


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

A. M. Sirunyan *et al.**
(CMS Collaboration)

 (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](https://doi.org/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 $SU(2)_L$ 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 ($m_{H^\pm} < m_t$) charged Higgs boson in the decay channel $H^+ \rightarrow c\bar{s}$ (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 $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 100\%$.

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^-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

*Full author list given at the end of the article.

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

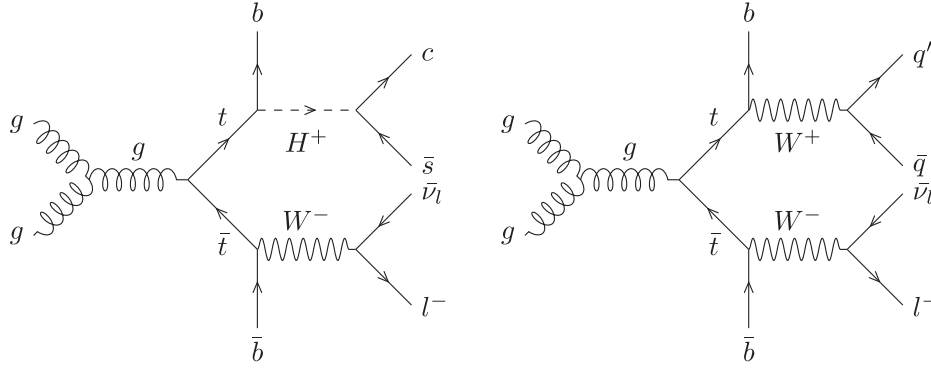


FIG. 1. Sample diagrams of $t\bar{t}$ production via gluon-gluon scattering. The left plot shows the signal process in which the $t\bar{t}$ pair decay products include a charged Higgs boson. The right plot shows the SM decay of a $t\bar{t}$ pair in the semileptonic decay channel.

$e^+e^- \rightarrow H^+H^-$. Assuming that H^+ decays only to $c\bar{s}$ and $\tau^+\nu_\tau$, i.e., the sum of the branching fractions $\mathcal{B}(H^+ \rightarrow \tau^+\nu_\tau) + \mathcal{B}(H^+ \rightarrow c\bar{s}) = 1$, 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 $\mathcal{B}(H^+ \rightarrow \tau^+\nu_\tau) + \mathcal{B}(H^+ \rightarrow q\bar{q}') = 1$, 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 $t \rightarrow H^+b$. The CDF Collaboration [18] set a 95% CL upper limit on the branching fraction $\mathcal{B}(t \rightarrow H^+b)$ 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 $\mathcal{B}(t \rightarrow H^+b)\mathcal{B}(H^+ \rightarrow \tau^+\nu_\tau)$ 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 $\mathcal{B}(t \rightarrow H^+b)$ 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 $H^+ \rightarrow c\bar{b}$ channel and put the most stringent upper limit at 95% CL on $\mathcal{B}(t \rightarrow H^+b)$ 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 $H^+ \rightarrow \tau^+\nu$, $H^+ \rightarrow t\bar{b}$, $H^+ \rightarrow W^+Z$, and $H^+ \rightarrow W^+A$ [25–30]. The most stringent upper limit on $\sigma(pp \rightarrow tH^+ + X)\mathcal{B}(H^+ \rightarrow \tau^+\nu)$ 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 $\sigma(pp \rightarrow tH^+ + X)\mathcal{B}(H^+ \rightarrow t\bar{b})$ 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 μ s. 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 ($p_{\text{T}}^{\text{miss}}$), 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 $\sigma_{t\bar{t}} = 832 \pm_{29}^{20} (\text{scale}) \pm 35 (\text{PDF} + \alpha_S) pb$ [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 $W^- \rightarrow \ell^- \bar{\nu}_{\ell}$ (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 $W + \text{jets}$ and $Z/\gamma + \text{jets}$ 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 $p_{\text{T}}^{\text{miss}}$ 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, γ + jet, Z + 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^{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/γ + jets, VV , or W + 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 $I_{\text{rel}}^\mu < 0.15$ and the electron is required to have $I_{\text{rel}}^e < 0.08$ (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 $I_{\text{rel}}^\mu < 0.25$, or an electron with $p_T^e > 15$ GeV, $|\eta| < 2.5$, and $I_{\text{rel}}^e < 0.18$ (0.16) in the barrel (end cap) regions, are rejected.

