these results will be complementary to the more sensitive results from the $H/A \to \tau^+\tau^-$ and $H/A \to bb$ channels. In other SUSY models, which have a more complicated Higgs sector, it is important to establish limits both on $(M_{H^\pm}, \tan\beta)$, as well as $(M_A, \tan\beta)$, since the MSSM mass relation between $M_{H^\pm}$ and M_A does not necessarily apply.

Should the discovered neutral state instead be the heavier CP-even MSSM Higgs boson, the situation is changed completely: the charged Higgs should be accessible in top decays, and with a rate that is close to current limits. It will be very interesting to see already what the full 2012 dataset can deliver, and hopefully we shall have the answer before the next cHarged meeting. In the long run, it is important to perform an unambiguous experimental test of the heavy Higgs scenario from charged Higgs searches. As we have argued, this requires pushing the limit on $\mathrm{BR}(t \to bH^+)$ to the level of few permille. To achieve this goal provides an interesting challenge both for experimentalists and theorists for the years to come.

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References

[1] ATLAS Collaboration, G. Aad *et. al. Phys. Lett.* **B716** (2012) 1–29, [`arXiv:1207.7214`].

[2] CMS Collaboration, S. Chatrchyan *et. al. Phys. Lett.* **B716** (2012) 30–61, [`arXiv:1207.7235`].

[3] Y. Okada, M. Yamaguchi, and T. Yanagida *Prog. Theor. Phys.* **85** (1991) 1–6; J. R. Ellis, G. Ridolfi, and F. Zwirner *Phys. Lett.* **B257** (1991) 83–91; H. E. Haber and R. Hempfling *Phys. Rev. Lett.* **66** (1991) 1815–1818.

[4] P. Kant, R. Harlander, L. Mihaila, and M. Steinhauser *JHEP* **1008** (2010) 104, [`arXiv:1005.5709`].

[5] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, and G. Weiglein *Eur. Phys. J.* **C28** (2003) 133–143, [`hep-ph/0212020`].

[6] O. Stål *PoS* **CHARGED2010** (2010) 024, [`arXiv:1012.2709`].

[7] ATLAS Collaboration, G. Aad *et. al.* *JHEP* **1206** (2012) 039, [`arXiv:1204.2760`].

[8] CMS Collaboration, S. Chatrchyan *et. al.* *JHEP* **1207** (2012) 143, [`arXiv:1205.5736`].

[9] M. S. Carena, D. Garcia, U. Nierste, and C. E. M. Wagner *Nucl. Phys.* **B577** (2000) 88–120, [`hep-ph/9912516`].

[10] M. Hashemi, S. Heinemeyer, R. Kinnunen, A. Nikitenko, and G. Weiglein, [`arXiv:0804.1228`].

[11] D. Eriksson, F. Mahmoudi, and O. Stål *JHEP* **11** (2008) 035, [`arXiv:0808.3551`].

[12] M. S. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, [`hep-ph/9912223`]; M. S. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein *Eur. Phys. J.* **C26** (2003) 601–607, [`hep-ph/0202167`].

[13] ALEPH, DELPHI, L3 and OPAL Collaborations, S. Schael *et. al.* *Eur. Phys. J.* **C47** (2006) 547–587, [`hep-ex/0602042`].

[14] ATLAS Collaboration `ATLAS-CONF-2012-094`.

[15] CMS Collaboration, S. Chatrchyan *et. al.* *Phys.Lett.* **B713** (2012) 68–90, [`arXiv:1202.4083`].

[16] S. Heinemeyer, O. Stål, and G. Weiglein *Phys. Lett.* **B710** (2012) 201–206, [`arXiv:1112.3026`].

[17] L. J. Hall, D. Pinner, and J. T. Ruderman *JHEP* **1204** (2012) 131, [`arXiv:1112.2703`]; H. Baer, V. Barger, and A. Mustafayev *Phys. Rev.* **D85** (2012) 075010, [`arXiv:1112.3017`]; A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, and J. Quevillon *Phys. Lett.* **B708** (2012) 162–169, [`arXiv:1112.3028`]; P. Draper, P. Meade, M. Reece, and D. Shih *Phys. Rev.* **D85** (2012) 095007, [`arXiv:1112.3068`].

[18] S. Heinemeyer, W. Hollik, and G. Weiglein *Comput. Phys. Commun.* **124** (2000) 76–89, [`hep-ph/9812320`].

[19] P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams *Comput. Phys. Commun.* **181** (2010) 138–167, [`arXiv:0811.4169`]; P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, and K. E. Williams *Comput. Phys. Commun.* **182** (2011) 2605–2631, [`arXiv:1102.1898`].

[20] Talk by T. Stefaniak at this conference; *PoS* **CHARGED2012** (2012) 024, [`arXiv:1301.2345`].

[21] CMS Collaboration, S. Chatrchyan *et. al.* CMS-PAS-HIG-12-050.

[22] P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, and L. Zeune, [`arXiv:1211.1955`].

[23] M. Drees *Phys. Rev.* **D86** (2012) 115018, [`arXiv:1210.6507`].

[24] U. Ellwanger *JHEP* **1203** (2012) 044, [`arXiv:1112.3548`]; G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang, S. Kraml, *et. al.* *JHEP* **1301** (2013) 069, [`arXiv:1210.1976`].

[25] S. Kraml, B. Allanach, M. Mangano, H. Prosper, S. Sekmen, *et. al.* *Eur. Phys. J.* **C72** (2012) 1976, [`arXiv:1203.2489`].