Editors' Suggestion

Search for Higgs Boson Decay to a Charm Quark-Antiquark Pair in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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A search for the standard model Higgs boson decaying to a charm quark-antiquark pair, $H \to c\bar{c}$, produced in association with a leptonically decaying V (W or Z) boson is presented. The search is performed with proton-proton collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1}. Novel charm jet identification and analysis methods using machine learning techniques are employed. The analysis is validated by searching for $Z \to c\bar{c}$ in VZ events, leading to its first observation at a hadron collider with a significance of 5.7 standard deviations. The observed (expected) upper limit on $\sigma(VH)\mathcal{B}(H \to c\bar{c})$ is 0.94 ($0.50^{+0.22}_{-0.15}$)pb at 95% confidence level (C.L.), corresponding to 14 ($7.6^{+3.4}_{-2.3}$) times the standard model prediction. For the Higgs-charm Yukawa coupling modifier, κ_c, the observed (expected) 95% C.L. interval is $1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$), the most stringent constraint to date.

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The discovery of a Higgs boson (H) with the LHC Run 1 data by the ATLAS [1] and CMS [2,3] experiments in 2012 was a major advance in the understanding of the electroweak (EW) symmetry breaking mechanism. The measured Higgs boson mass is 125.38 ± 0.14 GeV [4]. The observed interactions with gauge bosons and third-generation fermions [5–15], and all measured properties [4,16–24], are compatible with standard model (SM) predictions. Recently, the CMS Collaboration reported the first evidence of Higgs boson decays to muons, i.e., second-generation leptons [25]. An important next milestone is the observation of its coupling to second-generation quarks. In this Letter, we focus on a search for Higgs boson decay to $c\bar{c}$, a charm quark-antiquark pair. The corresponding Yukawa coupling, y_c, can be significantly modified in the presence of physics beyond the SM [26–31]. However, the small branching fraction predicted by the SM, ubiquitous production of quark and gluon jets at the LHC, and the difficulty of identifying charm quark jets in a hadronic environment, including distinguishing them from bottom quark jets, make this a challenging measurement. Searches for $H \to c\bar{c}$ reported in Refs. [32–34] by the ATLAS and CMS Collaborations target the associated production of a Higgs boson with a V (W or Z) boson. Using 139 fb^{-1} of data at 13 TeV, the most recent search by the ATLAS Collaboration obtains an observed (expected) upper limit on the product of the production cross section $\sigma(VH)$ and branching fraction $\mathcal{B}(H \to c\bar{c})$ of 26 (31) times the SM prediction at 95% confidence level (C.L.) [34].

This Letter presents a search for $H \to c\bar{c}$ in VH production using proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV, collected by the CMS detector in 2016–2018, and corresponding to an integrated luminosity of 138 fb^{-1} [35–37]. Building upon a previous analysis by the CMS Collaboration [33], advanced c jet reconstruction and identification algorithms and sophisticated analysis techniques using machine learning (ML) have been further developed to significantly improve sensitivity.

The CMS apparatus [38] is a multipurpose, nearly hermetic detector, designed to trigger on [39,40] and identify electrons, muons, photons, and (charged and neutral) hadrons [41–43]. A global reconstruction "particle-flow" (PF) algorithm [44] combines the information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from gas-ionization muon detectors embedded in the solenoid flux-return yoke, to reconstruct charged and neutral hadrons, electrons, photons, and muons (PF candidates) and build τ leptons, jets, missing transverse momentum, and other physics objects [45–47].

Two collections of jets, formed by PF candidates clustered with the anti-k_T algorithm [48,49], are used in the search. The first uses a distance parameter $R = 0.4$, and will be referred to as "small-R" jets. The second uses $R = 1.5$ and contains what are referred to as "large-R" jets. The impact of particles from additional pp interactions within

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the same or nearby bunch crossings (pileup) is mitigated via the charged hadron subtraction algorithm [44] for small-R jets, and via the PUPPI [50,51] algorithm for large-R jets. A regression algorithm [52] is developed to improve large-R jet mass reconstruction that exploits properties of the PF candidates and secondary vertices associated to the jet using the ParticleNet graph neural network [53]. Mass resolution is improved by about 50% over traditional jet grooming algorithms [54,55]. The small-R (large-R) jets are required to have transverse momentum (p_T) above 25 (200) GeV and to be within the tracker acceptance.

