PROCEEDINGS OF SCIENCE

Charged Higgs boson searches in ATLAS and CMS

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Results from searches for charged Higgs bosons in ATLAS and CMS are presented. The searches cover singly charged Higgs boson decays in the $H^+ \to \tau\nu$, $H^+ \to t\bar{b}$, $H^+ \to c\bar{s}$, and $H^+ \to W^+Z$ modes, and doubly charged Higgs boson decays in the $\Phi^{++}\Phi^{--} \to 4l$ and $\Phi^{++}\Phi^{-} \to 3l$ modes, with 7 TeV and 8 TeV data from the Run 1 of the LHC. The first search for charged Higgs bosons with 13 TeV data in the $H^+ \to \tau\nu$ decay mode with ATLAS is also presented. The results are interpreted in various theoretical models.

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1. Introduction

With the discovery of a Higgs boson with a mass of $125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV [1] at the Large Hadron Collider (LHC), we are now faced with the question if it acts alone or if it is part of a larger scalar sector. Both the two-Higgs doublet models (2HDM) and various Higgs triplet models extend the scalar sector of the SM, and predict the existence of charged Higgs bosons. The discovery of a charged Higgs boson would be a spectacular sign of new physics.

In the 2HDM, the recently discovered Higgs boson takes the role of one of the CP-even neutral scalars (h or H), and it is accompanied by a CP-odd neutral scalar (A) and two oppositely charged scalars ($H^{\pm}$). The scalar sector of the Minimal Supersymmetric Standard Model (MSSM) is a special case of the Type-II 2HDM, where the first doublet couples to up-type quarks, while the second couples to down-type quarks and charged leptons. The ratio of the two vacuum expectation values (*vev*) associated with each doublet is called $\tan\beta$. Together with one of the (hereto undiscovered) Higgs boson masses, typically m_A, it determines all parameters of the MSSM scalar sector at tree level. Due to its coupling to mass, the charged Higgs boson is predicted to be produced in decays of or in association with top quarks. The Feynman diagrams of the main production processes are shown in Figure 1.

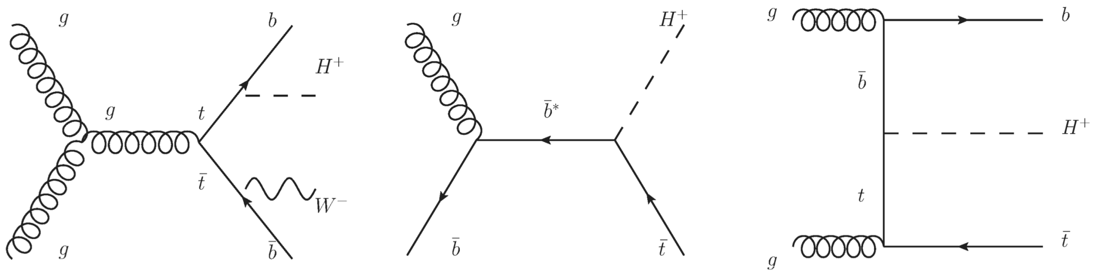

Figure 1: The main production modes of the charged Higgs boson in the MSSM for $m_{H^+} < m_t$ (left), and for $m_{H^+} > m_t$ in the five- (middle) and four-flavour scheme (right) [2].

Several benchmark scenarios have been considered for the hypothetical MSSM scalar sector. The m_h^{max} scenario is aimed at maximizing the mass of the lightest Higgs boson (h), to provide conservative bounds on $\tan\beta$ for a fixed value of the supersymmetry (SUSY) breaking scale (m_{SUSY}). It has been modified to incorporate the SM Higgs boson as the light CP-even state h together with a reduction of the mixing of the *stop* sector (X_t). The new scenario [3] is defined for both a positive and negative sign of X_t ($m_h^{\text{mod}+}$, $m_h^{\text{mod}-}$).

The mass of the discovered Higgs boson can provide constraints on the parameters in this sector via radiative corrections. In the hMSSM scenario [4], the light CP-even Higgs boson is assumed to have a mass of 125 GeV, and as a result the dominant radiative corrections are fixed and the parameters of the MSSM Higgs sector can be described to a good approximation by $\tan\beta$ and m_A (even beyond tree level.) The radiative corrections to the h mass from the top quark and its supersymmetric partner place constraints on its effective couplings.

Figure 2 shows 95 % confidence-level (CL) exclusions in the m_A–$\tan\beta$ plane interpreted in the hMSSM scenario (ATLAS) [5] and the $m_h^{\text{mod}+}$ scenario (CMS) [6]. In the hMSSM, the observed couplings of the light CP-even Higgs boson, together with the direct search for $A/H \to \tau\tau$, results in the exclusion of a large region of the m_A–$\tan\beta$ parameter space, while the observed exlusion from the direct search for $H^+ \to \tau\nu$ is confined to a region of low m_A and high $\tan\beta$. In the $m_h^{\mathrm{mod}+}$ scenario, the direct search for $H^+ \to \tau\nu$ results in an observed exclusion at $m_A \lesssim 150\,\mathrm{GeV}$ for the range $\tan\beta = 1 - 60$.

