Search for a light charged Higgs boson in the $H^{\pm} \to cs$ channel in proton-proton collisions at $\sqrt{s} = 13$ TeV

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(Received 18 May 2020; accepted 19 August 2020; published 5 October 2020)

A search is conducted for a low-mass charged Higgs boson produced in a top quark decay and subsequently decaying into a charm and a strange quark. The data sample was recorded in proton-proton collisions at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC and corresponds to an integrated luminosity of 35.9 fb^{-1}. The search is performed in the process of top quark pair production, where one top quark decays to a bottom quark and a charged Higgs boson and the other to a bottom quark and a W boson. With the W boson decaying to a charged lepton (electron or muon) and a neutrino, the final state comprises an isolated lepton, missing transverse momentum, and at least four jets, of which two are tagged as b jets. To enhance the search sensitivity, one of the jets originating from the charged Higgs boson is required to satisfy a charm tagging selection. No significant excess beyond standard model predictions is found in the dijet invariant mass distribution. An upper limit in the range 1.68%–0.25% is set on the branching fraction of the top quark decay to the charged Higgs boson and bottom quark for a charged Higgs boson mass between 80 and 160 GeV.

DOI: 10.1103/PhysRevD.102.072001

I. INTRODUCTION

The discovery of the Higgs boson in 2012 by the ATLAS [1] and CMS [2,3] experiments at the CERN LHC has given rise to a wide set of measurements to establish the nature of the discovered particle. The Higgs boson could be the first of many elementary scalars present in nature to be observed in the laboratory. Various extensions of the standard model (SM), such as the two Higgs doublet model (2HDM) [4], including supersymmetry [5–7], predict multiple scalars as the remnants of an additional $\mathrm{SU}(2)_L$ complex doublet introduced to address some known limitations of the SM, such as the origin of dark matter [8,9] and the hierarchy problem [10]. After spontaneous symmetry breaking, out of the eight degrees of freedom of the two Higgs doublets, three are used to make the W and Z bosons massive, leaving five physical scalar particles. Of these, two are neutral Higgs bosons that are CP even (scalar), one is neutral and CP odd (pseudoscalar), and the remaining two are charged Higgs bosons ($H^{\pm}$).

The 2HDM can be classified into different categories depending on the type of interaction of the two doublets with quarks and charged leptons. For example, in the type II 2HDM, leptons and down-type quarks have Yukawa couplings to the first doublet, and up-type quarks couple to the second doublet. The nature of the Yukawa coupling determines the branching fraction $\mathcal{B}$ of the charged Higgs boson decays into different final states. We are interested in the search for a low-mass ($m_{H^+} < m_t$) charged Higgs boson in the decay channel $H^+ \to c\bar{s}$ (and its charge conjugate), whose branching fraction can range up to 100%, depending on the type of Yukawa coupling. The latter is expressed in terms of the parameter $\tan\beta = v_2/v_1$, where v_1 and v_2 are the vacuum expectation values of the two Higgs doublets. In the minimal supersymmetric standard model, this is the dominant decay channel for low values of $\tan\beta$ for most of the mass range considered in this analysis [11,12]. We assume that $\mathcal{B}(H^+ \to c\bar{s}) = 100\%$.

As illustrated in Fig. 1, in the signal process for H^+ production, one of the top quarks decays to H^+b and the other to $W^-\bar{b}$, with H^- production proceeding by the charge conjugate of this process. The principal SM background to this search consists of $t\bar{t}$ pair production where both top quarks decay to a W boson and a b quark. In this search, we consider the mode where the W^+/H^+ decays hadronically into a charm and strange antiquark, whereas the W^- decays leptonically (in the $t\bar{t}$ case, this is called the "semileptonic" decay channel); we define two channels depending on whether the lepton produced in the W^- decay is a muon or an electron (events with tau leptons are not specifically considered but can be selected if the tau lepton decays into a muon or an electron).

There have been many earlier searches for charged Higgs bosons at LEP, the Tevatron, and the LHC. At LEP, these were expected to be dominantly produced by the process

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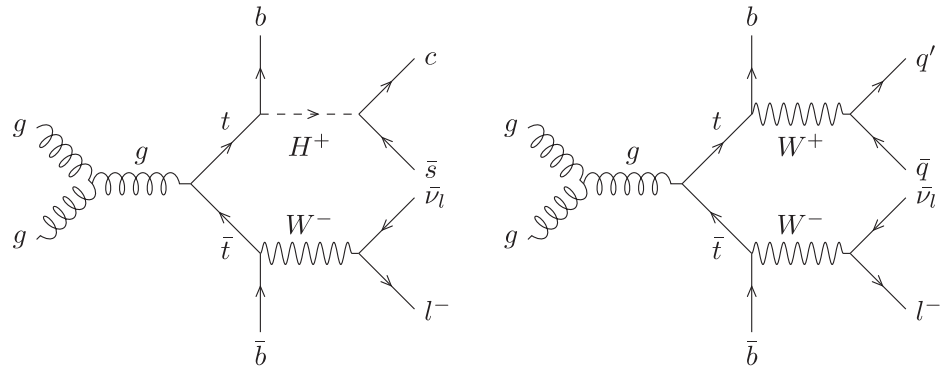

FIG. 1. Sample diagrams of $t\bar{t}$ production via gluon-gluon scattering. The left plot shows the signal process in which the $t\bar{t}$ pair decay products include a charged Higgs boson. The right plot shows the SM decay of a $t\bar{t}$ pair in the semileptonic decay channel.

$e^+e^- \to H^+H^-$. Assuming that H^+ decays only to $c\bar{s}$ and $\tau^+\nu_\tau$, i.e., the sum of the branching factions $\mathcal{B}(H^+ \to \tau^+\nu_\tau) + \mathcal{B}(H^+ \to c\bar{s}) = 1$, lower limits of 79.3 and 80.0 GeV were set on the charged Higgs boson mass at 95% confidence level (CL) from individual collaborations [13–15] and combined LEP data [16], respectively. Under a more general assumption $\mathcal{B}(H^+ \to \tau^+\nu_\tau) + \mathcal{B}(H^+ \to q\bar{q}') = 1$, a slightly less stringent constraint of 76.3 GeV was obtained at 95% CL [17].

Limits on charged Higgs boson production at hadron colliders were set by the Tevatron and LHC experiments, assuming the production mode $t \to H^+b$. The CDF Collaboration [18] set a 95% CL upper limit on the branching fraction $\mathcal{B}(t \to H^+b)$ of 10%–30% for a charged Higgs boson mass lying in the range 60–150 GeV, assuming that H^+ decays only to $c\bar{s}$. Similar limits were obtained by the D0 Collaboration [19]. Using 8 TeV data, the ATLAS [20] and CMS [21] Collaborations set an upper limit at 95% CL on the product $\mathcal{B}(t \to H^+b)\mathcal{B}(H^+ \to \tau^+\nu_\tau)$ of 1.3%–0.23% and 1.2%–0.13%, respectively, for a charged Higgs boson mass in the range 80–160 GeV. A search for a charged Higgs boson decaying into $c\bar{s}$ was performed with 7 (8) TeV data by the ATLAS (CMS) Collaboration, which set an upper limit at 95% CL on $\mathcal{B}(t \to H^+b)$ in the range < 5.1 (6.5–1.2)% for a charged Higgs boson mass between 90 and 160 GeV [22,23]. The CMS Collaboration also performed a search for a charged Higgs boson in the $H^+ \to c\bar{b}$ channel and put the most stringent upper limit at 95% CL on $\mathcal{B}(t \to H^+b)$ in the range 0.8%–0.5% for a charged Higgs boson mass in the range 90–150 GeV [24].