Signal and background processes are simulated using various Monte Carlo event generators. The detector response is modeled with GEANT4 [56]. The WH and quark-induced ZH signal processes are generated at next-to-leading order (NLO) accuracy in quantum chromodynamics (QCD) using the POWHEG v2 [57–59] event generator extended with the multiscale improved NLO (MiNLO) procedure [60,61], while the gluon-induced ZH process is generated at leading order (LO) accuracy with POWHEG v2. The Higgs boson mass is set to 125 GeV for all simulations. The production cross sections of the signal processes [62] are corrected as a function of $p_T(V)$ to next-to-next-to-leading order (NNLO) QCD + NLO EW accuracy combining the VHNNLO [63–66], VH@NNLO [67,68], and HAWK v2.0 [69] generators, as described in Ref. [62].

The V + jets background samples are generated with MadGraph5_aMC@NLO v2.6.0 [70] at NLO with up to two additional partons. The top quark pair ($t\bar{t}$) [71] and single top quark production processes [72–74] are generated to NLO accuracy with POWHEG v2. The production cross sections for the $t\bar{t}$ samples are scaled to the NNLO prediction with the next-to-next-to-leading logarithmic resummation result obtained from TOP++ v2.0 [75], and the differential cross sections as a function of top quark p_T are corrected to the NNLO QCD + NLO EW prediction [76]. Diboson backgrounds are generated at NLO with POWHEG v2 (MadGraph5_aMC@NLO v2.4.2) for the WW [77] (WZ and ZZ) process. Production cross sections of the diboson processes are reweighted as a function of the subleading vector boson p_T to NNLO QCD + NLO EW accuracy [78].

The NLO NNPDF3.0 [79] (NNLO NNPDF3.1 [80]) parton distribution function (PDF) set is used for the 2016 (2017 and 2018) simulations. For parton showering and hadronization, including the $H \to c\bar{c}$ decay, matrix element generators are interfaced with PYTHIA v8.230 [81] with the CUETP8M1 [82] (CP5 [83]) underlying event tune for 2016 (2017 and 2018) samples. The matching of jets from matrix element calculations and those from parton showers is done with the FxFx [84] (MLM [85]) prescription for NLO (LO) samples. For all samples, pileup interactions are simulated with PYTHIA and added to the hard-scattering process. Events are then reweighted to match the pileup profile observed in data.

The analysis is carried out in mutually exclusive channels targeting leptonic decays of the vector bosons: $Z \to \nu\nu$, $W \to \ell\nu$, and $Z \to \ell\ell$, where ℓ is an electron or a muon, and referred to as the $0L$, $1L$, and $2L$ channels. Events are collected using triggers based on large missing transverse momentum, or the presence of one, or two well-identified and isolated leptons. The event selection criteria are detailed in Ref. [33].

As for the previous search [33], the analysis reconstructs the Higgs boson candidate (H_{cand}) assuming either a "merged-jet" topology, in which the hadronization products of the two charm quarks are reconstructed as a single large-R jet, or a "resolved-jet" topology, in which the H_{cand} is reconstructed from two well-separated and individually resolved small-R c jets. These two topologies can have significant overlap and are made distinct in reference to whether a given H_{cand}, identified through a large-R jet in the event, has p_T above or below a threshold of 300 GeV for the definition of the merged-jet and the resolved-jet topology, respectively, where the dividing line is chosen to maximize sensitivity to $VH(H \to c\bar{c})$.

