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Charged Higgs Bosons in the LHCHXSWG

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Searches for charged Higgs bosons are an integral part of current and future investigations at the LHC. The LHC Higgs Cross Section Working Group (LHCHXSWG) was created to provide cross sections, branching ratios, analysis strategies etc. for Higgs boson searches at the LHC. We briefly review progress and results for charged Higgs bosons in and for the LHCHXSWG.

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1. Introduction

A major goal of the particle physics program at the high energy frontier, currently being pursued at the CERN Large Hadron Collider (LHC), is to unravel the nature of electroweak symmetry breaking (EWSB). While the existence of the massive electroweak gauge bosons ($W^{\pm}, Z$), together with the successful description of their behavior by non-abelian gauge theory, requires some form of EWSB to be present in nature, the underlying dynamics remained unknown for several decades. An appealing theoretical suggestion for such dynamics is the Higgs mechanism [1], which implies the existence of one or more Higgs bosons (depending on the specific model considered). Therefore, the search for a Higgs boson was considered a major cornerstone in the physics program of the LHC.

The spectacular discovery of a Higgs-like particle with a mass around $M_H \simeq 125$ GeV, which has been announced by ATLAS [2] and CMS [3], marks a milestone of an effort that has been ongoing for almost half a century and opens up a new era of particle physics. Both ATLAS and CMS reported a clear excess in the two photon channel, as well as in the $ZZ^{(*)}$ channel. The discovery was further corroborated, though not with high significance, by the $WW^{(*)}$ channel and by the final Tevatron results [4]. Latest ATLAS/CMS results, also for evidence on the Higgs decay into fermions can be found in Refs. [5, 6].

Many theoretical models employing the Higgs mechanism in order to account for electroweak symmetry breaking have been studied in the literature, of which the most popular ones are the Standard Model (SM) [7] and the Minimal Supersymmetric Standard Model (MSSM) [8], The newly discovered particle can be interpreted as the SM Higgs boson. The MSSM has a richer Higgs sector, containing two neutral $\mathcal{CP}$-even, one neutral $\mathcal{CP}$-odd and two charged Higgs bosons. The newly discovered particle can also be interpreted as the light (or the the heavy) $\mathcal{CP}$-even state [9]. Among alternative theoretical models beyond the SM and the MSSM, the most prominent are the (more general) Two Higgs Doublet Model (2HDM) [10, 11], non-minimal supersymmetric extensions of the SM (e.g. extensions of the MSSM by an extra singlet superfield [12]), or models involving Higgs triplets [13]. Many of these models not only predict more than one Higgs boson, but they predict electrically charged Higgs bosons.

The ATLAS and CMS analyses leading to the conclusion that (within the uncertainties) the newly discovered particle can be interpreted as the SM Higgs boson requires, besides the obvious experimental data, also precise theory predictions for the SM Higgs boson cross section, branching ratios, angular distributions as well as strategies how to extract certain "measurements" (e.g. coupling strength factors) from the data. In this respect it is crucial that ATLAS and CMS not only use predictions with highest precision, but in particular that they use the *same* theory predictions, the *same* strategies for the extraction of "measurements". Only then it is possible to readily compare ATLAS and CMS results, and in the future combine them. To ensure this, in the year 2010 the "LHC Higgs Cross Section Group" (LHCHXSWG) [14] was founded. This group, formed of theoretical and experimental physicists, officially takes care of providing cross section and branching ratio predictions (including uncertainty evaluations), as well as the strategies for the extraction of, e.g., coupling strength factors from experimental data [15–18]. While initially the SM Higgs boson was in the focus of the LHCHXSWG, soon also models beyond the SM (BSM) were investigated (see also Ref. [19]). In particular within the MSSM cross sections and branching ratios for the extended Higgs sector have been evaluated, see, e.g., Ref. [20] for an example on the neutral Higgs production cross sections. Latest results can be found at Ref. [21].