At 13 TeV, the ATLAS and CMS Collaborations have performed several searches for charged Higgs bosons in different search channels such as $H^+ \to \tau^+\nu$, $H^+ \to t\bar{b}$, $H^+ \to W^+Z$, and $H^+ \to W^+A$ [25–30]. The most stringent upper limit on $\sigma(pp \to tH^+ + \mathrm{X})\mathcal{B}(H^+ \to \tau^+\nu)$ at 95% CL is 4.2–0.0025 pb for a charged Higgs boson mass in the range from 90 to 2000 GeV from ATLAS [26]. The ATLAS Collaboration has also set an upper limit at 95% CL on $\sigma(pp \to tH^+ + \mathrm{X})\mathcal{B}(H^+ \to t\bar{b})$ in the range 9.6–0.01 pb for a charged Higgs boson mass in the range 200–3000 GeV [27]. Low values of $\tan\beta < 1$ are excluded for a charged Higgs boson mass up to 160 GeV by both ATLAS and CMS [26,30].

This paper is organized as follows. A brief introduction about the CMS detector is given in Sec. II, followed by the description of collision data and simulated samples in Sec. III. The reconstruction of various physics objects such as the primary vertex, muons, electrons, jets, and missing transverse momentum are described in Sec. IV. The event selection and background estimation method are explained in Sec. V. The kinematic fitting and categorization of events based on charm jet tagging is discussed in Sec. VI. The systematic and statistical uncertainties are described in Sec. VII. The results are presented in Sec. VIII, followed by the summary in Sec. IX.

II. THE CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. The silicon pixel and tracker detectors identify the trajectory of charged particles and accurately measure their transverse momentum p_T up to pseudorapidity $|\eta| \leq 2.5$. Forward calorimeters extend the η coverage provided by the barrel and end cap detectors. Segmented calorimeters provide sampling of electromagnetic and hadronic showers up to $|\eta| \leq 5$. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, in the range of $|\eta| \leq 2.4$.

Events of interest are selected using a two-tiered trigger system [31]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second

level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [32].

III. DATA AND SIMULATION

The data used for the analysis were collected with the CMS detector in 2016, in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV, and correspond to an integrated luminosity of 35.9 fb^{-1}.

As shown in Fig. 1, the charged Higgs boson is assumed to decay into $c\bar{s}$ or $\bar{c}s$ only. As a result, in the final state, there will be four jets (two b jets, one c jet, and one s jet), one lepton (μ or e; τ is not considered in this analysis), and missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$), which is attributed to the neutrino. The SM processes that give the same final states (four jets + one lepton + missing transverse momentum) are considered as background processes for this analysis. Signal and background processes are modeled using simulated samples, generated using the MadGraph5_aMC@NLOv2.3.3 [33] and POWHEGv2.0 [34–37] generators at parton level, with the NNPDF 3.0 [37] parton distribution functions (PDFs), with the order matching that in the matrix element calculations. In all cases, these parton-level events are hadronized using PYTHIA8.212 [38] with the CUETP8M1 underlying event tune [39] and then passed to GEANT4 [40] for simulation of the CMS detector response. Finally, the events are reconstructed after complete detector simulation using the same reconstruction process as for data.

The SM $t\bar{t}$ process is an irreducible background and represents the largest contribution, about 94% of the total expected background in the signal region. The parton-level SM inclusive $t\bar{t}$ events, which have contributions from semileptonic, fully leptonic, and fully hadronic decay modes, are generated at next-to-leading order (NLO) using POWHEG. The next-to-NLO cross section for $t\bar{t}$ is calculated to be $\sigma_{t\bar{t}} = 832\,^{+20}_{-29}\,(\mathrm{scale}) \pm 35(\mathrm{PDF} + \alpha_{\mathrm{S}})\,pb$ [41]. The top quark mass in the simulated samples is taken to be 172.5 GeV.

The charged Higgs boson signal samples are generated using MadGraph5_aMC@NLO at leading order (LO). Only H^+ samples are generated, and H^- production is assumed to be the same. The signal sample is generated for several mass points in the range of 80–160 GeV (80, 90, 100, 120, 140, 150, 155, and 160 GeV). The generated cross section for the signal is taken to be $0.21\sigma_{t\bar{t}}$, where the factor of 0.21 is the branching fraction of $W^- \to \ell^-\bar{\nu}_\ell$ (where $\ell = \mu$ or e, neglecting the small contribution from potential τ decays) [42].

The single top quark production processes, where a top quark is produced with jets in the s channel, t channel, or tW channel, can also mimic the signal topology. The s-channel single top production samples are generated using MadGraph5_aMC@NLO [33] at NLO, while the t-channel and tW-channel samples are generated using POWHEG [43,44] at NLO. The production of W and Z bosons with jets, and vector boson pair production, are also considered as background processes. The inclusive W + jets and Z/γ + jets samples are generated at LO using MadGraph5_aMC@NLO with up to four partons included in the matrix element calculations. The MLM technique [45] is used to avoid the double counting of jets from the matrix element calculation and the parton shower. The vector boson pair production samples ($WW/WZ/ZZ$, collectively referred to as "VV") are generated using PYTHIA at LO.

Furthermore, SM events containing only jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events, can also produce a final state identical to the signal topology, even though these events contain only quarks and gluons at the parton level. QCD multijet events can have reconstructed leptons from, for example, jets misidentified as isolated leptons or decays of bottom and charm hadrons and $p_{\mathrm{T}}^{\mathrm{miss}}$ due to the mismeasurement of hadronic activity inside the CMS detector.

The expected yield for each background process is determined from simulation, with the exception of the QCD multijet background, which is estimated from data, as described in Sec. V.

IV. OBJECT RECONSTRUCTION

The physics objects of interest are leptons, jets, missing transverse momentum, vertices of pp collisions, and displaced vertices from the decay of bottom or charm hadrons. The particle-flow (PF) algorithm [46] is used to reconstruct these objects by optimally using various subsystems of the CMS detector.

The collision vertices are obtained using reconstructed tracks in the silicon tracker [47]. First, candidate vertices are obtained by clustering tracks using the deterministic annealing algorithm. Subsequently, candidate vertices with at least two tracks are fitted using the adaptive vertex fitter. A primary vertex associated with a hard interaction is expected to be accompanied by a large number of tracks. The reconstructed vertex with the largest value of summed physics object p_{T}^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [48,49] with the tracks assigned to the vertex as inputs, and the missing transverse momentum associated with those jets, taken as the negative vector sum of their p_{T}. Furthermore, the reconstructed primary vertex is required to be within 24 cm along the beam axis and within 2 cm in the transverse direction from the nominal pp interaction region.