On average, the H_{cand} large-R jets in the signal process have larger p_T than those from the V + jets and $t\bar{t}$ backgrounds. Thus, the high-p_T regime explored in the merged-jet topology, although amounting to less than 5% of the signal cross section, provides significant sensitivity to the search. Because the highly boosted Higgs boson decay produces a more narrowly concentrated collection of final-state particles, the use of a single large-R jet enhances the probability of correctly capturing the hadronization products of both charm quarks, and facilitates the accounting of final-state radiation (FSR) emitted by the quarks. A detailed discussion of the advantages can be found in Refs. [33,55,86].

State-of-the-art performance in the reconstruction and identification of the pair of c quarks from the Higgs boson decay is achieved with ParticleNet [53], a novel jet identification algorithm. Using PF candidates and secondary vertices associated with large-R jets as inputs, ParticleNet simultaneously exploits information related to jet substructure, flavor, and pileup with a graph neural network [87], yielding substantial gains over other approaches [88,89]. Decorrelation of the algorithm's response with the jet mass is achieved by training it with a dedicated set of simulations produced with the same jet mass distributions for the signal and background processes [88]. Figure 1 shows the performance of the $c\bar{c}$ discriminant in identifying a pair of c quarks from Higgs boson decay for large-R jets with $p_T > 300$ GeV. ParticleNet is compared to the previous state-of-the-art $c\bar{c}$ discriminant "DeepAK15" [33,90], yielding an improvement by a factor of 4 to 7 in the rejection of other jet flavors. Three working points are defined on the $c\bar{c}$ discriminant distribution with approximately 58%, 40%,

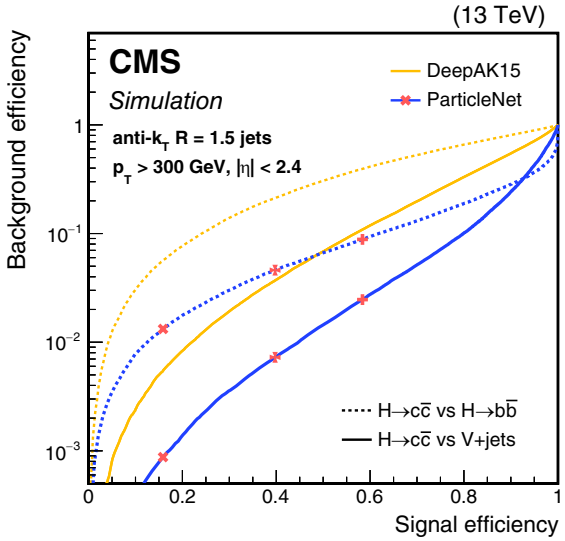


FIG. 1. Performance of ParticleNet (blue lines) for identifying a $c\bar{c}$ pair for large-R jets with $p_T > 300$ GeV. The solid (dashed) line shows the efficiency to correctly identify $H \to c\bar{c}$ vs the efficiency of misidentifying quarks or gluons from the $V+$jets process (vs $H \to b\bar{b}$). The red crosses represent the three working points used in the merged-jet analysis. The performance of DeepAK15 (yellow lines) used in Ref. [33] is shown for comparison.

and 16% efficiencies for identifying a $c\bar{c}$ pair. The corresponding misidentification rates of light quark and gluon jets ($b\bar{b}$ jets) are 2 (9)%, 0.7 (5)%, and 0.08 (1)%. These working points are used to separate events into three mutually exclusive categories with different $c\bar{c}$ purity to improve the sensitivity of the analysis. The $c\bar{c}$ identification efficiency in data is measured using a sample of events containing a gluon splitting to $c\bar{c}$. To increase the similarity to $H \to c\bar{c}$ decay, a dedicated boosted decision tree (BDT) classifier is developed to enrich jets where a large fraction of momentum is carried by the quark pair from gluon splitting rather than by additionally radiated gluons [91]. The p_T-dependent data-to-simulation efficiency ratios (used as corrective scale factors) are typically 0.9–1.3 with corresponding uncertainties of 20%–30%.