Jets are selected by requiring $p_T^j > 25$ GeV, $|\eta^j| < 2.4$, 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_T^{miss} , isolated) and (low p_T^{miss} , anti-isolated) regions; then the QCD background distribution is determined from the (high p_T^{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_T^{miss} , isolated). The low- and high- p_T^{miss} regions are

defined by $p_T^{\text{miss}} < 20$ GeV and $p_T^{\text{miss}} > 20$ GeV, respectively. In the muon channel, the isolated and anti-isolated regions are defined by $I_{\text{rel}}^\mu < 0.15$ and $0.15 < I_{\text{rel}}^\mu < 0.4$, respectively. For the electron channel, the isolated region corresponds to $I_{\text{rel}}^e < 0.08$ (0.07) and the anti-isolated region to $0.08(0.07) < I_{\text{rel}}^e < 0.3$ for electrons in the barrel (end cap) regions. The QCD multijet background is estimated after applying both b and c tagging.

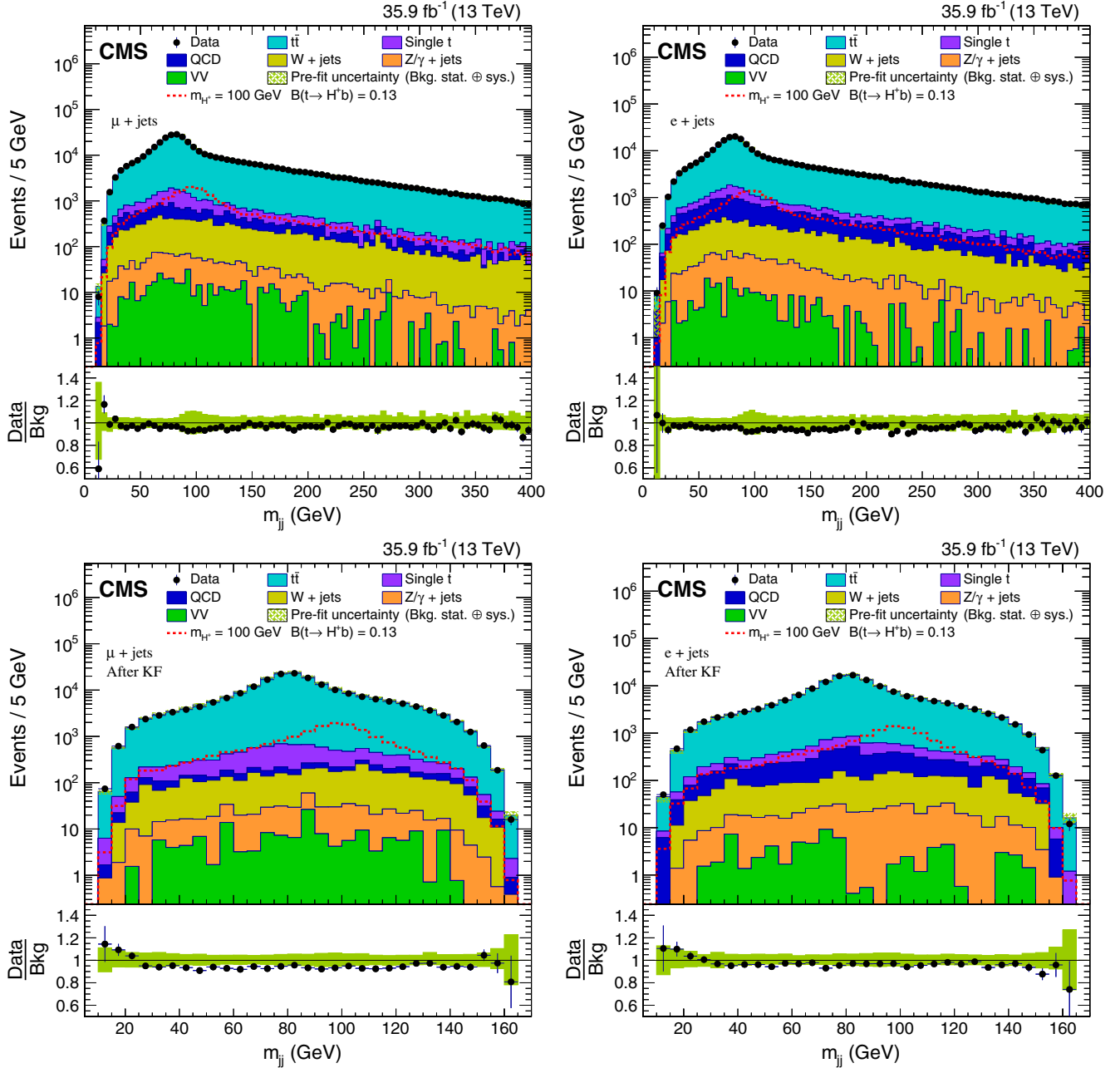


FIG. 2. Distributions of m_{jj} , prior to the fit to data, of the two highest p_T non- b jets for the muon + jets channel (left column) and the electron + jets channel (right column). The two distributions in the upper row are obtained using reconstructed jets. The distributions in the lower row are 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 $\mathcal{B}(t \rightarrow H^+ b)$ obtained at 8 TeV [23].