Muons, being minimum ionizing particles, can traverse a long distance in the CMS detector. The trajectory of the

muon is bent due to the presence of a strong magnetic field inside the solenoid and the return magnetic field in the opposite direction outside the solenoid. Muon candidates are identified in the muon detectors and matched to tracks measured in the silicon tracker, resulting in an excellent p_T resolution between 1% and 10% for p_T values up to 1 TeV [50].

Electrons are reconstructed from the tracks in the tracker and energy deposits in the ECAL [51]. The reconstructed trajectory in the tracker is mapped to the energy deposit in the ECAL to form an electron candidate. The bending direction of the trajectory in the tracker is used to identify the charge of an electron.

Because of color confinement [52], the quarks and gluons produced in pp collisions cannot exist in free states; instead, they produce a cluster of colorless hadrons, most of which subsequently decay to leptons and photons. As mentioned above, jets are clustered from the PF candidates using the anti-k_T algorithm [48,49] with a distance parameter of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, where ϕ is the azimuthal angle. Each jet is required to pass dedicated quality criteria to suppress the impact of instrumental noise and misreconstruction. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute extra tracks and calorimetric energy deposits, increasing the apparent jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [46]. Jet energy corrections are derived from simulation studies so that the average measured response of jets becomes identical to that of particle-level jets. *In situ* measurements of the momentum balance in dijet, $\gamma + \text{jet}$, $Z + \text{jet}$, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are applied [53].

The missing transverse momentum vector $\vec{p}_T^{\text{miss}}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all PF objects in an event. Its magnitude is referred to as p_T^{miss}. Neutrinos, being weakly interacting particles with a very low cross section, cannot be directly detected by the CMS detector and thus contribute to p_T^{miss}. The reconstruction of p_T^{miss} is improved by propagating the jet energy corrections to it.

There are two b jets in the final state as illustrated in Fig. 1, in both the charged Higgs boson signal process and the SM $t\bar{t}$ background. An accurate identification of b jets substantially reduces the SM backgrounds from other processes, such as $Z/\gamma + \text{jets}$, VV, or $W + \text{jets}$. The combined secondary vertex (CSV) algorithm [54] is used to tag a b jet. The algorithm combines information on track impact parameters and secondary vertices within a jet into an artificial neural network classifier that provides separation between a b jet and jets of other flavors. As the charged Higgs boson decays to a charm and a strange antiquark, the identification of charm jets is expected to increase the signal significance. A charm tagger has been developed [54], which is based on the CSV method and works similarly to the b tagging procedure.

The p_T of jets in the simulated samples is corrected using the jet energy scale (JES) and jet energy resolution (JER) data-to-simulation scale factors [53]. The lepton reconstruction, b, and c tagging efficiencies are different in data and simulated samples; to correct for this, the corresponding data-to-simulation scale factors are applied to the simulated events.

V. EVENT SELECTION

In the event topology of interest, there are four jets (two b jets, one c jet, and one light-flavor jet), one charged lepton, and p_T^{miss}. Various selection requirements are applied to ensure the resulting events have this topology.

The online event selection requires, at the L1 trigger level, either a muon candidate with $p_T > 22$ GeV or electron or photon candidate with $p_T > 30$ GeV (22 GeV if it is isolated); at the HLT level, an isolated muon (electron) with $p_T > 24$ (27) GeV is required. The relative isolation (I_{rel}) of a lepton is defined as the ratio of the sum of p_T for all the other particles within a cone of $\Delta R = 0.4$ around the lepton direction, divided by the lepton p_T after correcting for the contribution from pileup [50,55].

In the offline analysis, events that pass the trigger selection and contain a muon (electron) with $p_T > 26$ (30) GeV and $|\eta| < 2.4$ (2.5) are selected. To eliminate events where the lepton is found within a jet, the muon is required to have $I^{\mu}_{\text{rel}} < 0.15$ and the electron is required to have $I^{e}_{\text{rel}} < 0.08$ (0.07) in the barrel (end cap) regions. No charge requirement is applied to the lepton. The signal event topology has only one lepton, so events having a second muon with $p_T^{\mu} > 15$ GeV, $|\eta| < 2.4$, and $I^{\mu}_{\text{rel}} < 0.25$, or an electron with $p_T^{e} > 15$ GeV, $|\eta| < 2.5$, and $I^{e}_{\text{rel}} < 0.18$ (0.16) in the barrel (end cap) regions, are rejected.

Jets are selected by requiring $p_T^{\text{j}} > 25$ GeV, $|\eta^{\text{j}}| < 2.4$, neutral hadron energy fraction < 0.99, neutral electromagnetic energy fraction < 0.99, number of constituents > 1, charged hadron energy fraction > 0, charged-hadron multiplicity > 0, and charged-hadron electromagnetic energy fraction < 0.99, as detailed in Ref. [46]; at least four jets are required. The p_T^{miss} must exceed 20 GeV. The events are required to have at least two b jets with a selection that has 63% b tagging efficiency [54]. The corresponding probability of a light-flavor (charm) jet being misidentified as a b jet is 1% (12%), where "light flavor" refers to jets originating from u, d, s, or g. The events are categorized depending on the charm tagging results for the jets, as discussed in Sec. VI.

To estimate QCD multijet background, a matrix method based on the two uncorrelated variables I_{rel} and p_T^{miss}, also

known as an "ABCD" method, is used, which proceeds as follows. First, a normalization is determined from the (low $p_{\mathrm{T}}^{\mathrm{miss}}$, isolated) and (low $p_{\mathrm{T}}^{\mathrm{miss}}$, anti-isolated) regions; then the QCD background distribution is determined from the (high $p_{\mathrm{T}}^{\mathrm{miss}}$, anti-isolated) region. By using the normalization obtained on the distribution, the expected QCD multijet contribution is determined in the signal region (high $p_{\mathrm{T}}^{\mathrm{miss}}$, isolated). The low- and high-$p_{\mathrm{T}}^{\mathrm{miss}}$ regions are defined by $p_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV and $p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, respectively. In the muon channel, the isolated and anti-isolated regions are defined by $I_{\mathrm{rel}}^{\mu} < 0.15$ and $0.15 < I_{\mathrm{rel}}^{\mu} < 0.4$, respectively. For the electron channel, the isolated region corresponds to $I_{\mathrm{rel}}^{e} < 0.08$ (0.07) and the anti-isolated region to $0.08(0.07) < I_{\mathrm{rel}}^{e} < 0.3$ for electrons in the barrel (end cap) regions. The QCD multijet background is estimated after applying both b and c tagging.