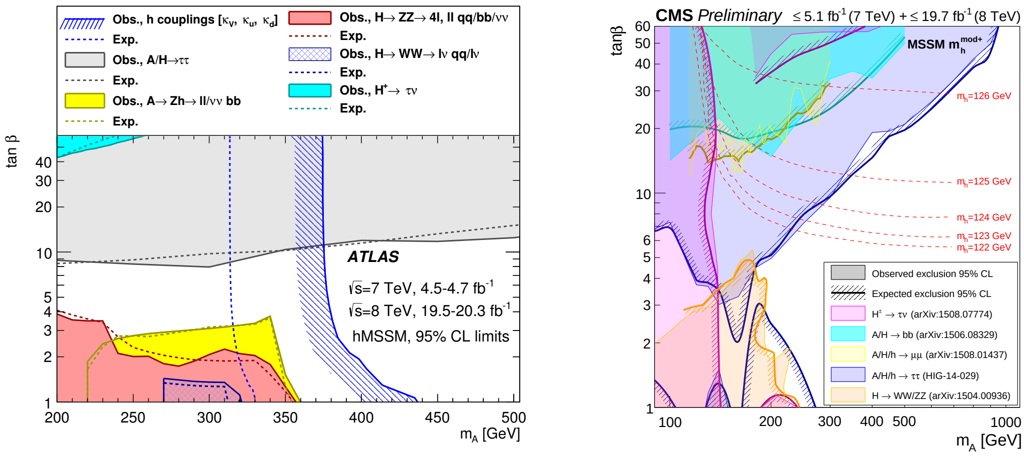

Figure 2: Exclusion limits from direct searches and from constraints on the coupling strengths in the hMSSM scenario in ATLAS [5] (left), and from direct searches interpreted in the $m_h^{\mathrm{mod}+}$ scenario in CMS [6] (right).

2. Light charged Higgs boson searches

If the charged Higgs boson is lighter than the top quark, it predominantly decays as $H^+ \to \tau\nu$ for most of the considered $\tan\beta$ range ($\tan\beta > 3$), while for lower values of $\tan\beta$, $H^+ \to c\bar{s}$ becomes increasingly important. A light charged Higgs boson is a possibility if the Higgs boson at 125 GeV takes the role of the heavy CP-even Higgs boson of the MSSM (H) [3]. Searches for light charged Higgs bosons in $H^+ \to c\bar{s}$ decays have been conducted in ATLAS [7] and CMS [8]. The searches are performed with 8 TeV (7 TeV) data corresponding to an integrated luminosity of $19.0\,\mathrm{fb}^{-1}$ ($4.7\,\mathrm{fb}^{-1}$) in CMS (ATLAS). Both searches focus on leptonic (e or μ) decays of one of the top quarks, and use a kinematic fit to fully reconstruct the $t\bar{t}$ event. Model independent upper limits are set on the branching fraction $\mathscr{B}(t \to H^+ b)$, assuming $\mathscr{B}(H^+ \to c\bar{s}) = 100\,\%$, ranging from 6.5 % to 1.2 % for charged Higgs boson masses of 90 GeV–160 GeV for the CMS search. ATLAS reports a similar result. Figure 3 shows the discriminating power of the kinematic fit in the di-jet mass distribution using simulated events, and the corresponding distribution measured in data.

Searches for light charged Higgs bosons in the $H^+ \to \tau\nu$ decay have also been conducted by both experiments, with 8 TeV data corresponding to an integrated luminosity of $19.5\,\mathrm{fb}^{-1}$ for ATLAS [9] and $19.7\,\mathrm{fb}^{-1}$ for CMS [10]. The signature consists of the hadronic decay of a tau lepton, large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$), the presence of two jets from a hadronic W boson decay, and two b-tagged jets. The discriminating variable used in these searches is the transverse mass of the hadronic τ and the $E_{\mathrm{T}}^{\mathrm{miss}}$. Figure 4 shows the transverse mass distribution from the search in ATLAS.