The main backgrounds, $t\bar{t}$ and $V+$jets, are suppressed by a separate BDT classifier for each channel, using kinematical variables that are not correlated with the H_{cand} mass, $m(H_{\text{cand}})$, or the $c\bar{c}$ discriminant as inputs. The BDT design relies on previous developments [33] with improvements in variable selection and training procedure, leading to ≈15% enhancement of the sensitivity of the analysis. The BDT discriminants are used to define 2 (1) signal regions (SRs) in the $1L$ ($0L$ and $2L$) channel. Events in the SRs are further subdivided into the three $c\bar{c}$ discriminant categories mentioned above. The $m(H_{\text{cand}})$ distributions are used to separate signal and background contributions in each SR, as both the BDTs and the $c\bar{c}$ discriminant are designed to be largely independent of $m(H_{\text{cand}})$.

More than 95% of the VH events have a Higgs boson with $p_T(H) < 300$ GeV, corresponding to the phase space region where the Higgs boson decay products generally give rise to two distinctly reconstructed small-R jets. The resolved-jet topology exploits a large fraction of this phase space, which, however, contains higher background contamination than that used in the merged-jet analysis. The H_{cand} is reconstructed via two distinct small-R jets. The identification of c jets relies on the ML-based DeepJet algorithm [92,93]. The discrimination between c jets and light quark or gluon jets (b jets) is achieved via the ratio of the corresponding probabilities, defined as Cvs$L$ (Cvs$B$) [94]. Potential differences in the discriminant shapes between data and simulation are taken into account by flavor-dependent simulation-to-data efficiency scale factors [94], which are typically in the 0.9–1.0 range. The corresponding uncertainties range from ≈2% for light quark and gluon jets or b jets, to ≈5% for c jets.

The two jets with the highest Cvs$L$ discriminants in each event are selected to reconstruct the H_{cand} momentum four-vector. To improve sample purity, criteria are imposed on Cvs$L$ and Cvs$B$ for the leading jet that correspond to ≈40% c jet efficiency, for ≈4 (≈16)% light quark or gluon jet (b jet) misidentification rate. Multiple corrections are applied to improve the $m(H_{\text{cand}})$ reconstruction. To account for a potential underestimation of the c jet energy, due to the presence of undetected neutrinos in c hadron decays, a ML-based jet energy regression algorithm [95], originally developed for b jets, is adapted for c jets. In addition, small-R jets reconstructed in the vicinity of H_{cand} jets, often stemming from FSR, are included in the H_{cand} reconstruction [33]. The $m(H_{\text{cand}})$ resolution in the $2L$ channel is further improved via a kinematic fit by balancing the momenta of the two small-R jets and the lepton pair within experimental uncertainties [96]. These steps improve the $m(H_{\text{cand}})$ resolution up to 20%. Finally, a BDT classifier is developed to maximize the discrimination power between signal and background processes in each channel, using event-level kinematical variables, c jet identification discriminants, and properties of H_{cand}, including $m(H_{\text{cand}})$, as inputs [33].

The signal strength modifier μ, defined as $(\sigma\mathcal{B})_{\text{obs}}/(\sigma\mathcal{B})_{\text{SM}}$ where σ is the signal production cross section and $\mathcal{B}$ is the branching fraction, is measured via a binned maximum likelihood fit to data. The best-fit value of μ and an approximate 68% C.L. confidence interval are extracted following the procedure in Ref. [17]. The fitted variable is $m(H_{\text{cand}})$ in the merged-jet analysis, and the BDT discriminant in the resolved-jet analysis. The normalizations of the main backgrounds, namely, $V+$jets and $t\bar{t}$, are estimated by including dedicated control regions in the fit following the strategy detailed in Ref. [33]. Contributions from single top, diboson, and $VH(H \to b\bar{b})$ processes are estimated from simulation assuming SM production rates. Because of improvements in c jet identification, the difficult $VH(H \to b\bar{b})$ background contribution in the high $c\bar{c}$ purity SRs is

TABLE I. The relative contributions to the total uncertainty in the signal strength modifier μ for the $VH(H \to c\bar{c})$ process, where the best fit is $\mu_{VH(H\to c\bar{c})} = 7.7^{+3.8}_{-3.5}$.