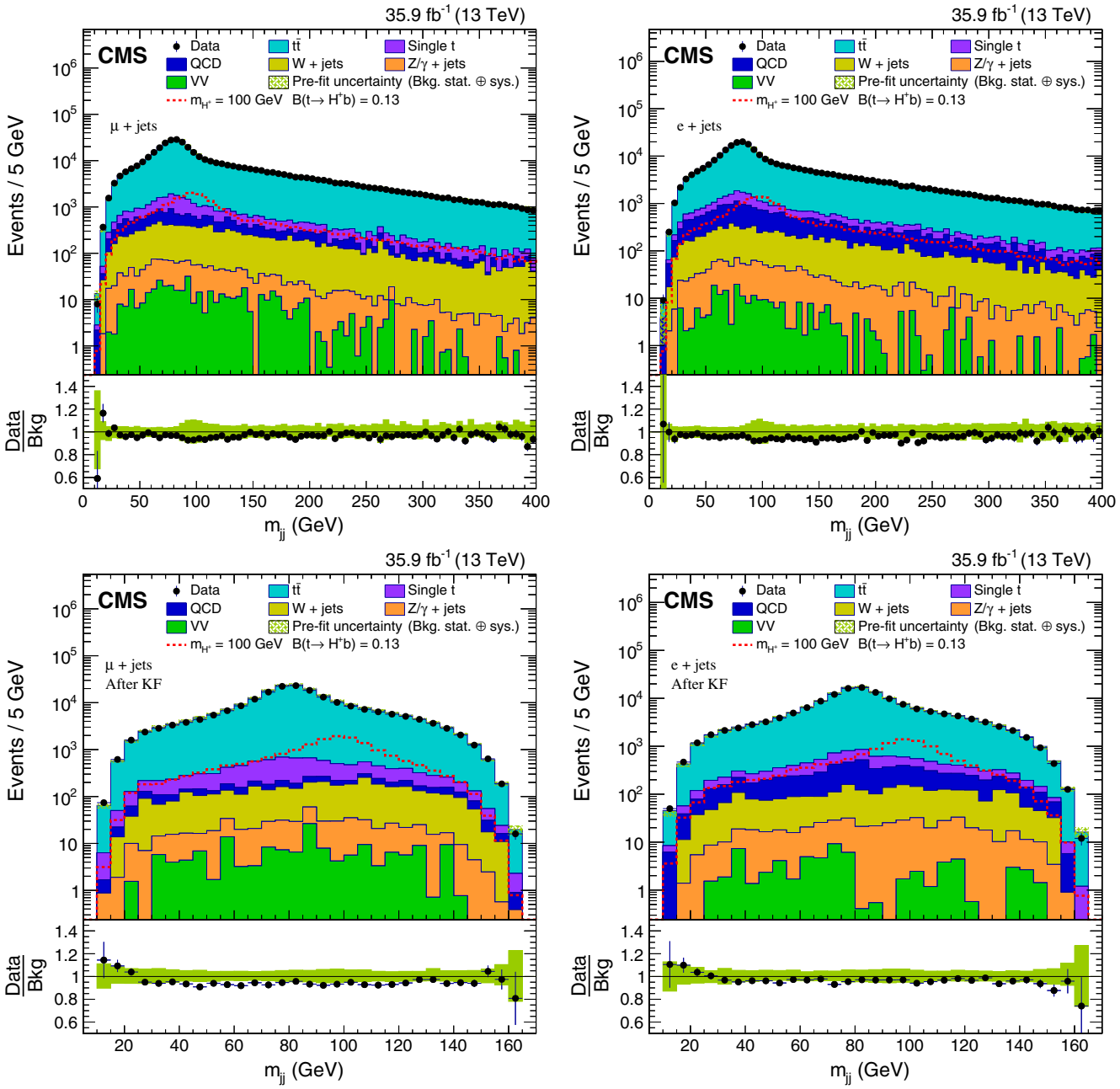

FIG. 2. Distributions of m_{jj}, prior to the fit to data, of the two highest p_{T} non-b jets for the muon + jets channel (left column) and the electron + jets channel (right column). The two distributions in the upper row are obtained using reconstructed jets. The distributions in the lower row are calculated using jets after the kinematic fit. The uncertainty band (showing the absolute uncertainty in the upper panels and the relative uncertainty in the lower panels) includes both statistical and systematic components. The signal events are scaled by twice the maximum observed upper limit on $\mathcal{B}(t \to H^{+}b)$ obtained at 8 TeV [23].