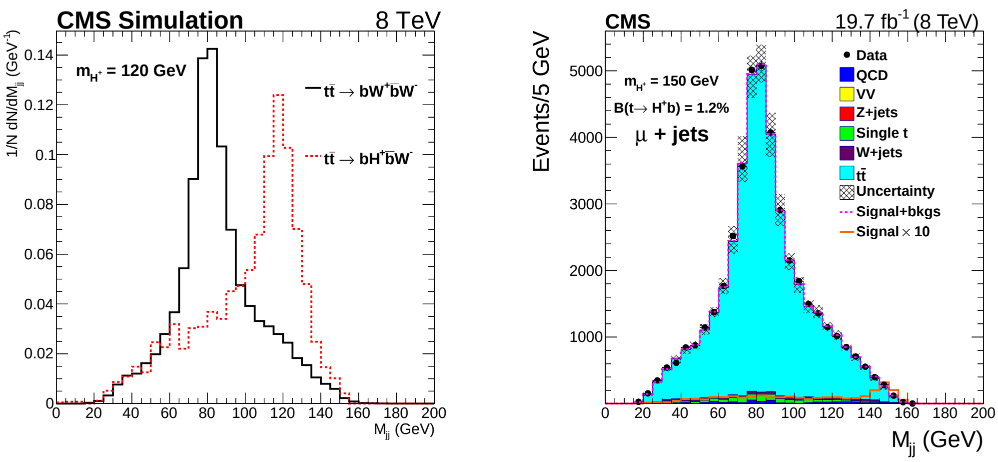

Figure 3: The distribution of the di-jet mass (M_{jj}) in simulated signal and background events (left), and in events in 8 TeV data in the search for $H^+ \to c\bar{s}$ with CMS [8].

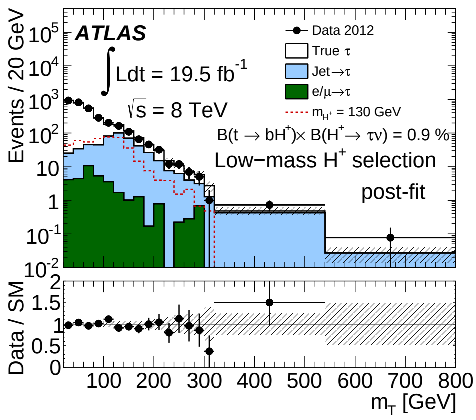

Figure 4: Distribution of the transverse mass in the search for $H^+ \to \tau\nu$ with light charged Higgs bosons in the fully hadronic mode with ATLAS [9].

Both searches yield comparable results for the model independent upper limits on the product of branching fractions $\mathscr{B}(t \to H^+b) \times \mathscr{B}(H^+ \to \tau\nu)$, which are 1.3 %–0.23 % and 1.2 %–0.15 % in the charged Higgs boson mass range 80 GeV–160 GeV for the searches in ATLAS and CMS respectively. Figure 5 shows the model independent upper limit from ATLAS, and its interpretation in the $m_h^{\text{mod}+}$ scenario.

3. Heavy charged Higgs boson searches

For charged Higgs masses greater than the top-quark mass, the $H^+ \to t\bar{b}$ decay mode becomes dominant. The signature investigated for this decay mode includes a lepton from a W boson decay, and a multitude of light and b-tagged jets. This signature is difficult to separate from the $t\bar{t}$ background with extra heavy-flavour jets, and for this reason, the $H^+ \to \tau\nu$ decay mode continues to play an important role for heavy charged Higgs bosons, owing to its cleaner signature.

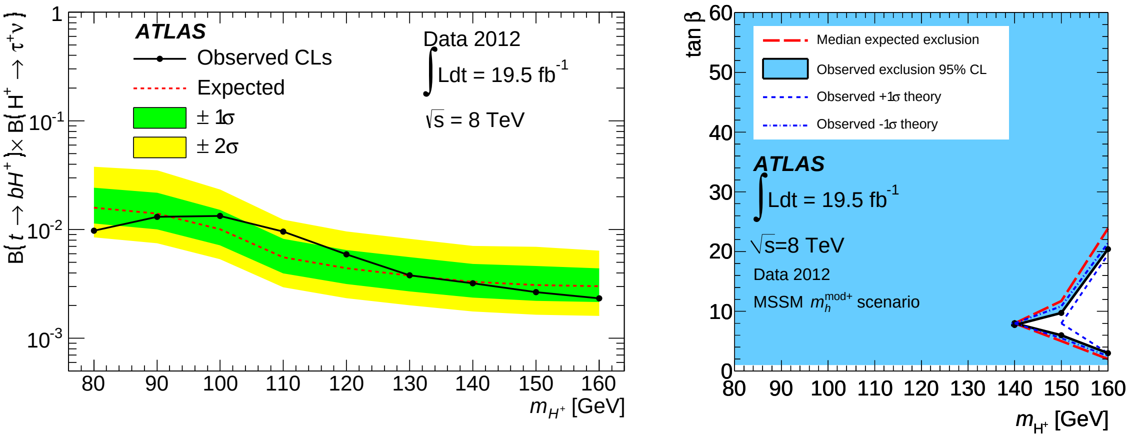

Figure 5: The model independent limit on the product of branching fractions $\mathscr{B}(t \to H^+b) \times \mathscr{B}(H^+ \to \tau\nu)$, and its interpretation in the $m_h^{\text{mod}+}$ scenario with ATLAS [9].