Uncertainty source	$\Delta\mu/(\Delta\mu)_{\text{tot}}$ (%)
Statistical	85
Background normalizations	37
Experimental	48
Sizes of the simulated samples	37
c jet identification efficiencies	23
Jet energy scale and resolution	15
Simulation modeling	11
Integrated luminosity	6
Lepton identification efficiencies	4
Theory	22
Backgrounds	17
Signal	15

reduced from about twenty times to only about twice that expected for $VH(H \to c\bar{c})$, and the $VZ(Z \to b\bar{b})$ yield is reduced from more than 100% to about 10% of that expected for $VZ(Z \to c\bar{c})$. Contributions from $H \to \tau\tau$ decays are negligible after the above-mentioned selection criteria, and are not considered.

Systematic uncertainties affecting normalizations and shapes of fitted variables are taken into account via nuisance parameters. The relative contribution of each uncertainty source to the total uncertainty in the fitted μ is summarized in Table I. The leading uncertainty is statistical because of the limited number of events in the SRs as well as the control regions used to extract background normalizations. The main experimental systematic uncertainties are associated with limited simulation sample sizes, particularly due to large fractions of negatively weighted events in the NLO $V+$jets samples, and the c jet identification efficiencies, representing ≈37% and ≈23% of the total, respectively. Theoretical uncertainties in the cross sections, p_T spectra, PDFs, and renormalization and factorization scales, represent ≈22% of the total uncertainty in μ.

A search for the analogous SM process $VZ(Z \to c\bar{c})$ is performed to validate the analysis strategy. The BDTs in the resolved-jet topology are modified by training them with $VZ(Z \to c\bar{c})$ as the signal. No modification is needed for the BDTs in the merged-jet topology as they are independent of $m(H_{\text{cand}})$. The best fit μ of this process is $\mu_{VZ(Z\to c\bar{c})} = 1.01^{+0.23}_{-0.21}$, in agreement with the SM expectation. Figure 2 (left) shows the distribution of events in all channels, sorted into bins of similar signal-to-background ratios. The observed data show a visible excess over the expected backgrounds. The significance of the excess is computed using the asymptotic distribution of a test statistic based on the profile likelihood ratio [97,98]. The observed (expected) significance is 4.4 (4.7) standard deviations for the merged-jet analysis, 3.1 (3.3) standard deviations for the resolved-jet analysis, and 5.7 (5.9) standard deviations for their combination. This is the first observation of $Z \to c\bar{c}$ at a hadron collider.