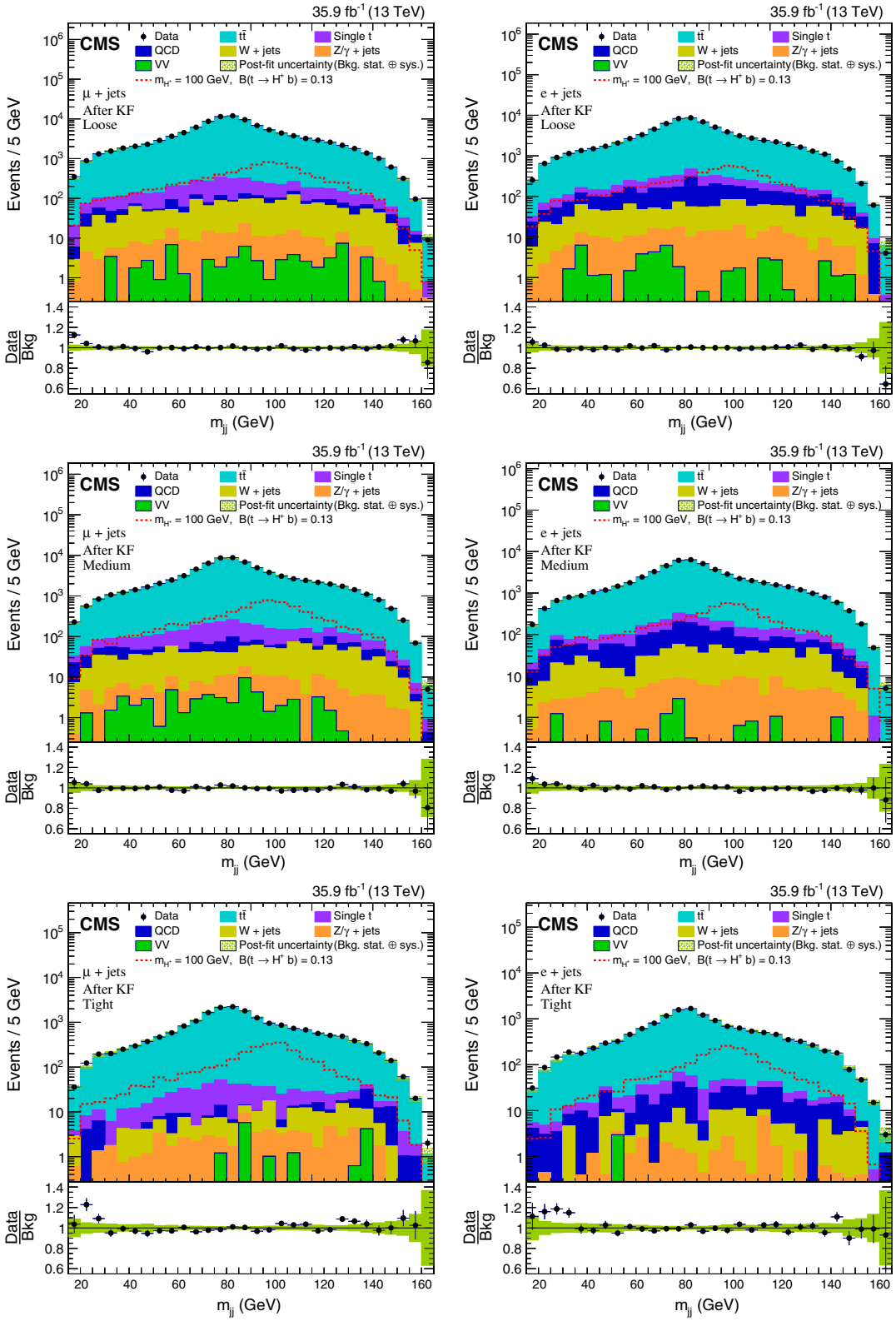

FIG. 3. Distributions of m_{jj}, after a background-only fit to the data, in the exclusive charm tagging categories for the muon + jets (left column) and electron + jets (right column) channels. The upper row shows the exclusive loose category, the middle row shows the exclusive medium category, and the lower row shows the exclusive tight category. The expected signal significance (prior to the fit) can be observed to vary across the different categories. The uncertainty band (showing the absolute uncertainty in the upper panels and the relative uncertainty in the lower panels) includes both statistical and systematic components after the background-only fit. The signal distributions are scaled by twice the maximum observed upper limit on $\mathcal{B}(t \to H^+ b)$ obtained at 8 TeV [23].

TABLE I. The efficiency of the c jet tagger to tag a jet from a c quark (ϵ^c), a b quark (ϵ^b), or light flavor (ϵ^{udsg}) at different working points, as determined from simulation [54].

Working point	ϵ^c (%)	ϵ^b (%)	ϵ^{udsg} (%)
Loose	88	36	91
Medium	40	17	19
Tight	19	20	1.2

VI. DIJET INVARIANT MASS DISTRIBUTION

The invariant mass of the system of the two non-b jets (m_{jj}), assumed to be $c\bar{s}$ or $\bar{c}s$, is used as the final observable. The m_{jj} distribution of the two highest-p_{T} non-b jets is shown in the top row of Fig. 2 for the two leptonic channels. If the two observed non-b jets come from a semileptonic $t\bar{t}$ decay, then the m_{jj} distribution should have a peak at the W boson mass. The observed mean of the m_{jj} distribution is much higher (around 138 GeV), reflecting the fact that the two non-b jets in each event may not necessarily come from the decay of a W boson.

To identify semileptonic $t\bar{t}$ events, a kinematic fit (KF) is performed on the reconstructed objects using the top quark kinematic fitter package [56]. The top kinematic fitter takes physics objects such as leptons, jets, $p_{\mathrm{T}}^{\mathrm{miss}}$, and their resolutions as input and gives improved four-vectors of leptons, jets, and a neutrino, along with the overall χ^2 and fit probability for the event, as the output. The x and y components of the neutrino momentum are taken from $p_{\mathrm{T}}^{\mathrm{miss}}$, as the missing transverse momentum is attributed to the neutrino, and the z component of the neutrino momentum, p_z^ν, is determined from the fit. The following kinematic constraints are imposed on the semileptonic $t\bar{t}$ system:

$$m_{\mathrm{inv}}(b_{\mathrm{had}}q\bar{q}) = m_t = 172.5\ \mathrm{GeV} \tag{1a}$$

$$m_{\mathrm{inv}}(b_{\mathrm{lep}}\ell\nu_\ell) = m_t = 172.5\ \mathrm{GeV}, \tag{1b}$$

where m_{inv} is the corresponding invariant mass and $b_{\mathrm{had(lep)}}$ is the b quark produced by the hadronic (leptonic) top decay. After the fit, p_z^ν is determined from Eq. (1b). For every event, a χ^2 is constructed and minimized by varying the p_{T}, η, and ϕ of each object within their resolution. The values of p_{T}, η, and ϕ are finally selected that minimize the χ^2 and at the same time satisfy Eq. (1). In the output, the top quark kinematic fitter gives exactly four jets (two b jets, one from each of the leptonic and hadronic t decays, and two non-b jets from the hadronic t decay), a lepton, and a neutrino. No cut is placed on χ^2 and events for which the fit does not converge are discarded.

Also, the same kinematic requirements (on p_{T}, η, and I_{rel}) as for the reconstructed objects are applied to the fitted objects. The directions of the kinematically fitted jets and lepton are required to be compatible with those of the reconstructed jets and lepton ($\Delta R < 0.2$), respectively. The efficiency of the KF selection for data, simulated $t\bar{t}$, and simulated signal events is 43%, 47%, and 49%, respectively. The m_{jj} distributions after the KF selection are

TABLE II. Expected event yields for different signal mass scenarios and backgrounds in each of the channels and event categories. The number of events is shown along with its uncertainty, including statistical and systematic effects. The yields of the background processes are obtained after a background-only fit to the data. The total uncertainty in the background process is calculated by taking into account all the positive as well as negative correlations among the fit parameters. The signal event yields are scaled by twice the maximum observed upper limit on $\mathcal{B}(t \to H^+b)$ obtained at 8 TeV [23].

	Loose		Medium		Tight	
Process	μ + jets	e + jets	μ + jets	e + jets	μ + jets	e + jets
$m_{H^+} = 80$ GeV	7690 ± 550	5430 ± 380	6560 ± 490	4700 ± 370	2670 ± 270	1860 ± 180
$m_{H^+} = 90$ GeV	7710 ± 550	5620 ± 400	6770 ± 510	4860 ± 380	2630 ± 260	1870 ± 190
$m_{H^+} = 100$ GeV	7950 ± 590	5550 ± 400	7070 ± 540	4950 ± 360	2770 ± 270	2000 ± 200
$m_{H^+} = 120$ GeV	7620 ± 570	5360 ± 400	6870 ± 510	4780 ± 360	2650 ± 260	1960 ± 190
$m_{H^+} = 140$ GeV	6160 ± 500	4370 ± 360	5420 ± 420	3840 ± 310	2010 ± 210	1500 ± 150
$m_{H^+} = 150$ GeV	4530 ± 390	3230 ± 280	3850 ± 330	2800 ± 250	1340 ± 140	1030 ± 120
$m_{H^+} = 155$ GeV	3700 ± 340	2560 ± 250	2980 ± 270	2230 ± 220	1020 ± 120	766 ± 86
$m_{H^+} = 160$ GeV	2780 ± 270	2080 ± 200	2370 ± 230	1710 ± 180	728 ± 83	510 ± 59
$t\bar{t}$	100540 ± 410	71800 ± 470	73210 ± 320	52340 ± 290	18760 ± 130	13380 ± 130
Single t quark	2750 ± 220	1970 ± 160	1940 ± 160	1400 ± 110	421 ± 35	302 ± 26
QCD multijet	520 ± 130	2120 ± 470	498 ± 98	1460 ± 210	88 ± 28	346 ± 39
W + jets	1360 ± 140	1061 ± 90	950 ± 110	681 ± 58	127 ± 23	102 ± 9
Z/γ + jets	189 ± 18	240 ± 25	132 ± 13	132 ± 14	56 ± 7	31 ± 4
VV	61 ± 9	43 ± 6	56 ± 8	11 ± 4	15 ± 5	3 ± 1
All background	105410 ± 500	77240 ± 690	76780 ± 390	56020 ± 380	19470 ± 140	14160 ± 140
Data	105474	77244	76807	56051	19437	14179

shown in the bottom row of Fig. 2, showing that the mean of the m_{jj} distribution is closer to the W boson mass.