The ATLAS $H^+ \to t\bar{b}$ search [11] looks for these decays in events with one lepton, five or more jets (of which three or more are b-tagged), and $E_{\text{T}}^{\text{miss}}$. To discriminate between signal and background, a boosted decision tree (BDT) algorithm is trained with simulated events of the H^+ signal, separately for each mass hypothesis, against the $t\bar{t} + b\bar{b}$ background. The search is dominated by systematic uncertainties. At $m_{H^+} = 500\,\text{GeV}$, the systematic uncertainty on the modelling of $t\bar{t}$ events and the b-tagging uncertainty respectively correspond to 33 % and 24 % of the total uncertainty, while the statistical uncertainty is 18 %. Figure 6 shows the distribution of the BDT score, and the model independent upper limits on $\sigma(gb \to tH^+) \times \mathscr{B}(H^+ \to t\bar{b})$. The observed upper limits are approximately 6.5 pb–0.25 pb for $m_{H^+} =$ 200 GeV–600 GeV, which is about two standard deviations above the expected limits in the entire mass range.

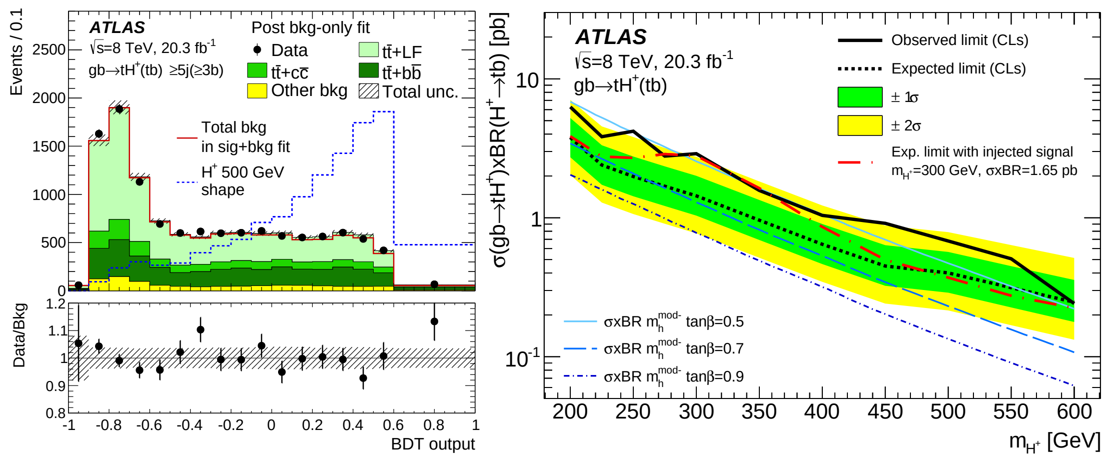

Figure 6: BDT score in the $m_{H^+} = 500\,\text{GeV}$ mass hypothesis in the signal region, where the systematic uncertainties are constrained by a simultaneous fit in control regions (left), and model independent limits on $\sigma(gb \to tH^+) \times \mathscr{B}(H^+ \to t\bar{b})$ (right) in the $H^+ \to t\bar{b}$ search with ATLAS [11]. The expected limit from an injected signal of $\sigma = 1.65\,\text{pb}$ with $m_{H^+} = 300\,\text{GeV}$ is included for comparison.

The search for heavy charged Higgs bosons with CMS covers both the $H^+ \to \tau\nu$ and the $H^+ \to t\bar{b}$ decay modes, and is conducted in the τ+jets ($H^+ \to \tau\nu$ only), $\mu\tau$ (both), ll' (both), and l+jets ($H^+ \to t\bar{b}$ only) ($l = e, \mu$) channels. With the $H^+ \to \tau\nu$ decay mode, the single-lepton and dilepton channels are not found to contribute to the sensitivity of the search. For the τ+jets channel, the transverse mass of the τ and the $E_{\mathrm{T}}^{\mathrm{miss}}$ is again used as the discriminating variable, and model independent upper limits are set on $\sigma(pp \to t(b)H^+) \times \mathscr{B}(H^+ \to \tau\nu)$ to 0.38 pb–0.025 pb for $m_{H^+} = 200\,\mathrm{GeV}$–$600\,\mathrm{GeV}$. Figure 7 shows the distribution of the transverse mass, as well as the expected and observed upper limits.