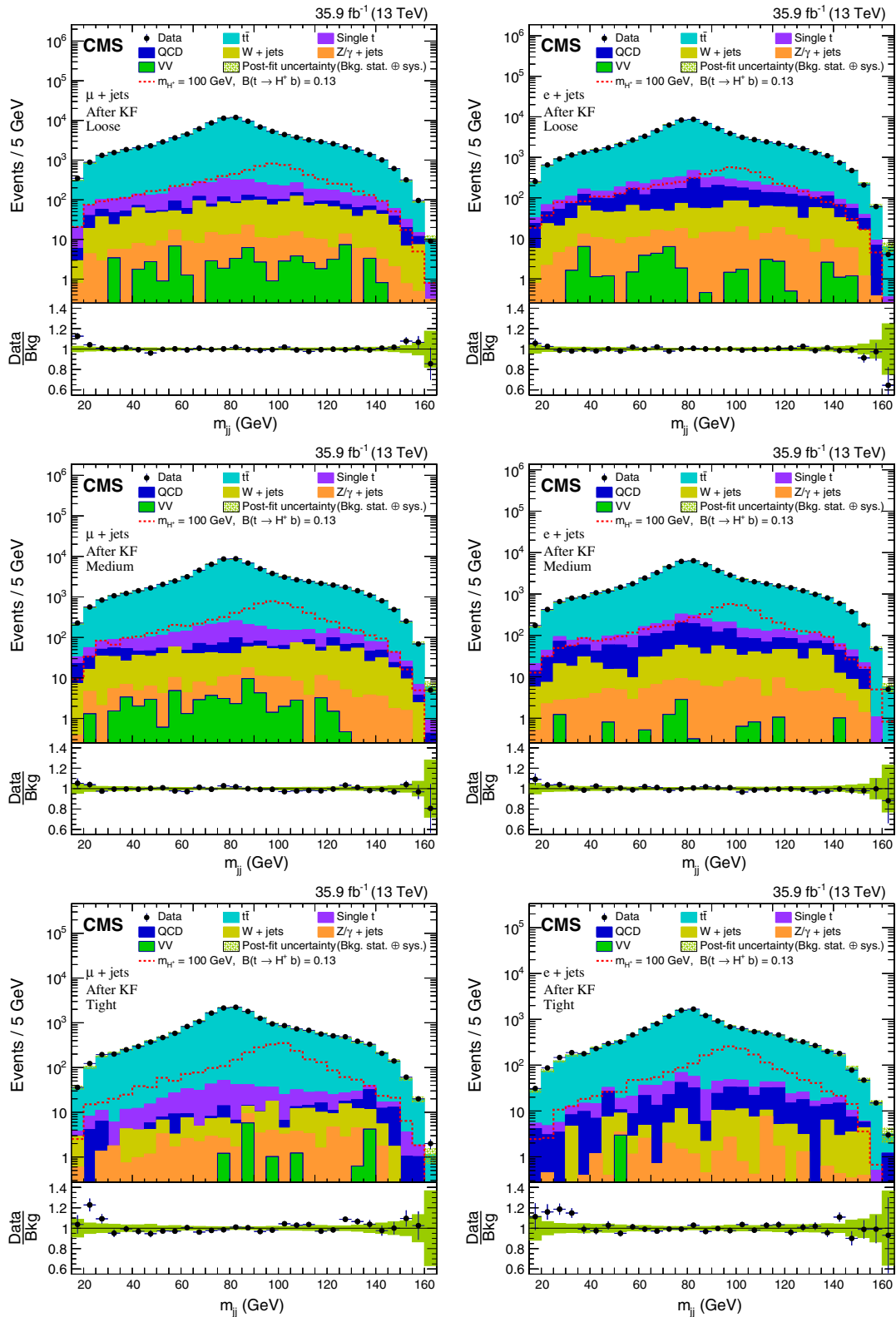


FIG. 3. Distributions of m_{jj} , after a background-only fit to the data, in the exclusive charm tagging categories for the muon + jets (left column) and electron + jets (right column) channels. The upper row shows the exclusive loose category, the middle row shows the exclusive medium category, and 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 $\mathcal{B}(t \rightarrow H^+ b)$ 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_T^{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_T^{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:

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

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

where m_{inv} is the corresponding invariant mass and $b_{\text{had(lep)}}$ 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 $\mathcal{B}(t \rightarrow H^+b)$ obtained at 8 TeV [23].

Process	Loose		Medium		Tight	
	$\mu + \text{jets}$	$e + \text{jets}$	$\mu + \text{jets}$	$e + \text{jets}$	$\mu + \text{jets}$	$e + \text{jets}$
$m_{H^+} = 80 \text{ GeV}$	7690 ± 550	5430 ± 380	6560 ± 490	4700 ± 370	2670 ± 270	1860 ± 180
$m_{H^+} = 90 \text{ GeV}$	7710 ± 550	5620 ± 400	6770 ± 510	4860 ± 380	2630 ± 260	1870 ± 190
$m_{H^+} = 100 \text{ GeV}$	7950 ± 590	5550 ± 400	7070 ± 540	4950 ± 360	2770 ± 270	2000 ± 200
$m_{H^+} = 120 \text{ GeV}$	7620 ± 570	5360 ± 400	6870 ± 510	4780 ± 360	2650 ± 260	1960 ± 190
$m_{H^+} = 140 \text{ GeV}$	6160 ± 500	4370 ± 360	5420 ± 420	3840 ± 310	2010 ± 210	1500 ± 150
$m_{H^+} = 150 \text{ GeV}$	4530 ± 390	3230 ± 280	3850 ± 330	2800 ± 250	1340 ± 140	1030 ± 120
$m_{H^+} = 155 \text{ GeV}$	3700 ± 340	2560 ± 250	2980 ± 270	2230 ± 220	1020 ± 120	766 ± 86
