Vol. 51 (2020) *Acta Physica Polonica B* No 6

SEARCHES FOR A SINGLY CHARGED HIGGS BOSON AT CMS*

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(Received April 17, 2020)

We present recent results on searches for a singly charged Higgs boson from the CMS experiment. The searches are based on proton–proton collision data at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. Various production and decay modes of a singly charged Higgs boson in two-Higgs-doublet models and the Georgi–Machacek model were investigated. No statistically significant evidence of a singly charged Higgs boson was found, and upper limits were set on the production and decay rate of a singly charged Higgs boson in each search channel.

DOI:10.5506/APhysPolB.51.1279

1. Introduction

In 2012, the discovery of a particle with a mass of 125 GeV was announced by the CMS and ATLAS Collaborations [1–3]. The measured properties of the particle are consistent with those of the Higgs boson in the Standard Model (SM) [4, 5]. However, there are still a variety of physics models in which the Higgs sector is larger than in the SM and consistent with the discovered particle. The alternative physics scenarios with an extended Higgs sector can have various motivations such as the hierarchy problem, additional sources of CP violation, and the origin of the smallness of the neutrino masses. An evidence for the extended Higgs sector can shed light on the principles underlying these issues. The CMS Collaboration has been searching for signatures of Higgs bosons in beyond Standard Models (BSM). In this article, we report the latest results on the singly charged Higgs boson

* Presented at XXVI Cracow Epiphany Conference on LHC Physics: Standard Model and Beyond, Kraków, Poland, January 7–10, 2020.

(H^+) from the CMS experiment. The results are based on proton–proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}, collected using the CMS detector [6].

2. Charged Higgs bosons in two-Higgs-doublet models

The H^+ boson arises in the doublet extension of the Higgs sector. In the two-Higgs-doublet models (2HDM), there are five Higgs states, two neutral CP-even (h and H), one neutral CP-odd (A), and two charged Higgs ($H^{\pm}$) bosons. The particle with a mass of 125 GeV can play the role of the CP-even Higgs boson in 2HDM, and it is denoted by h in this article. In order to avoid conflicts with the experimental results on flavor changing neutral currents (FCNC), restrictions are considered upon the general 2HDM. As an example, the models in which the fermions with the same quantum numbers couple to the same Higgs doublet do not exhibit tree-level FCNC. These models are categorized into type I, II, X, and Y based on the couplings of Higgs doublets to up-type quarks, down-type quarks, and charged leptons [7].

In the LHC experiments, the H^+ bosons in 2HDM are expected to be predominantly produced in the Yukawa production modes. The H^+ bosons are mainly produced in the decay of top quarks in $t\bar{t}$ events ($pp \to t\bar{t} \to b\bar{b}H^+W^-$) for the H^+ boson mass (m_{H^+}) smaller than the top-quark mass (m_t), and in association with a single top quark ($pp \to \bar{t}bH^+$) for the m_{H^+} value larger than m_t. Charge-conjugated processes are implied throughout this article. When the m_{H^+} value is close to m_t, all diagrams responsible for $pp \to b\bar{b}H^+W^-$ need to be considered.

The main decay modes of the H^+ boson in 2HDM depend on parameters of the models. The main fermionic decay modes can be $\tau\nu$, $c\bar{s}$, $c\bar{b}$, and $t\bar{b}$. For m_{H^+} values smaller than m_t, the $\tau\nu$ decay mode is the dominant fermionic decay mode of the H^+ boson in most scenarios. However, for a small value of $\tan\beta$, defined as the ratio of vacuum expectation values of the two Higgs doublets, the $c\bar{s}$ decay mode becomes prominent in type II and X 2HDM, and for a large value of $\tan\beta$, the $c\bar{b}$ decay mode constitutes the largest portion of the partial fermionic decay rate in type Y 2HDM [8]. On the other hand, the $t\bar{b}$ decay mode is predominant for m_{H^+} values larger than m_t, with an exception of the large $\tan\beta$ region in type X 2HDM, where the $\tau\nu$ decay mode is the main one [9]. Regarding bosonic decay modes, the H^+ boson can mainly decay in the W^+A and W^+H modes, if kinematically allowed [10, 11]. The W^+h decay mode is expected to be suppressed in parameter regions of 2HDM consistent with the experimental results on the h boson [5], regardless of the m_{H^+} value. In addition, the W^+Z mode is expected to be suppressed due to the absence of the H^+W^+Z interaction in 2HDM at tree level.