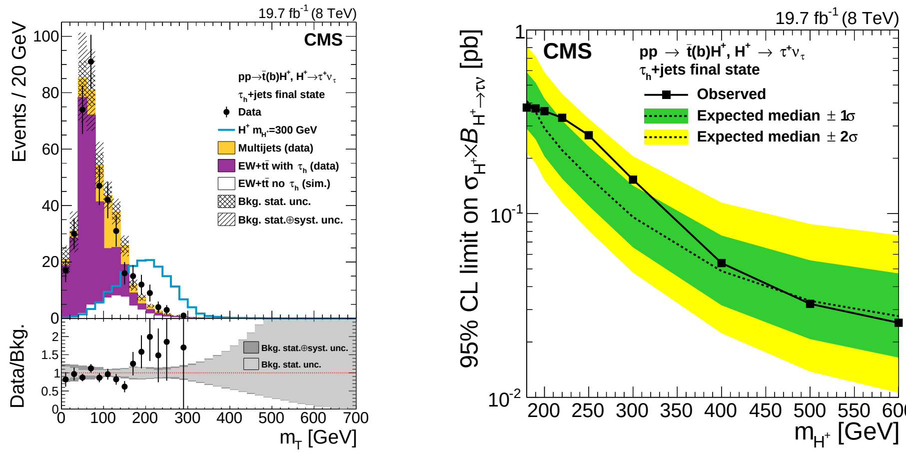

Figure 7: Distribution of the transverse mass of the τ and the $E_{\mathrm{T}}^{\mathrm{miss}}$ (left), and upper limits on $\sigma(pp \to t(b)H^+) \times \mathscr{B}(H^+ \to \tau\nu)$ (right) in the heavy m_{H^+} search in the $H^+ \to \tau\nu$ decay mode with CMS [10].

In the $\mu\tau$ and ll' final states of the $H^+ \to t\bar{b}$ search, the b-jet multiplicity is sensitive to the presence of a signal, while in the l+jets channel, the scalar sum of transverse momenta (p_{T}) of all jets (H_{T}) is used. Figure 8 shows the distributions of these variables for the different channels.

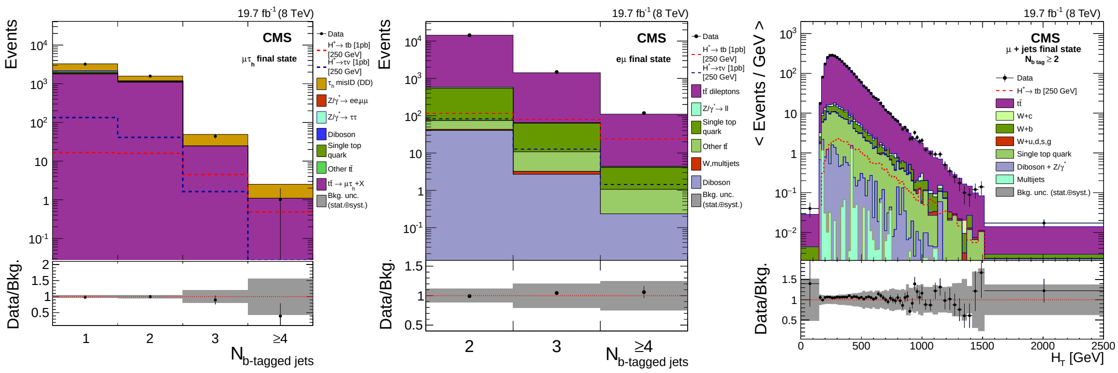

Figure 8: Distribution of the number of b-tagged jets in the $\mu\tau$ (left) and ll' channels (middle), and of H_{T} in the l+jets channel (right) in the search for heavy charged Higgs bosons in $H^+ \to t\bar{b}$ with CMS [10].

The statistical analysis involves using a binned maximum likelihood fit, and the resulting 95 % CL upper limits on $\sigma(pp \to t(b)H^+)$ (assuming $\mathscr{B}(H^+ \to t\bar{b}) = 1$) are found to be 2.0 pb–0.13 pb for $m_{H^+} = 160\,\mathrm{GeV}$–$600\,\mathrm{GeV}$. Figure 9 shows the model independent upper limits, as well as the exclusion in the m_A–$\tan\beta$ plane in the $m_h^{\mathrm{mod}-}$ scenario.

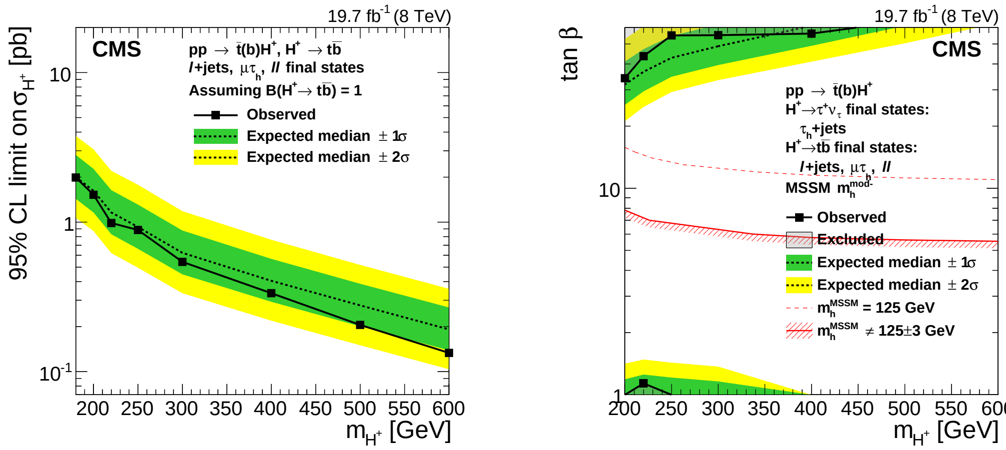

Figure 9: Upper limits on $\sigma(pp \to t(b)H^+)$ (assuming $\mathscr{B}(H^+ \to t\bar{b}) = 1$) (left) and their interpretation in the $m_h^{\text{mod}-}$ scenario (right) for the search for heavy charged Higgs bosons in $H^+ \to t\bar{b}$ with CMS [10].