As discussed above, electrically charged Higgs bosons form a natural part of many BSM models. The charged Higgs bosons of the MSSM (or a more general 2HDM) have been searched at LEP, the Tevatron and the LHC, and will be searched for (or hopefully analyzed at) a Linear Collider such as ILC or CLIC. The LEP searches [22] yielded a robust bound of $M_{H^\pm} \gtrsim 80$ GeV [23]. The Tevatron bounds [24] are by now superseeded by the LHC charged Higgs searches [25]. At the ILC, if the charged Higgs is in the kinematical reach, a high-precision determination of the charged Higgs boson properties will be possible [26, 27]. Here, besides some basics, we briefly review activities and results obtained within and for the LHCHXSWG regarding charged Higgs bosons, which will mainly concern the 2HDMs and the MSSM.

Within the 2HDM and the MSSM the main production channels of charged Higgs bosons at the LHC are

$$pp \to t\bar{t} + X, \quad t\bar{t} \to t\, H^-\bar{b} \text{ or } H^+ b\, \bar{t}, \tag{1.1}$$

$$gb \to H^- t \text{ or } g\bar{b} \to H^+\bar{t} \quad (\text{5FS}), \tag{1.2}$$

$$gg/q\bar{q} \to H^- t\bar{b} \text{ or } gg/q\bar{q} \to H^+\bar{t}b \quad (\text{4FS}). \tag{1.3}$$

The decay used in the analysis to detect the charged Higgs boson is

$$H^\pm \;\to\; \tau\nu_\tau \;\to\; \text{hadrons } \nu_\tau. \tag{1.4}$$

The "light charged Higgs boson" is characterized by $M_{H^\pm} < m_t$. The main production channel is given in Eq. (1.1). Close to threshold also Eq. (1.2) contributes. The relevant (i.e. detectable) decay channel is given by Eq. (1.4).

The "heavy charged Higgs boson" is characterized by $M_{H^\pm} \gtrsim m_t$. Here Eq. (1.2) in the "five flavor scheme" (5FS) and/or Eq. (1.3) in the "four flavor scheme" (4FS) gives the largest contribution to the production cross section, and very close to threshold Eq. (1.1) can contribute somewhat. The relevant decay channel is again given in Eq. (1.4).

2. Charged Higgs bosons in 2HDMs

The 2HDM can be classified in types I-IV [11], where the MSSM, see Sect. 3 at the tree-level contains a 2HDM type II. The relevant free (input) parameters are $M_{H^\pm}$ and the ratio of the two vacuum expectation values, $\tan\beta \equiv v_2/v_1$. Analyses at ATLAS and CMS in the case of light charged Higgs bosons in the context of 2HDMs evaluate the production cross section from $\sigma(pp \to t\bar{t} + X)$ as evaluated in the SM at the NNLO level [28]. Limits are then presented for $\text{BR}(t \to H^\pm b)$ as a function of the charged Higgs boson mass, $M_{H^\pm}$.

For heavy charged Higgs bosons, $M_{H^\pm} \gtrsim m_t$, associated production $pp \to tbH^\pm$+X is the dominant production mode. Two different formalisms can be employed to calculate the cross section for associated $tbH^\pm$ production. In the four-flavor scheme (4FS) with no b quarks in the initial state, the lowest-order QCD production processes are given in Eq. (1.3).

On the other hand, potentially large logarithms $\propto \ln(\mu_\mathrm{F}/m_b)$ (where μ_F denotes the factorization scale), which arise from the splitting of incoming gluons into nearly collinear $b\bar{b}$ pairs, can be summed to all orders in perturbation theory by introducing bottom parton densities, i.e. in the five flavor scheme (5FS) [29], see Eq. (1.2).