The two non-b jets coming from the hadronic t decay are further used for charm tagging. There are three c tagging working points (loose, medium, and tight) based on the efficiency of a c quark being tagged as a c jet [54]. The corresponding efficiencies are shown in Table I. The events are divided exclusively into loose, medium, and tight categories, based on whether at least one of the non-b jets passes the loose but neither passes the medium, at least one passes the medium but neither passes the tight, or at least one passes the tight working points of the charm tagging selection requirements shown in Table I, respectively. The m_{jj} distributions for the exclusive charm categories are shown in Fig. 3 after a background-only maximum likelihood fit to data. From these figures, it can be seen that the expected signal-to-background ratio increases for the charm categories with tighter requirements, so partitioning the events into categories results in an enhanced signal sensitivity. Table II shows the corresponding event yields for the different charm categories after the background-only fit to the data reported in Sec. VIII, with statistical and systematic uncertainties as discussed in Sec. VII.

VII. SYSTEMATIC UNCERTAINTIES

There are various sources of systematic uncertainty, which may arise due to detector calibration effects, uncertainty in the measured reconstruction efficiency, the theoretical modeling of signal events, and other effects.

The uncertainty in the integrated luminosity is 2.5% [57]. Each distribution for simulated events is normalized to the expected number of events in data, using the factor $L_{data}\sigma_{sim}/N_{sim}$, where L_{data} is the integrated luminosity of the data sample, N_{sim} is the total number of events in the simulated sample, and σ_{sim} is the cross section for the simulated process considered; the uncertainties in σ_{sim} thus contribute to the uncertainty in each background prediction. The uncertainties in σ_{sim} for $t\bar{t}$, single t quark, $W+$jets, $Z/\gamma+$jets, and VV processes are 6.1%, 7.0%, 4.5%, 5.0%, and 4.0%, respectively. To account for the uncertainty in the pileup distribution, the total inelastic cross section of 69.2 mb is varied by its uncertainty of 4.7% [58] and the simulated events are reweighted to match the pileup distribution in the data. The systematic uncertainty in the data-to-simulation scale factor for the lepton reconstruction efficiencies is 3.0% for both muons and electrons [50,51].

The systematic uncertainties due to JES and JER data-to-simulation scale factors in the p_T of the jets and p_T^{miss} are estimated by varying these within their uncertainties [53]. The b and c tag data-to-simulation scale factors are varied within their uncertainties to estimate the corresponding uncertainties, with correlations applied [54].

To estimate the systematic uncertainty in the QCD multijet background estimation, the muon (electron) relative isolation threshold is conservatively changed to 0.17 (0.11) and the corresponding changes in the QCD yields are determined.

It is found that the p_T distribution of t quarks in $t\bar{t}$ events in data is softer compared to that in simulated samples [59]. This is corrected by applying the following weight as a function of p_T for SM $t\bar{t}$ and charged Higgs boson signal samples:

$$w_t = \sqrt{\mathrm{SF}(t)\mathrm{SF}(\bar{t})},$$
$$\text{with } \mathrm{SF} \equiv \exp(0.09494 - 0.00084 p_T). \quad (2)$$

The values in the exponent are derived in Ref. [60]. The generator-level p_T of the t and $\bar{t}$ are used to calculate SF. To evaluate the systematic uncertainty due to w_t, it is varied to 1 and w_t^2.

The SM $t\bar{t}$ sample was generated with $m_t = 172.5$ GeV. To evaluate the effect of the chosen m_t on the m_{jj} distribution, alternate $t\bar{t}$ samples with $m_t = 171.5$ and 173.5 GeV are considered. To observe the effect of NLO matrix element parton shower matching, additional SM $t\bar{t}$ samples are generated by changing the default damping parameter h_{damp} value of $1.58m_t$ to $2.24m_t$ and m_t [61]. Similarly, SM $t\bar{t}$ samples where the common nominal value of renormalization and factorization scales is simultaneously changed by factors of 0.5 and 2 are used to evaluate the uncertainties due to these scales [62]. The systematic uncertainties due to t quark mass, parton shower matching, and renormalization and factorization scales are in the ranges 0.2%–3.3%, 0.7%–1.9%, and 0.4%–1.6%, respectively, depending on the channel and charm tagging category.

The signal extraction procedure is based on a binned maximum likelihood fit of the m_{jj} distributions, as described in Sec. VI. The systematic uncertainties prior to the fit on the different process yields are listed in Table III, when they differ from process to process. All systematic uncertainties are incorporated into the fit as nuisance parameters, where the effect of each systematic uncertainty on the overall normalization of the m_{jj} distribution is included as a lognormal probability distribution. The statistical uncertainties in the total yield of all backgrounds and the signal samples are also shown in Table III. However, these are not incorporated in the likelihood. To account for the statistical uncertainty in each bin of m_{jj}, one nuisance parameter per bin is considered for the sum of all backgrounds and charged Higgs boson samples [63].

The most important sources of uncertainties in terms of impact on the expected limit on $\mathcal{B}(t \to H^+ b)$ for $m_{H^+} = 100$ GeV, after the individual charm tagging categories and the muon and electron channels have been combined, as discussed in Sec. VIII, are the lepton selection (3.8%), QCD multijet background estimate (2.4%), $t\bar{t}$ cross section (1.9%), and b/c tagging (1.9%). The effect of each

TABLE III. Systematic and statistical uncertainties in the event yield for the different processes in percent, when they differ from process to process, prior to the fit to data, for the exclusive charm categories in the muon (electron) channel. The "…" indicates that the corresponding uncertainties are either not considered for the given process or too small to be measured.