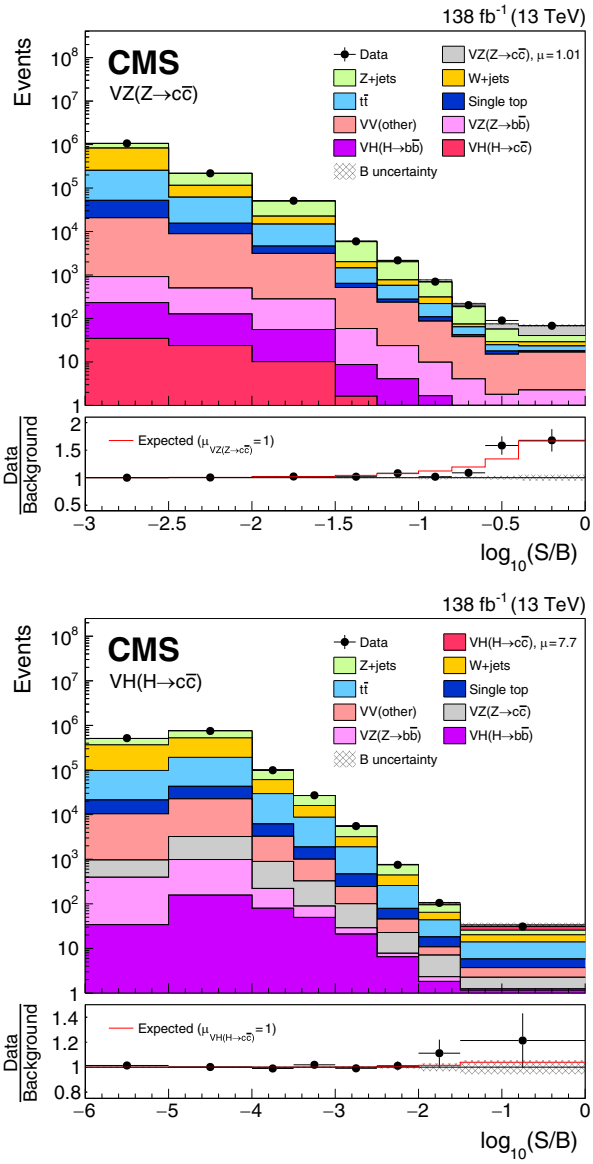


FIG. 2. Distribution of events as a function of S/B in the $VZ(Z \to c\bar{c})$ (left) and $VH(H \to c\bar{c})$ (right) searches, where S and B are the postfit signal and background yields, respectively, in each bin of the fitted $m(H_{\text{cand}})$ or BDT discriminant distributions. The bottom panel shows the ratio of data to the total background, with the uncertainty in background indicated by gray hatching. The red line represents background plus the SM signal divided by background.

Figure 2 (right) compares the observed data to the SM prediction in the search for $VH(H \to c\bar{c})$, where the best fit is $\mu_{VH(H\to c\bar{c})} = 7.7^{+3.8}_{-3.5}$. The fitted $m(H_{\text{cand}})$ distribution in the merged-jet topology is displayed in Fig. 3. No significant excess over the background-only hypothesis is observed. An upper limit on $\mu_{VH(H\to c\bar{c})}$ is extracted using the CL_s criterion [99,100]. The test statistic is the profile

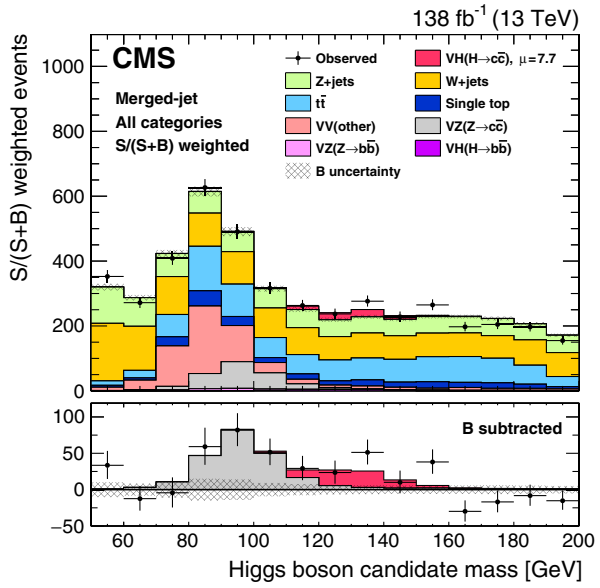


FIG. 3. Combined $m(H_{\text{cand}})$ distribution in all channels of the merged-jet analysis. The fitted $m(H_{\text{cand}})$ distribution in each SR is weighted by $S/(S+B)$, where S and B are the postfit $VH(H \to c\bar{c})$ signal and total background yields. The lower panel shows data (points) and the fitted $VH(H \to c\bar{c})$ (red) and $VZ(Z \to c\bar{c})$ (gray) distributions after subtracting all other processes. Error bars represent presubtraction statistical uncertainties in data, while the gray hatching indicates the total uncertainty in the signal and all background processes.