The CMS Collaboration has investigated all main fermionic decay modes of the H^+ bosons in Run 1, and the results on $\tau\nu$, $c\bar{s}$, and $t\bar{b}$ channels are updated in Run 2 and are reported in this article. In addition, the W^+A bosonic decay mode was first investigated using the $A \to \mu^+\mu^-$ subdecay mode in Run 2.

2.1. Search for the H^+ boson in the W^+A decay mode

The W^+A decay mode was investigated for the ranges of m_A between 15 and 75 GeV and m_{H^+} between $(m_A + 85$ GeV) to 160 GeV. Among the decay modes of the A and W bosons, produced in decays of the top quark and the H^+ boson, the $A \to \mu^+\mu^-$ and $WW \to \ell\nu q\bar{q}'$ ($\ell = e$ or μ) decay channels were targeted. A resonant signature in the $\mu^+\mu^-$ invariant mass spectrum is searched in trilepton ($e\mu\mu$ and $\mu\mu\mu$) events with b-tagged jets. No statistically significant evidence for the signal was found, hence upper limits at 95% confidence level (C.L.) were set on the product of branching fractions, $\mathcal{B}_{\rm sig} = \mathcal{B}(t \to bH^+)\mathcal{B}(H^+ \to W^+A)\mathcal{B}(A \to \mu^+\mu^-)$, which varies between 1.9×10^{-6} and 8.6×10^{-6} depending on the assumed values of m_A and m_{H^+} (Fig. 1). These are the first limits on the $H^+ \to W^+A$ decay mode in the $A \to \mu^+\mu^-$ subdecay channel, and upper limits on $\mathcal{B}(t \to bH^+)\mathcal{B}(H^+ \to W^+A)$ at the order of 10^{-2} (10^{-3}) in 2HDM of type I and II (X) can be derived.

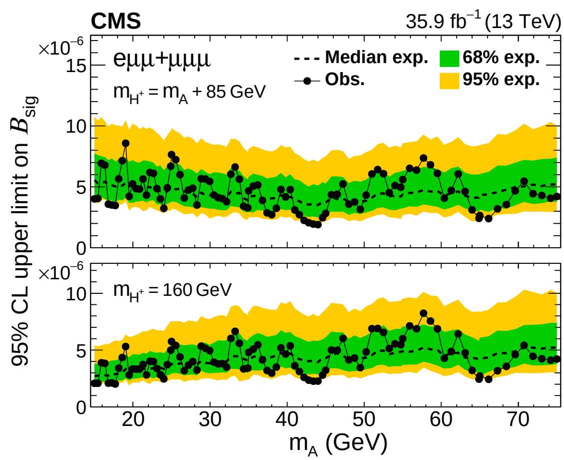

Fig. 1. The upper limits at 95% C.L. on $\mathcal{B}_{\rm sig} = \mathcal{B}(t \to bH^+)\mathcal{B}(H^+ \to W^+A)\mathcal{B}(A \to \mu^+\mu^-)$ [12]. In the upper (lower) panel, the m_{H^+} values are assumed to be $m_A +$ 85 GeV (160 GeV).