ATLAS is the first experiment to have presented results of a search for charged Higgs bosons in 13 TeV data [12]. The search is performed in $H^+ \to \tau\nu$ decays, with data collected in 2015 corresponding to an integrated luminosity of 3.2 fb^{-1}. Events are selected with an $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, where the trigger efficiency is derived in data and applied to simulated events. Events in the τ+jets channel are considered, with a hadronic τ decay candidate, no additional lepton, one or more b-tagged jets, and $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV to ensure a high efficiency of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. The large background from misidentified hadronic τ decays is modelled with a data-driven method. Figure 10 shows the distribution of the transverse mass after the full event selection.

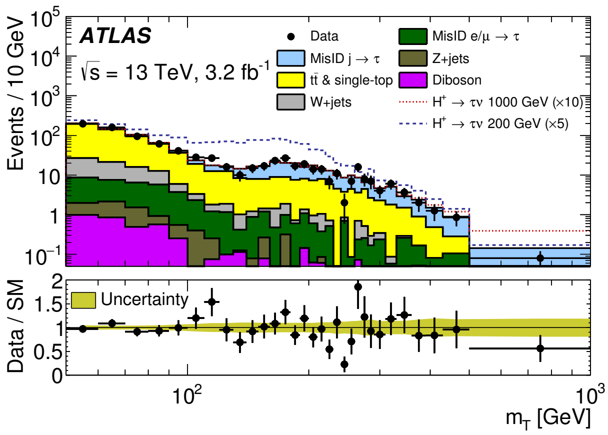

Figure 10: Distribution of the transverse mass in the search for $H^+ \to \tau\nu$ in 13 TeV data with ATLAS [12]. Events that pass the full event selection are considered, and the backgrounds are fitted to the background-only hypothesis. The $m_{H^+} = 200\,\mathrm{GeV}(1000\,\mathrm{GeV})$ signal hypotheses are plotted on top of the background prediction, scaled to 5 (10) times the cross section predicted by the hMSSM scenario at $\tan\beta = 60$.

Model independent upper limits are set on $\sigma(pp \to t(b)H^+) \times \mathscr{B}(H^+ \to \tau\nu)$ in the range from 1.9 pb to 15 fb for $m_{H^+} =$ 200 GeV–2000 GeV. The results are interpreted in the hMSSM scenario, where an exclusion of $m_{H^+} =$ 200 GeV–340 GeV for $\tan\beta = 60$ is determined. This exclusion is an improvement of the result from the $H^+ \to \tau\nu$ search in 8 TeV data with ATLAS [9]. Figure 11 shows the expected and observed upper limits, and their interpretation in the hMSSM scenario.

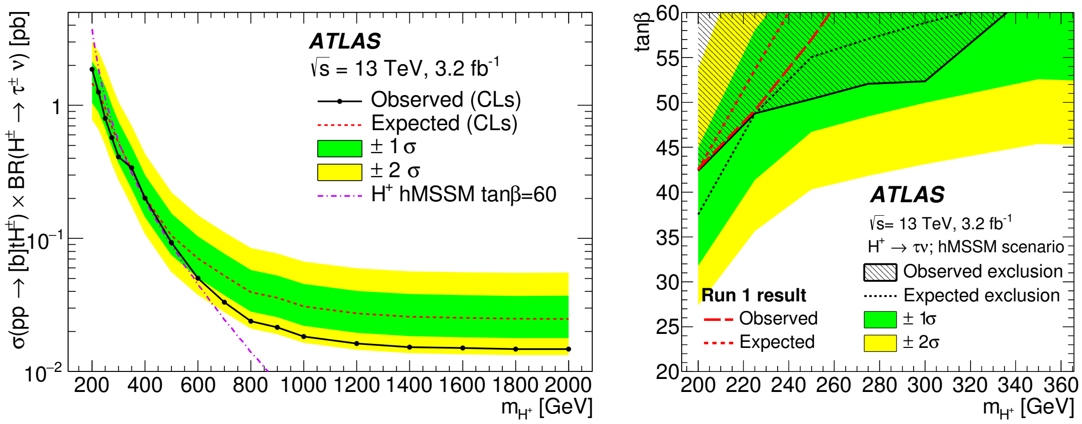

Figure 11: Upper limits on $\sigma(pp \to t(b)H^+) \times \mathscr{B}(H^+ \to \tau\nu)$ (left) and the exclusion in the m_A–$\tan\beta$ plane as interpreted in the hMSSM model (right) in the search for $H^+ \to \tau\nu$ in 13 TeV data with ATLAS [12]. The result from the search in 8 TeV data with ATLAS is indicated in the exclusion.