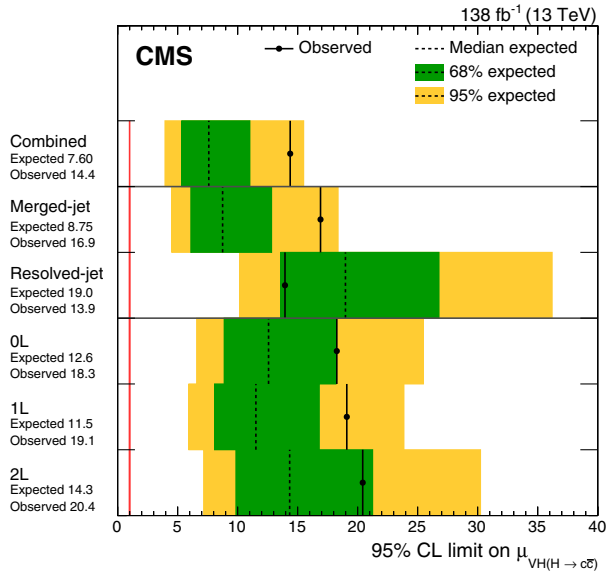


FIG. 4. The 95% C.L. upper limits on $\mu_{VH(H\to c\bar{c})}$. Green and yellow bands indicate the 68 and 95% intervals on the expected limits, respectively. The vertical red line indicates the SM value $\mu_{VH(H\to c\bar{c})} = 1$.

likelihood ratio modified for upper limits [97], and the asymptotic approximation [98] is used in the limit setting procedure. The observed (expected) 95% C.L. upper limit on $\mu_{VH(H\to c\bar{c})}$ is 14 $(7.6^{+3.4}_{-2.3})$, which is equivalent to an observed (expected) upper limit on $\sigma(VH)\mathcal{B}(H \to c\bar{c})$ of 0.94 $(0.50^{+0.22}_{-0.15})$ pb. Contributions from the individual channels are summarized in Fig. 4. Tabulated results are provided in the HEPData record for this analysis [101].

The result is interpreted in the κ framework [62,102] by reparameterizing $\mu_{VH(H\to c\bar{c})}$ in terms of the Higgs-charm Yukawa coupling modifier κ_c, assuming only the Higgs boson decay widths are altered:

$$\mu_{VH(H\to c\bar{c})} = \frac{\kappa_c^2}{1 + \mathcal{B}_{\text{SM}}(H \to c\bar{c})(\kappa_c^2 - 1)}. \qquad (1)$$

The observed 95% C.L. interval is $1.1 < |\kappa_c| < 5.5$, and the corresponding expected constraint is $|\kappa_c| < 3.4$.

In summary, a search for the SM Higgs boson decaying to a pair of charm quarks in the CMS experiment is presented. Novel jet reconstruction and identification tools, and analysis techniques are developed for this analysis, which is validated by measuring the $VZ(Z \to c\bar{c})$ process. The observed Z boson signal relative to the SM prediction is $\mu_{VZ(Z\to c\bar{c})} = 1.01^{+0.23}_{-0.21}$, with an observed (expected) significance of 5.7 (5.9) standard deviations above the background-only hypothesis. This is the first observation of $Z \to c\bar{c}$ at a hadronic collider.

The observed (expected) upper limit on $\sigma(VH)\mathcal{B}(H \to c\bar{c})$ is 0.94 $(0.50^{+0.22}_{-0.15})$ pb, corresponding to 14 $(7.6^{+3.4}_{-2.3})$ times the theoretical prediction for an SM Higgs boson mass of 125.38 GeV. The observed (expected) 95% C.L. interval on the modifier, κ_c, for the Yukawa coupling of the Higgs boson to the charm quark is $1.1 < |\kappa_c| < 5.5$ $(|\kappa_c| < 3.4)$. This is the most stringent constraint on κ_c to date.

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 and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN

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