$m_{H^+} = 160 \text{ GeV}$	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
$W + \text{jets}$	1360 ± 140	1061 ± 90	950 ± 110	681 ± 58	127 ± 23	102 ± 9
$Z/\gamma + \text{jets}$	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 $L_{\text{data}}\sigma_{\text{sim}}/N_{\text{sim}}$, 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, $W + \text{jets}$, $Z/\gamma + \text{jets}$, 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:

$$w_t = \sqrt{\text{SF}(t)\text{SF}(\bar{t})},$$

with $\text{SF} \equiv \exp(0.09494 - 0.00084p_T)$. (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 $\mathcal{B}(t \rightarrow H^+b)$ 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_T^{miss}	b & c jets	Normalization	Statistical	p_T (t)
Loose	$m_{H^\pm} = 100$ 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/γ + 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	$m_{H^\pm} = 100$ 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/γ + 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	$m_{H^\pm} = 100$ 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/γ + 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 $\mathcal{B}(t \rightarrow H^\pm b)$. An asymptotic 95% CL limit on $\mathcal{B}(t \rightarrow H^\pm b)$ is calculated using the CL_s method [64,65] with likelihood ratios [66]:

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

where the likelihood is defined as

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

In this equation, $x = \mathcal{B}(t \rightarrow H^\pm b)$ 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_{ij} 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,