4. Exotic charged Higgs boson searches

The $H^+ \to W^+Z$ decay mode is suppressed in 2HDM, but available at tree level in e.g. the Georgi-Machacek Higgs triplet model (GMHTM) [13]. A search is conducted in this channel in the vector-boson fusion (VBF) production mode in 8 TeV data corresponding to an integrated luminosity of 20.3 fb^{-1} with ATLAS [14]. Candidate VBF events are selected by requiring two jets that are not b-tagged in opposite hemispheres of the detector ($|\Delta\eta| > 4$), and with an invariant mass of $m_{jj} > 500$ GeV. The two highest-p_{T} central ($|\eta| < 2.5$) jets are used to reconstruct the W boson, and their invariant mass is required to be compatible with the W boson mass. The Z boson is reconstructed from two electrons or muons with $|\eta| < 2.5$, opposite sign charges, and an invariant mass compatible with the Z boson mass. The invariant mass of the two jets from the W boson decay and of the two leptons from the Z boson decay (m_{lljj}) is used to reconstruct m_{H^+}. Figure 12 shows the distribution of m_{lljj}.

The 95 % CL upper limits on $\sigma_{\mathrm{VBF}} \times \mathscr{B}(H^+ \to W^+Z)$ are shown in Figure 13, along with the exclusion in the s_H–m_{H^+} plane as predicted by the GMHTM. Here, s_H^2 is a free parameter that represents the fraction of the W and Z boson masses squared that is generated by the model.

A search for doubly-charged Higgs bosons is conducted in 8 TeV data corresponding to an integrated luminosity of 19.7 fb^{-1} with CMS [15]. The search is performed in decays to three or four electrons or muons in the Drell-Yan ($\Phi^{++}\Phi^{--}$) and associated ($\Phi^{++}\Phi^{-}$) production modes of the Higgs triplet model of the Type II minimal seesaw mechanism [16]. Events in the ee, $e\mu$, $\mu\mu$, $\mu\tau$, and $e\tau$ channels are considered (the $\tau\tau$ channel is omitted), where the tau leptons decay leptonically. The branching fractions of the individual channels are not fixed by the model, and their measurement can give access to neutrino parameters such as masses, CP-violating angles,

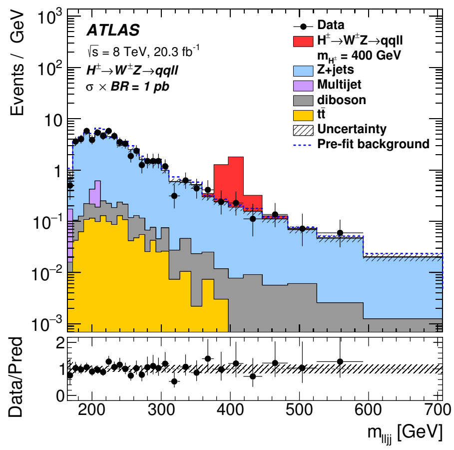

Figure 12: Distribution of the invariant mass of the two jets from the W boson decay and the two leptons from the Z boson decay in the $H^+ \to W^+Z$ search with ATLAS [14]. The distributions are shown after the fit to the background-only hypothesis. An example distribution from simulated signal events with $m_{H^+} = 400\,\mathrm{GeV}$ is plotted on top of the background distributions, where $\sigma_{\mathrm{VBF}} \times \mathscr{B}(H^+ \to W^+Z) = 1\,\mathrm{pb}$.

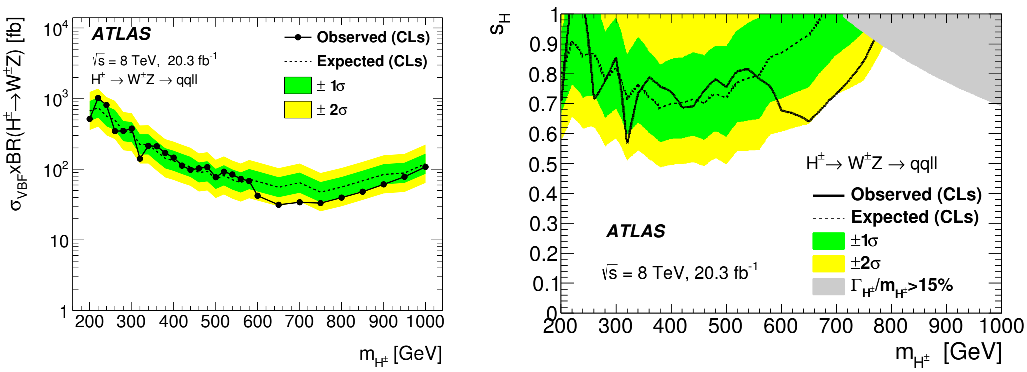

Figure 13: Upper limits on $\sigma_{\mathrm{VBF}} \times \mathscr{B}(H^+ \to W^+Z)$ (left), and the exclusion in the s_H–m_{H^+} plane as interpreted in the GMHTM model (right), in the search for $H^+ \to W^+Z$ in 8 TeV data with ATLAS [14].