To all orders in perturbation theory the four- and five-flavor schemes are identical, but the way of ordering the perturbative expansion is different, and the results do not match exactly at finite order. For more details see Ref. [16] and references therein. A simple and pragmatic formula for the combination of the four- and five-flavor scheme calculations of bottom-quark associated Higgs-boson production has been suggested in Ref. [30], the so-called "Santander matching". The main idea behind this matching scheme is the following: The 4FS and 5FS calculations provide the unique description of the cross section in the asymptotic limits $M_H/m_b \to 1$ and $M_H/m_b \to \infty$, respectively (where M_H denotes a generic Higgs boson mass, i.e. the arguments are valid for the neutral as well as for the charged Higgs production). The two approaches are combined in such a way that they are given a weight, depending on the value of the Higgs-boson mass. Since the difference between the 4FS and the 5FS is logarithmic, the dependence of their relative importance on M_H should be controlled by a logarithmic term. Consequently, the proposal for the "Santander matching" reads [30],

$$\sigma^{\mathrm{matched}} = \frac{\sigma^{\mathrm{4FS}} + t\,\sigma^{\mathrm{5FS}}}{1+t}\,, \qquad \text{with the weight } w \text{ defined as} \qquad t = \ln\frac{M_H}{m_b} - 2\,, \tag{2.1}$$

and σ^{4FS} and σ^{5FS} denote the total inclusive cross section in the 4FS and the 5FS, respectively. The theoretical uncertainties in the 4FS and the 5FS calculations should be added linearly, using the weight t. In this way it is ensured that the combined error is always larger than the minimum of the two individual errors [30]:

$$\Delta\sigma_\pm = \frac{\Delta\sigma_\pm^{\mathrm{4FS}} + t\,\Delta\sigma_\pm^{\mathrm{5FS}}}{1+t}\,, \tag{2.2}$$

where $\Delta\sigma_\pm^{\mathrm{4FS}}$ and $\Delta\sigma_\pm^{\mathrm{5FS}}$ denote the upper/lower uncertainty limits of the 4FS and the 5FS, respectively.

An up-to-date determination of the next-to-leading order total cross section in the type II 2HDM as a function of $M_{H^\pm}$ and $\tan\beta$ has recently been presented in Ref. [31], which constitutes the official recommendation of the LHCHXSWG for heavy charged Higgs bosons. Also included in Ref. [31] is an estimate of the theoretical uncertainties due to missing higher-order corrections, parton distribution functions and physical input parameters. Predictions in the 4FS and 5FS were compared and reconciled through a recently proposed scale-setting prescription. Applying the Santander matching the "best" cross section prediction for heavy charged Higgs bosons at the LHC is provided.

An interim recommendation of the LHCHXSWG on the evaluation of cross sections and branching ratios in the 2HDM has been presented in Ref. [32], however, with a focus on neutral Higgs bosons. The two codes recommended for the Higgs boson decays, `Hdecay` [33] and `2HDMC` [34] also include the evaluation of charged Higgs boson decays in types I-IV.

3. Charged Higgs bosons in the MSSM

While the MSSM contains (at the tree-level) a 2HDM type II, due to Supersymmetry (SUSY), special relations are enforced, and via loop corrections the full SUSY spectrum enters the predictions.

The Higgs sector of the MSSM contains two Higgs doublets, leading to five physical Higgs bosons. At tree-level these are the light and heavy $\mathcal{CP}$-even h and H, the $\mathcal{CP}$-odd A and the charged $H^{\pm}$. At lowest order the Higgs sector can be described besides the SM parameters by two additional independent parameters, chosen to be the mass of the A boson, M_A (in the case of vanishing complex phases) and $\tan\beta$. Accordingly, all other masses and couplings can be predicted at tree-level, e.g. the charged Higgs boson mass

$$m_{H^\pm}^2 = M_A^2 + M_W^2 \; . \tag{3.1}$$

$M_{Z,W}$ denote the masses of the Z and W boson, respectively. This tree-level relation receives higher-order corrections, where the loop corrected charged Higgs-boson mass is denoted as $M_{H^\pm}$. Three codes exist for the calculation of $M_{H^\pm}$ and the various decay widths, `FeynHiggs` [35–40], `CPsuperH` [41] and `Hdecay` [33].