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

and in the absence,

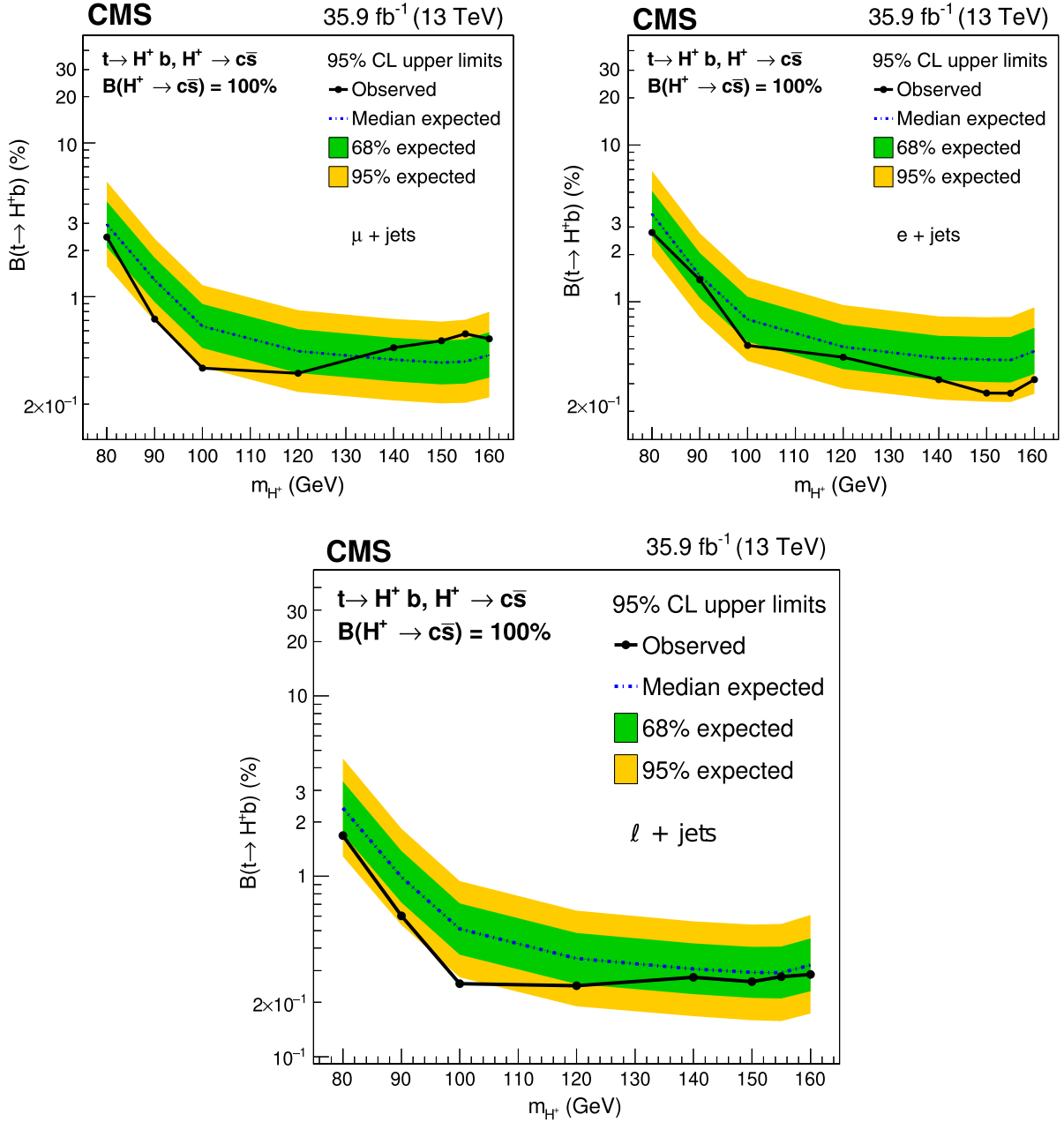


FIG. 4. The expected and observed upper limit in % on $\mathcal{B}(t \rightarrow H^+ b)$ as a function of m_{H^+} using m_{jj} after the individual charm tagging categories have been combined, for the muon + jets (upper left) and electron + jets (upper right) channels and their combination (lower).

$$N_{ij}(\Theta) = N_{ij}^{\bar{t} \rightarrow H^+ W^+ W^\mp}(\Theta) + N_{ij}^{\text{other}}(\Theta), \quad (6)$$

where $N_{ij}^{\bar{t} \rightarrow H^+ W^+ W^\mp}(\Theta)$ and $N_{ij}^{\bar{t} \rightarrow W^+ W^\mp}(\Theta)$ 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 $\mathcal{B}(t \rightarrow H^- \bar{b})$ for H^- are the same as those of H^+ .