2.2. Search for the H^+ boson in the $\tau\nu$ decay mode

The $\tau\nu$ decay mode was investigated for m_{H^+} values between 80 and 3000 GeV. The search targets the τ_h+jets, ℓ+jets, and $\tau_h+\ell$ decay channels of the τ lepton and W boson, where the hadronically decaying τ lepton is denoted by τ_h. The H^+ boson signal was searched by analyzing the transverse mass distribution of visible decay products from the τ lepton and the missing transverse momentum in multiple event regions sensitive to the signal. No statistically significant evidence of the H^+ boson was found, and upper limits at 95% C.L. were set on the production cross section times the branching fraction for the H^+ boson, $\sigma_{H^+}\mathcal{B}(H^+ \to \tau\nu)$, between 6 pb and 5 fb depending on the assumed m_{H^+} values (Fig. 2).

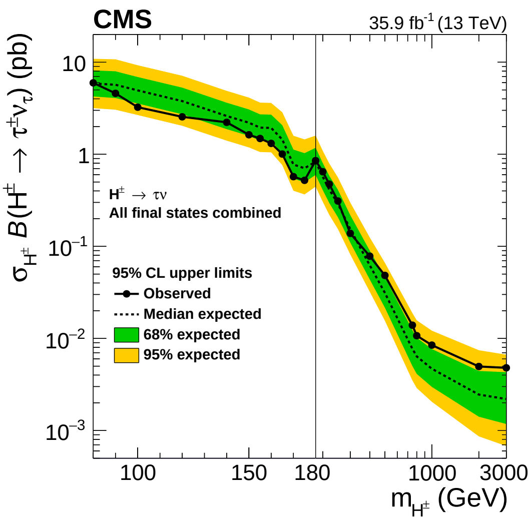

Fig. 2. The upper limits at 95% C.L. on $\sigma_{H^+}\mathcal{B}(H^+ \to \tau\nu)$ [13].

2.3. Search for the H^+ boson in the $c\bar{s}$ decay mode

The $c\bar{s}$ decay mode was investigated for m_{H^+} values between 80 and 160 GeV. The leptonic decay modes are considered for the W boson produced along with the H^+ boson. The search analyzes the invariant mass distribution of two jets, selected as candidates for the decay products of the H^+ boson. To reduce combinatorial backgrounds, the jet pair is selected from the assignment of reconstructed objects that best reproduces the invariant mass of the two top quarks that generated the decay chain. In addition, a recently developed technique of tagging a charm flavored jet is applied to improve the result. No statistically significant evidence of the H^+ boson was found in the analysis, hence upper limits at 95% C.L. are set on the branching fraction $\mathcal{B}(t \to bH^+)$ assuming $\mathcal{B}(H^+ \to c\bar{s}) = 1$ (Fig. 3). The upper limits on $\mathcal{B}(t \to bH^+)$ vary between 0.2% and 1.65% depending on the assumed m_{H^+} values.

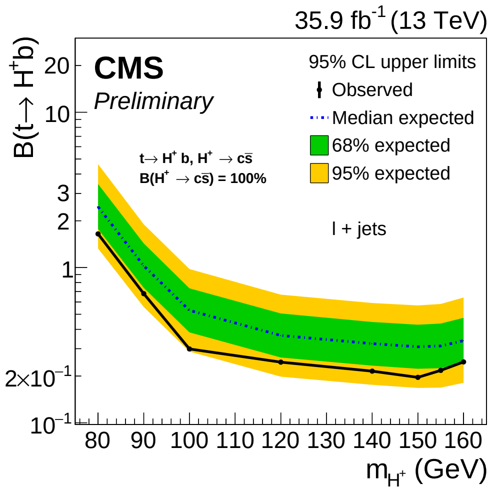

Fig. 3. The upper limits at 95% C.L. on $\mathcal{B}(t \to bH^+)$, assuming $\mathcal{B}(H^+ \to c\bar{s}) = 1$ [14].