Category	Process	Pileup	jet & $p_{\mathrm{T}}^{\mathrm{miss}}$	b & c jets	Normalization	Statistical	p_{T} (t)
Loose	$m_{H^+} = 100$ GeV	0.6 (1.1)	4.2 (3.5)	6.1 (6.1)	6.1 (6.1)	1.0 (1.2)	1.4 (1.8)
	$t\bar{t}$	0.9 (1.1)	3.6 (3.6)	5.8 (5.8)	6.1 (6.1)	0.2 (0.2)	1.5 (1.9)
	Single t quark	0.6 (0.8)	4.9 (5.4)	6.5 (6.6)	5.0 (5.0)	0.7 (0.8)	…
	$W+$ jets	2.3 (0.4)	13 (6.9)	10 (10)	5.0 (5.0)	3.9 (4.5)	…
	$Z/\gamma+$ jets	1.8 (2.4)	11 (8.4)	9.2 (9.0)	4.5 (4.5)	5.7 (4.2)	…
	VV	1.5 (7.9)	19 (13)	7.2 (7.0)	4.0 (4.0)	19 (22)	…
	QCD multijet	…	…	…	10 (10)	20 (7.3)	…
Medium	$m_{H^+} = 100$ GeV	0.4 (0.3)	3.5 (2.0)	6.7 (6.8)	6.1 (6.1)	1.1 (1.3)	1.6 (1.9)
	$t\bar{t}$	0.3 (0.4)	3.0 (3.0)	7.3 (7.3)	6.1 (6.1)	0.2 (0.3)	1.5 (2.0)
	Single t quark	0.3 (0.1)	4.4 (4.1)	8.1 (8.1)	5.0 (5.0)	0.9 (1.0)	…
	$W+$ jets	2.9 (1.6)	14 (6.8)	12 (11)	5.0 (5.0)	4.8 (5.7)	…
	$Z/\gamma+$ jets	0.7 (3.4)	9.0 (11)	12 (11)	4.5 (4.5)	5.9 (5.9)	…
	VV	0.6 (4.4)	15 (49)	10 (9.4)	4.0 (4.0)	20 (36)	…
	QCD multijet	…	…	…	10 (10)	19 (9.4)	…
Tight	$m_{H^+} = 100$ GeV	1.2 (1.3)	2.2 (3.0)	9.2 (9.2)	6.1 (6.1)	1.6 (1.9)	1.4 (1.8)
	$t\bar{t}$	0.9 (1.0)	2.7 (3.1)	9.4 (9.4)	6.1 (6.1)	0.4 (0.5)	1.4 (1.8)
	Single t quark	0.4 (0.5)	4.3 (4.5)	9.8 (9.8)	5.0 (5.0)	1.8 (2.1)	…
	$W+$ jets	1.1 (2.8)	23 (3.4)	13 (13)	5.0 (5.0)	12 (14)	…
	$Z/\gamma+$ jets	3.7 (2.7)	7.5 (10)	13 (12)	4.5 (4.5)	9.1 (15)	…
	VV	2.3 (8.9)	36 (0.3)	11 (10)	4.0 (4.0)	38 (100)	…
	QCD multijet	…	…	…	10 (10)	47 (17)	…

of the remaining systematic uncertainties on the expected limit is estimated to be less than 0.3%.

The number of events in the background processes and the corresponding uncertainty bands shown in Fig. 3 are obtained using a background-only fit to data. After the fit, several uncertainties (both statistical and systematic) are significantly anticorrelated, resulting in a reduction in the overall uncertainty. This is a feature of doing an extended maximum likelihood fit. The anticorrelations reflect the fact that while our analysis can constrain the background normalization with the statistical power of the data, it cannot distinguish as well between different sources which do not represent independent degrees of freedom in the model. Prior to the fit, as shown in Table III, they are either uncorrelated or positively correlated.

VIII. RESULTS

After applying all selection requirements, the expected number of background events agrees with the data within the uncertainties. The absence of a charged Higgs boson signal in the data is characterized by setting exclusion limits on the branching fraction $\mathcal{B}(t \to H^+ b)$. An asymptotic 95% CL limit on $\mathcal{B}(t \to H^+ b)$ is calculated using the $\mathrm{CL_s}$ method [64,65] with likelihood ratios [66]:

$$\tilde{q}_x = -2 \ln \frac{\mathcal{L}(\mathrm{data}|x, \hat{\Theta}_x)}{\mathcal{L}(\mathrm{data}|\hat{x}, \hat{\Theta})}, \tag{3}$$

where the likelihood is defined as

$$\mathcal{L}(\mathrm{data}|x, \Theta) = \prod_{j=1}^{3} \prod_{i=1}^{N} \frac{N_{ij}(x, \Theta)^{n_{ij}}}{n_{ij}!} \mathrm{e}^{-N_{ij}(x,\Theta)} \prod_k p(\tilde{\Theta}_k|\Theta_k). \tag{4}$$

In this equation, $x = \mathcal{B}(t \to H^+ b)$ is the parameter of interest, the first product over j designates the three charm tagging categories, and i runs over the bins of the m_{jj} distributions shown in Fig. 3. For a given mass bin i and charm tagging category j, n_{ij} is the observed number of events in that bin and charm tagging category, and $N_{ij}(\Theta)$ is the expected number of events. The last term is the product over the individual nuisance parameters k of the probability density function $p(\tilde{\Theta}_k|\Theta_k)$, where Θ_k is the value of the nuisance parameter. The estimators $\hat{x}$ and $\hat{\Theta}$ correspond to the global maximum of the likelihood defined in Eq. (4). The expected number of events $N_{ij}(\Theta)$ is given by, in the presence of signal,

$$N_{ij}(x, \Theta) = 2x(1-x) N_{ij}^{t\bar{t} \to H^+ W^-}(\Theta) + (1-x)^2 N_{ij}^{t\bar{t} \to W^\pm W^\mp}(\Theta) + N_{ij}^{\mathrm{other}}(\Theta), \tag{5}$$