The exclusion limits on $\mathcal{B}(t \rightarrow H^+ b)$ 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 $\mathcal{B}(\bar{t} \rightarrow H^- \bar{b})$ are the same as those on $\mathcal{B}(t \rightarrow H^+ b)$.

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

m_{H^+} (GeV)	Expected					Observed
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
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 $\mathcal{B}(t \rightarrow H^+ b)$, after the individual charm tagging categories and the muon and electron channels have been combined.

m_{H^+} (GeV)	Expected					Observed
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
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 $\mathcal{B}(t \rightarrow H^+ b)$ has been computed by assuming $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 100\%$. 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 NKFI 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 Thalís 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).

-
- [1] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* **716**, 1 (2012).
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* **716**, 30 (2012).
- [3] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* **06** (2013) 081.
- [4] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Theory and phenomenology of two-Higgs-doublet models, *Phys. Rep.* **516**, 1 (2012).
- [5] S. P. Martin, A supersymmetry primer, in *Perspectives on Supersymmetry II* (World Scientific, 1997), p. 1.
- [6] Yu. A. Golfand and E. P. Likhtman, Extension of the algebra of Poincaré group generators and violation of P invariance, *JETP Lett.* **13**, 323 (1971).
- [7] J. Wess and B. Zumino, Supergauge transformations in four dimensions, *Nucl. Phys.* **70**, 39 (1974).
- [8] P. A. R. Ade *et al.* (Planck Collaboration), Planck 2013 results. XVI. Cosmological parameters, *Astron. Astrophys.* **571**, A16 (2014).
- [9] P. A. R. Ade *et al.* (Planck Collaboration), Planck 2013 results. I. Overview of products and scientific results, *Astron. Astrophys.* **571**, A1 (2014).
- [10] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, The hierarchy problem and new dimensions at a millimeter, *Phys. Lett. B* **429**, 263 (1998).
- [11] M. Aoki, S. Kanemura, K. Tsumura, and K. Yagyu, Models of Yukawa interaction in the two Higgs doublet model, and their collider phenomenology, *Phys. Rev. D* **80**, 015017 (2009).
- [12] E. Ma, D. P. Roy, and J. Wudka, Enhanced Three-Body Decay of the Charged Higgs Boson, *Phys. Rev. Lett.* **80**, 1162 (1998).
- [13] P. Achard *et al.* (L3 Collaboration), Search for charged Higgs bosons at LEP, *Phys. Lett. B* **575**, 208 (2003).
- [14] A. Heister *et al.* (ALEPH Collaboration), Search for charged Higgs bosons in e^+e^- collisions at energies up to $\sqrt{s} = 209$ GeV, *Phys. Lett. B* **543**, 1 (2002).
- [15] J. Abdallah *et al.* (DELPHI Collaboration), Search for charged Higgs bosons at LEP in general two Higgs doublet models, *Eur. Phys. J. C* **34**, 399 (2004).
- [16] ALEPH, DELPHI, L3, and OPAL Collaborations and LEP working group on Higgs boson searches, Search for charged Higgs bosons: Combined results using LEP data, *Eur. Phys. J. C* **73**, 2463 (2013).
- [17] G. Abbiendi *et al.* (OPAL Collaboration), Search for charged Higgs bosons in e^+e^- collisions at $\sqrt{s} = 189$ – 209 GeV, *Eur. Phys. J. C* **72**, 2076 (2012).