Majorana phases, as well as the Higgs triplet *vev*. Figure 14 shows the invariant mass distributions of lepton pairs in the three and four lepton categories after the preselection.

The final event selection includes the compatibility with a window around the Φ^{++} mass hypothesis of $0.9m_\Phi < m_\Phi < 1.1m_\Phi$ and $0.5m_\Phi < m_\Phi < 1.1m_\Phi$ for events with and without tau lepton decays respectively. The exclusion limits on the Φ^{++} mass are shown in Figure 15 for the five channels, assuming a 100 % branching fraction individually, and for four Type II seesaw benchmark points corresponding to four different neutrino mass hypotheses.

5. Conclusion

This note presents an overview of searches for charged Higgs bosons in $H^+ \to \tau\nu$, $H^+ \to t\bar{b}$, $H^+ \to c\bar{s}$, and $H^+ \to W^+Z$ decay modes with 7 TeV and 8 TeV data in ATLAS and CMS. Both light ($m_{H^+} < m_t$) and heavy ($m_{H^+} > m_t$) charged Higgs bosons are considered. Searches for doubly

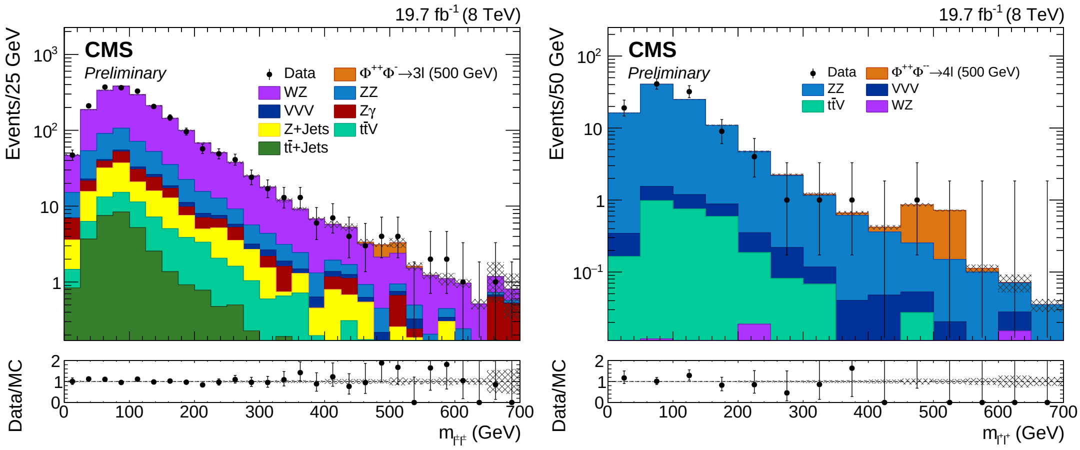

Figure 14: Distributions of the invariant mass of same-sign charge leptons in the three (left) and four (right) lepton categories, after the preselection, in the search for doubly charged Higgs bosons with CMS [15]. The background is estimated from simulated events.

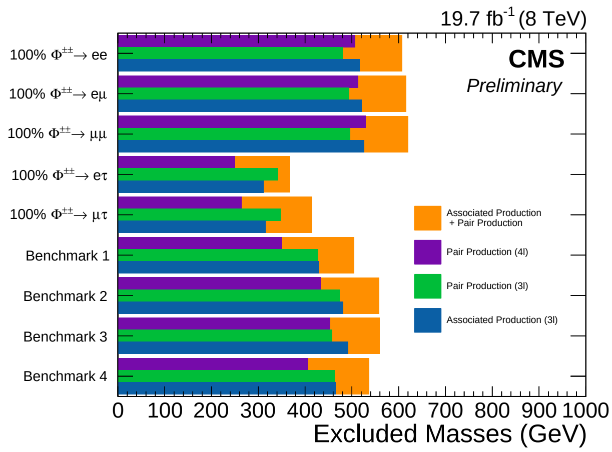

Figure 15: Exclusion limits on the Φ^{++} mass in the five decay channels, assuming a 100 % branching fraction, and four Type II seesaw mechanism benchmark points (BP1–4). The exclusions are derived in the search for doubly charged Higgs bosons with CMS [15].

charged Higgs bosons in three and four lepton decays with 8 TeV data in CMS, as well as the first search for charged Higgs bosons with 13 TeV data in the $H^+ \to \tau\nu$ decay mode with ATLAS are also presented. The results are compatible with the SM, and no hints of a charged Higgs boson signal are found. Model independent 95 % CL upper limits are derived for all searches, and the results are interpreted in the m_h^{mod} and hMSSM scenarios of the Type-II 2HDM in MSSM, as well as in the Georgi-Machacek Higgs triplet model, and the minimal Type-II seesaw mechanism.

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