2.4. *Search for the H^+ boson in the $t\bar{b}$ decay mode*

The $t\bar{b}$ decay mode was investigated for m_{H^+} values between 200 and 3000 GeV. The H^+ boson in this mass range is produced along with a single top quark, hence the subsequent $H^+ \to t\bar{b}$ and $t \to bW^+$ decays produce two W bosons in the decay chain. The analysis targets all decay modes of the two W bosons except the decay modes that include hadronically decaying τ leptons. The analyses on the single lepton and dilepton decay channels extract the signal using discriminants of multivariate analysis algorithms, which are trained to discriminate the H^+ boson signal events from the $t\bar{t}$ background process [15]. The analysis on the fully hadronic decay channel extracts the signal using the invariant mass of a reconstructed top quark and a b-tagged jet, and the scalar sum of the transverse momentum of jets in events [16]. This is the first analysis using the fully hadronic final states among the searches for the H^+ boson in the $t\bar{b}$ decay mode. No statistically significant evidence of the H^+ boson was found in the analyses. The upper limits at 95% C.L. are set on the production cross section times branching fraction for the H^+ boson, $\sigma_{H^+}\mathcal{B}(H^+ \to t\bar{b})$, which varies between 9.25 pb and 5 fb (Fig. 4). The upper limit is mainly driven by the analysis on the single lepton final states, while the analyses on the dilepton and fully hadronic final states provide improvements in the combination, as can be seen in the figure.

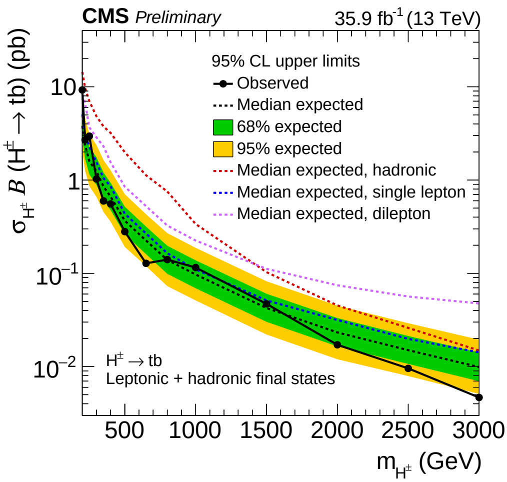

Fig. 4. The upper limits at 95% C.L. on $\sigma_{H^+}\mathcal{B}(H^+ \to t\bar{b})$ [16].

3. Charged Higgs bosons in the Georgi–Machacek model

The presence of singly charged Higgs bosons is also expected in triplet extensions of the Higgs sector. As an example, the Georgi–Machacek model (GM), of which the Higgs sector is extended by one real and one complex triplet, contains two doubly charged, four singly charged, and four neutral Higgs bosons. The singly charged Higgs bosons in GM exhibit features that are phenomenologically different from 2HDM. Particularly, those from the quintuplet of custodial symmetry have the tree-level H^+W^+Z coupling, but do not couple to fermions. In this section, these singly charged Higgs bosons will be denoted by H^+. These bosons can be produced from vector boson fusion processes and mainly decay to a W- and Z-boson pair. The CMS Collaboration has investigated this production and decay mode of the H^+ boson.

3.1. Search for the H^+ boson in the W^+Z decay mode

The W^+Z decay mode was searched using single lepton, dilepton, and trilepton final states. The analysis on the trilepton final states was done for m_{H^+} values between 300 and 2000 GeV, and the single lepton and dilepton final states were analyzed for m_{H^+} values between 600 and 2000 GeV. The trilepton final states have smaller branching fractions than the other decay modes, but they are more sensitive to the signal processes with lower m_{H^+} values due to very small background yields. For the range of m_{H^+} values considered for the single and dilepton final states, the jets originating from these vector boson decays are expected to be merged due to the

Lorentz boost, hence jet substructure techniques are used to identify the vector bosons in hadronic decay modes. The trilepton final states are analyzed using the transverse mass distribution of reconstructed vector boson pairs, and the invariant mass distribution of reconstructed vector boson pairs is used in the analysis on single lepton and dilepton final states. No statistically significant evidence of the H^+ boson was found, and upper limits at 95% C.L. are set on the production cross section times branching fraction for the H^+ boson, $\sigma_{H^+}\mathcal{B}(H^+ \to W^+Z)$ (Fig. 5). The result from the analysis on the trilepton final states is more stringent for m_{H^+} values lower than ≈ 1.5 TeV, and the analysis on the single lepton final states provide stricter limits beyond that mass point.