- [18] T. Aaltonen *et al.* (CDF Collaboration), Search for Charged Higgs Bosons in Decays of Top Quarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. Lett.* **103**, 101803 (2009).
- [19] V. M. Abazov *et al.* (D0 Collaboration), Search for charged Higgs bosons in top quark decays, *Phys. Lett. B* **682**, 278 (2009).
- [20] ATLAS Collaboration, Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu$ in fully hadronic final states using pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector, *J. High Energy Phys.* **03** (2015) 088.
- [21] CMS Collaboration, Search for a charged Higgs boson in pp collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **11** (2015) 018.
- [22] ATLAS Collaboration, Search for a light charged Higgs boson in the decay channel $H^+ \rightarrow c\bar{s}$ in $t\bar{t}$ events using pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *Eur. Phys. J. C* **73**, 2465 (2013).
- [23] CMS Collaboration, Search for a light charged Higgs boson decaying to $c\bar{s}$ in pp collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **12** (2015) 178.
- [24] CMS Collaboration, Search for a charged Higgs boson decaying to charm and bottom quarks in proton-proton collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **11** (2018) 115.
- [25] ATLAS Collaboration, Search for charged Higgs bosons produced in association with a top quark and decaying via $H^\pm \rightarrow \tau\nu$ using pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector, *Phys. Lett. B* **759**, 555 (2016).
- [26] ATLAS Collaboration, Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau^\pm \nu_\tau$ in the τ + jets and τ + lepton final states with 36 fb^{-1} of pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS experiment, *J. High Energy Phys.* **09** (2018) 139.
- [27] ATLAS Collaboration, Search for charged Higgs bosons decaying into top and bottom quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* **11** (2018) 085.
- [28] CMS Collaboration, Search for a Light Charged Higgs Boson Decaying to a W boson and a CP -odd Higgs Boson in Final States with $e\mu\mu$ or $\mu\mu\mu$ in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **123**, 131802 (2019).
- [29] CMS Collaboration, Search for Charged Higgs Bosons Produced via Vector Boson Fusion and Decaying into a pair of W and Z Bosons Using pp Collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **119**, 141802 (2017).
- [30] CMS Collaboration, Search for charged Higgs bosons in the $H^\pm \rightarrow \tau^\pm \nu_\tau$ decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **07** (2019) 142.
- [31] CMS Collaboration, The CMS trigger system, *J. Instrum.* **12**, P01020 (2017).
- [32] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* **3**, S08004 (2008).
- [33] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [34] S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with parton shower simulations: The POWHEG method, *J. High Energy Phys.* **11** (2007) 070.
- [35] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* **11** (2004) 040.
- [36] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: The POWHEG BOX, *J. High Energy Phys.* **06** (2010) 043.
- [37] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions from high-precision collider data, *Eur. Phys. J. C* **77**, 663 (2017).
- [38] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA8.2, *Comput. Phys. Commun.* **191**, 159 (2015).
- [39] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, *Eur. Phys. J. C* **76**, 155 (2016).
- [40] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [41] M. Beneke, P. Falgari, S. Klein, and C. Schwinn, Hadronic top-quark pair production with NNLL threshold resummation, *Nucl. Phys.* **B855**, 695 (2012).
- [42] M. Tanabashi *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **98**, 030001 (2018).
- [43] S. Alioli, P. Nason, C. Oleari, and E. Re, NLO single-top production matched with shower in POWHEG: s - and t -channel contributions, *J. High Energy Phys.* **09** (2009) 111; Erratum, *J. High Energy Phys.* **02** (2010) 011.
- [44] E. Re, Single-top Wt -channel production matched with parton showers using the POWHEG method, *Eur. Phys. J. C* **71**, 1547 (2011).
- [45] J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M. L. Mangano, M. Moretti, C. G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, and M. Worek, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, *Eur. Phys. J. C* **53**, 473 (2008).
- [46] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, *J. Instrum.* **12**, P10003 (2017).
- [47] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* **9**, P10009 (2014).
- [48] M. Cacciari, G. P. Salam, and G. Soyez, The anti- k_T jet clustering algorithm, *J. High Energy Phys.* **04** (2008) 063.
- [49] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, *Eur. Phys. J. C* **72**, 1896 (2012).
- [50] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. Instrum.* **13**, P06015 (2018).
- [51] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, *J. Instrum.* **10**, P06005 (2015).
- [52] A. M. Polyakov, Quark confinement and topology of gauge groups, *Nucl. Phys.* **B120**, 429 (1977).
- [53] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, *J. Instrum.* **12**, P02014 (2017).