and in the absence,

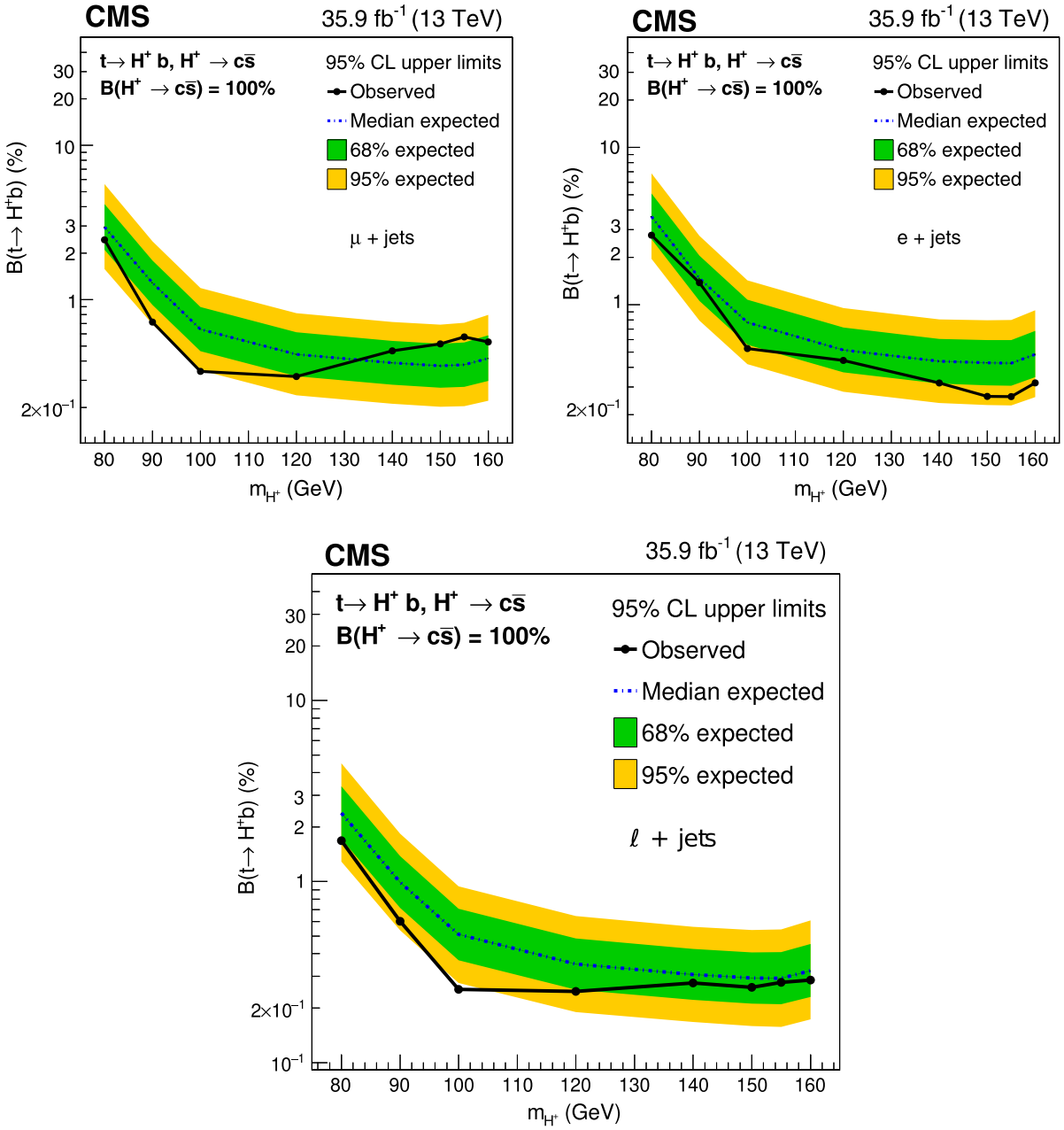

FIG. 4. The expected and observed upper limit in % on $\mathcal{B}(t \to H^+ b)$ as a function of m_{H^+} using m_{jj} after the individual charm tagging categories have been combined, for the muon + jets (upper left) and electron + jets (upper right) channels and their combination (lower).

$$N_{ij}(\Theta) = N_{ij}^{t\bar{t}\to W^{\pm}W^{\mp}}(\Theta) + N_{ij}^{\mathrm{other}}(\Theta), \tag{6}$$

where $N_{ij}^{t\bar{t}\to H^{+}W^{-}}(\Theta)$ and $N_{ij}^{t\bar{t}\to W^{\pm}W^{\mp}}(\Theta)$ are the number of events from the simulated signal process and the SM $t\bar{t}$ process, respectively. Both are normalized to the expected $t\bar{t}$ cross sections, as described in Sec. III. The factor of 2 in Eq. (5) is derived from the assumption that the event yield and $\mathcal{B}(t \to H^- \bar{b})$ for H^- are the same as those of H^+.

The exclusion limits on $\mathcal{B}(t \to H^+ b)$ as a function of charged Higgs boson mass using the m_{jj} distribution in the range 15–165 GeV and combining different exclusive event categories based on charm tagging are shown in Fig. 4 and in Tables IV and V. Among the individual categories, the expected limits from the exclusive medium category are most stringent, followed by those from the exclusive loose and tight categories. By construction, the exclusion limits on $\mathcal{B}(\bar{t} \to H^- \bar{b})$ are the same as those on $\mathcal{B}(t \to H^+ b)$.

TABLE IV. Expected and observed 95% CL exclusion limits in percent on $\mathcal{B}(t \to H^+ b)$ in the muon + jets (electron + jets) channel, after the individual charm tagging categories have been combined.

	Expected					
m_{H^+} (GeV)	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Observed
80	1.58 (1.96)	2.10 (2.61)	2.95 (3.63)	4.16 (5.10)	5.61 (6.84)	2.44 (2.77)
90	0.69 (0.79)	0.92 (1.06)	1.28 (1.47)	1.79 (2.05)	2.39 (2.74)	0.72 (1.38)
100	0.35 (0.42)	0.46 (0.56)	0.64 (0.77)	0.90 (1.08)	1.19 (1.43)	0.34 (0.53)
120	0.24 (0.28)	0.32 (0.37)	0.44 (0.52)	0.61 (0.72)	0.82 (0.95)	0.32 (0.44)
140	0.21 (0.24)	0.28 (0.32)	0.39 (0.44)	0.54 (0.61)	0.72 (0.81)	0.47 (0.32)
150	0.20 (0.23)	0.27 (0.31)	0.37 (0.43)	0.52 (0.60)	0.69 (0.80)	0.52 (0.26)
155	0.20 (0.23)	0.27 (0.31)	0.38 (0.42)	0.53 (0.60)	0.71 (0.80)	0.57 (0.26)
160	0.22 (0.26)	0.30 (0.35)	0.42 (0.48)	0.59 (0.68)	0.80 (0.92)	0.53 (0.32)

TABLE V. Expected and observed 95% CL exclusion limits in percent on $\mathcal{B}(t \to H^+ b)$, after the individual charm tagging categories and the muon and electron channels have been combined.

	Expected					
m_{H^+} (GeV)	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Observed
80	1.29	1.72	2.39	3.36	4.50	1.68
90	0.54	0.72	0.99	1.38	1.84	0.60
100	0.28	0.37	0.51	0.71	0.94	0.25
120	0.19	0.25	0.35	0.49	0.64	0.25
140	0.17	0.22	0.31	0.42	0.56	0.28
150	0.16	0.21	0.29	0.41	0.54	0.26
155	0.16	0.21	0.29	0.41	0.54	0.28
160	0.17	0.23	0.32	0.45	0.61	0.29

IX. SUMMARY

A search for a light charged Higgs boson produced by top quark decay has been performed in the muon + jets and electron + jets channels at $\sqrt{s} = 13$ TeV, using a data sample corresponding to an integrated luminosity of 35.9 fb^{-1}. The observed and predicted number of events from standard model processes are in agreement within the uncertainties. An exclusion limit at 95% confidence level on the branching fraction $\mathcal{B}(t \to H^+ b)$ has been computed by assuming $\mathcal{B}(H^+ \to c\bar{s}) = 100\%$. The observed exclusion limits are in the range, for a charged Higgs boson mass between 80 and 160 GeV, 2.44%–0.32%, 2.77%–0.26%, and 1.68%–0.25% for the muon + jets, electron + jets, and the combination of the two channels, respectively. These are the first results from the LHC at $\sqrt{s} = 13$ TeV for the above final states and represent an improvement by a factor of approximately 4 over the previous results at $\sqrt{s} = 8$ TeV.

ACKNOWLEDGMENTS

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR,

and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, Contracts No. 675440, No. 752730, and No. 765710 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation *à la* Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science—EOS"—be.h Project No. 30820817; the Beijing Municipal Science and Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy—EXC 2121 "Quantum Universe"—390833306; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research Grants No. 123842, No. 123959, No. 124845, No. 124850, No. 125105, No. 128713, No. 128786, and No. 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), Contracts No. Harmonia 2014/14/M/ST2/00428, No. Opus 2014/13/B/ST2/02543, No. 2014/15/B/ST2/03998, and No. 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, Grant No. 14.W03.31.0026 (Russia); the Tomsk Polytechnic University Competitiveness Enhancement Program and "Nauka" Project No. FSWW-2020-0008 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, Grant No. MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, Contract No. C-1845; and the Weston Havens Foundation (USA).

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