The relation between the bottom-quark mass and the Yukawa coupling h_b, which controls also the interaction between the Higgs fields and the sbottom quarks, is affected by higher-order corrections, summarized in the quantity Δ_b [42–44]. These, often called threshold corrections, are generated either by gluino–sbottom one-loop diagrams (resulting in $\mathcal{O}(\alpha_b\alpha_s)$ corrections), or by chargino–stop loops (giving $\mathcal{O}(\alpha_b\alpha_t)$ corrections). The effective Lagrangian for the charged Higgs is given by [43]

$$\mathcal{L} \sim V_{tb}\left[\left(\frac{\overline{m}_b}{1+\Delta_b}\tan\beta + \frac{m_t}{\tan\beta}\right) H^+ \overline{t_L} b_R\right] + \text{h.c.} \tag{3.2}$$

Here V_{tb} denotes the $(3,3)$ element of the CKM matrix, $\overline{m}_b$ is the running bottom quark mass, and m_t is the top quark mass. Analytically one finds $\Delta_b \propto \mu\tan\beta$, where μ is the Higgs mixing parameter, which is (generally) of the same size as SUSY mass scales. Large positive (negative) values of Δ_b lead to a strong suppression (enhancement) of the bottom Yukawa coupling.

For the evaluation of the light charged Higgs production cross section the decay $t \to H^\pm b$ has to be evaluated including SUSY loop corrections, where the main contribution stems from Eq. (3.2). The LHCHXSWG compared the codes `FeynHiggs` and `Hdecay` as shown in Fig. 1 [16]. The top row shows the decay width, while the bottom row contains the result for the branching ratios. The parameters are chosen according to the $m_h^{\max}$ scenario [45] with μ set to $200(1000)$ GeV in the left (right) column. One can see that the agreement between the two codes, despite some differences in the Δ_b evaluation (see Ref. [16] for details) is excellent.

The LHCHXSWG also estimated the overall uncertainty of the light charged Higgs production, evaluated in the $m_h^{\max}$ scenario. The result is shown in Fig. 2 [16], where

$$\sigma_{tt} \cdot \text{BR}(t \to bH^\pm) \cdot \text{BR}(t \to bW^\pm) \cdot 2 \tag{3.3}$$

is shown for $\sqrt{s} = 7$ TeV as a function of $M_{H^\pm}$. The uncertainty estimate combines the accuracies for the top quark production (parametric and intrinsic uncertainty) and for the top quark decay

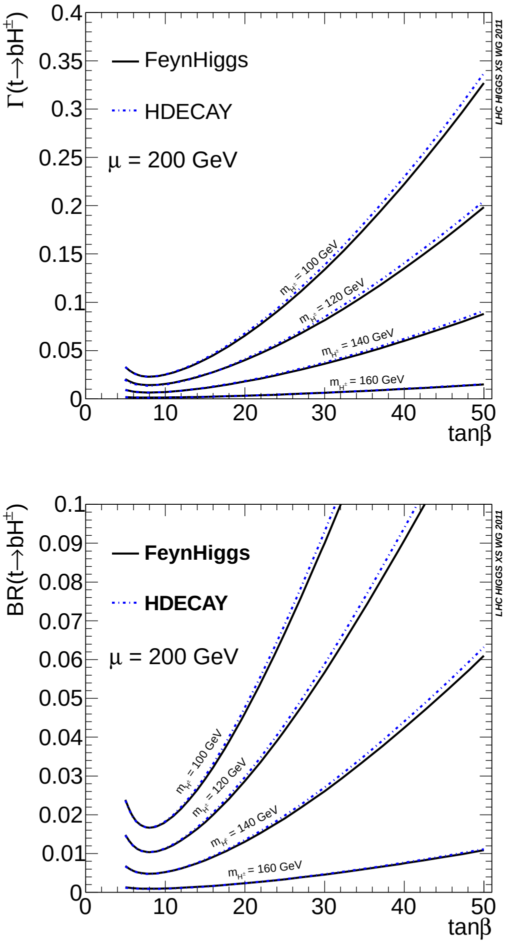

Figure 1: Comparison of the $\Gamma(t \to H^+ b)$ (upper row) and $\mathrm{BR}(t \to H^+ b)$ (lower row) between `FeynHiggs` and `Hdecay`. The results are shown for various values of $M_{H^\pm}$ and for $\mu = 200(1000)$ GeV in the left (right) column (taken from Ref. [16]).