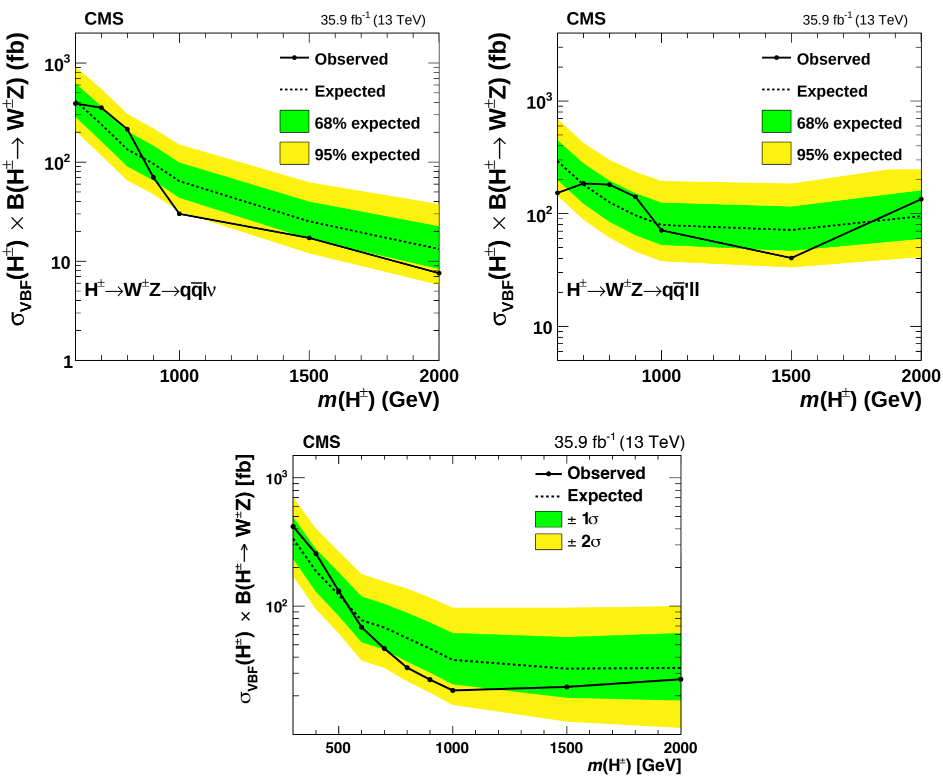

Fig. 5. The upper limits at 95% C.L. on $\sigma_{H^+}\mathcal{B}(H^+ \to W^+Z)$ from the analyses on the single lepton (upper left), dilepton (upper right), and trilepton final states (lower) [17, 18].

4. Summary

The CMS Collaboration has searched for a H^+ boson predicted in 2HDM and GM. The searches were performed using the data of proton–proton collisions at $\sqrt{s} = 13$ TeV, recorded using the CMS detector, corresponding to an integrated luminosity of 35.9 fb^{-1}. In the context of 2HDM, the $\tau\nu$, $c\bar{s}$, and $t\bar{b}$ decay modes were investigated for the fermionic decays of the H^+ boson, and the W^+A decay mode was investigated using the $A \to \mu^+\mu^-$ subdecay channel for the bosonic decays of the H^+ boson. In the context of GM, the W^+Z decay mode was investigated. No statistically significant evidence of the H^+ boson was found in the searches, and upper limits are set on the production and decay rates of the H^+ boson. The searches provide more stringent limits on the fermionic decay modes, when compared to the results from the CMS Collaboration in Run 1, and set direct constraints on the bosonic decay modes.

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