(including intrinsic uncertainties on Δ_b). The result is shown for $\tan\beta = 5, 10, 30, 50$. As can be seen, the uncertainties are still substantial. They have to be taken into account for reliable and robust bounds on the MSSM parameter space from the non-observation of a light charged Higgs. Conversely, using a potential observation of a light charged Higgs for a determination of the underlying parameters would require a substantial reduction of the uncertainties.

The LHCHXSWG also provides branching ratio predictions for the MSSM Higgs bosons, including the charged Higgs boson. The procedure adopted by the LHCHXSWG goes as follows. After the calculation of Higgs-boson masses and mixings from the original SUSY input, a combination of the results from `Hdecay` and `FeynHiggs` on the various decay channels is performed to obtain the most accurate result for the branching ratios currently available. (For the general procedure, see Ref. [46].) In a first step, all partial widths have been calculated as accurately as possible. Then the branching ratios have been derived from this full set of partial widths. Con-

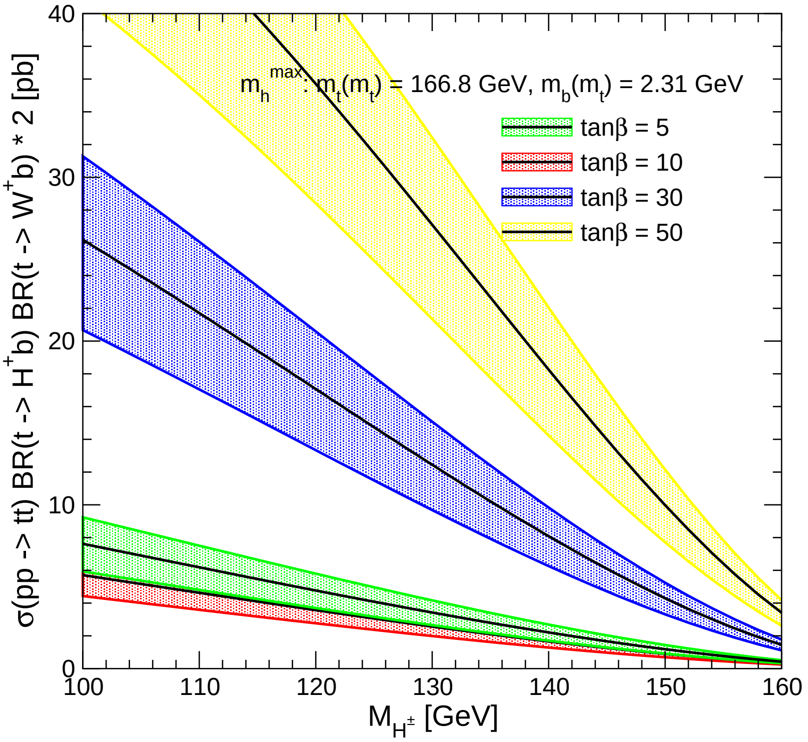

Figure 2: $\sigma_{tt} \cdot \text{BR}(t \to bH^\pm) \cdot \text{BR}(t \to bW^\pm) \cdot 2$ including scale and PDF uncertainties, uncertainties for missing electroweak and QCD corrections, and Δ_b-induced uncertainties for $\sqrt{s} = 7$ TeV (taken from Ref. [16]).

cretely, `FeynHiggs` was used for the evaluation of the Higgs-boson masses and couplings from the original input parameters, including corrections up to the two-loop level. The status of the various evaluations in `FeynHiggs` and `Hdecay` are detailed in Ref. [16]. The total decay width of the charged Higgs bosons is calculated as,

$$\begin{aligned}\Gamma_{H^\pm} = \;& \Gamma^{\text{FH}}_{H^\pm \to \tau\nu_\tau} + \Gamma^{\text{FH}}_{H^\pm \to \mu\nu_\mu} + \Gamma^{\text{FH}}_{H^\pm \to hW^\pm} + \Gamma^{\text{FH}}_{H^\pm \to HW^\pm} + \Gamma^{\text{FH}}_{H^\pm \to AW^\pm} \\ & + \Gamma^{\text{HD}}_{H^\pm \to tb} + \Gamma^{\text{HD}}_{H^\pm \to ts} + \Gamma^{\text{HD}}_{H^\pm \to td} + \Gamma^{\text{HD}}_{H^\pm \to cb} + \Gamma^{\text{HD}}_{H^\pm \to cs} + \Gamma^{\text{HD}}_{H^\pm \to cd} \\ & + \Gamma^{\text{HD}}_{H^\pm \to ub} + \Gamma^{\text{HD}}_{H^\pm \to us} + \Gamma^{\text{HD}}_{H^\pm \to ud} \;, \end{aligned} \tag{3.4}$$

followed by a corresponding evaluation of the respective branching ratio. Decays to strange quarks or other lighter fermions have been neglected.

Example results in the $m_h^{\text{mod}+}$ scenario [47] are given in Fig. 3 [17]. The left (right) plot show the BRs for $\tan\beta = 10(50)$ as a function of $M_{H^\pm}$. The various kinks visible in the left plot stem from the decay channels to a chargino/neutralino pair, which are not explicitely included into the BR predictions yet.

4. Conclusions

The LHCHXSWG forms an important part of the efforts to identify the mechanism of EWSB at the LHC. Among many other activities, it provides cross sections and branching ratios for

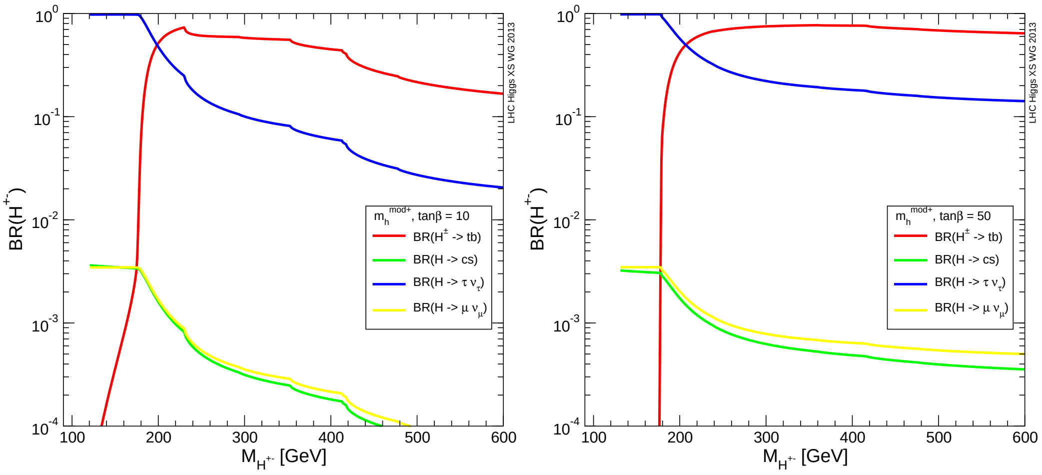

Figure 3: Charged Higgs boson branching ratios in the $m_h^{\rm mod+}$ scenario [47] for $\tan\beta = 10(50)$ in the left (right) plot as a function of $M_{H^\pm}$ (taken from Ref. [17]).

charged Higgs bosons as they are predicted by the 2HDM and/or the MSSM. Here we briefly reviewed some of the predictions for light and heavy charged Higgs bosons, including evaluations of the respective uncertainties.

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