- [54] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, *J. Instrum.* **13**, P05011 (2018).
- [55] M. Cacciari and G. P. Salam, Pileup subtraction using jet areas, *Phys. Lett. B* **659**, 119 (2008).
- [56] J. D’Hondt, S. Lowette, O. L. Buchmüller, S. Cucciarelli, F.-P. Schilling, M. Spiropulu, S. Paktinat-Mehdiabadi, D. Benedetti, and L. Pape, Fitting of event topologies with external kinematic constraints in CMS, CMS Note, Report No. 2006/023, 2006.
- [57] CMS Collaboration, CMS luminosity measurements for the 2016 data taking period, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-17-001, 2017.
- [58] CMS Collaboration, Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **07** (2018) 161.
- [59] CMS Collaboration, Measurement of differential cross sections for top quark pair production using the lepton + jets final state in proton-proton collisions at 13 TeV, *Phys. Rev. D* **95**, 092001 (2017).
- [60] CMS Collaboration, Measurements of $t\bar{t}$ differential cross sections in proton-proton collisions at $\sqrt{s} = 13$ tev using events containing two leptons, *J. High Energy Phys.* **02** (2019) 149.
- [61] CMS Collaboration, Investigations of the impact of the parton shower tuning in PYTHIA8 in the modelling of $t\bar{t}$ at $\sqrt{s} = 8$ and 13 TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-TOP-16-021, 2016.
- [62] J. Butterworth *et al.*, PDF4LHC recommendations for LHC Run II, *J. Phys. G* **43**, 023001 (2016).
- [63] R. J. Barlow and C. Beeston, Fitting using finite Monte Carlo samples, *Comput. Phys. Commun.* **77**, 219 (1993).
- [64] T. Junk, Confidence level computation for combining searches with small statistics, *Nucl. Instrum. Methods Phys. Res., Sect. A* **434**, 435 (1999).
- [65] A. L. Read, Presentation of search results: The CL_s technique, *J. Phys. G* **28**, 2693 (2002).
- [66] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* **71**, 1554 (2011); Erratum, *Eur. Phys. J. C* **73**, 2501 (2013).

A. M. Sirunyan,^{1,a} A. Tumasyan,¹ W. Adam,² F. Ambrogio,² T. Bergauer,² M. Dragicevic,² J. Erö,² A. Escalante Del Valle,² R. Frühwirth,^{2,b} M. Jeitler,^{2,b} N. Krammer,² L. Lechner,² D. Liko,² T. Madlener,² I. Mikulec,² F. M. Pitters,² N. Rad,² J. Schieck,^{2,b} R. Schöfbeck,² M. Spanring,² S. Templ,² W. Waltenberger,² C.-E. Wulz,^{2,b} M. Zarucki,² V. Chekhovskiy,³ A. Litomin,³ V. Makarenko,³ J. Suarez Gonzalez,³ M. R. Darwish,^{4,c} E. A. De Wolf,⁴ D. Di Croce,⁴ X. Janssen,⁴ T. Kello,^{4,d} A. Lelek,⁴ M. Pieters,⁴ H. Rejeb Sfar,⁴ H. Van Haeve, ⁴ P. Van Mechelen,⁴ S. Van Putte,⁴ N. Van Remortel,⁴ F. Blekman,⁵ E. S. Bols,⁵ S. S. Chhibra,⁵ J. D’Hondt,⁵ J. De Clercq,⁵ D. Lontkovskiy,⁵ S. Lowette,⁵ I. Marchesini,⁵ S. Moortgat,⁵ A. Morton,⁵ Q. Python,⁵ S. Tavernier,⁵ W. Van Doninck,⁵ P. Van Mulders,⁵ D. Beghin,⁶ B. Bilin,⁶ B. Clerbaux,⁶ G. De Lentdecker,⁶ B. Dorney,⁶ L. Favart,⁶ A. Grebenyuk,⁶ A. K. Kalsi,⁶ I. Makarenko,⁶ L. Moureaux,⁶ L. Pétré,⁶ A. Popov,⁶ N. Postiau,⁶ E. Starling,⁶ L. Thomas,⁶ C. Vander Velde,⁶ P. Vanlaer,⁶ D. Vannerom,⁶ L. Wezenbeek,⁶ T. Cornelis,⁷ D. Dobur,⁷ M. Gruchala,⁷ I. Khvastunov,^{7,e} M. Niedziela,⁷ C. Roskas,⁷ K. Skovpen,⁷ M. Tytgat,⁷ W. Verbeke,⁷ B. Vermassen,⁷ M. Vit,⁷ G. Bruno,⁸ F. Bury,⁸ C. Caputo,⁸ P. David,⁸ C. Delaere,⁸ M. Delcourt,⁸ I. S. Donertas,⁸ A. Giammanco,⁸ V. Lemaître,⁸ K. Mondal,⁸ J. Prisciandaro,⁸ A. Taliencio,⁸ M. Teklishyn,⁸ P. Vischia,⁸ S. Wuyckens,⁸ J. Zobec,⁸ G. A. Alves,⁹ G. Correia Silva,⁹ C. Hensel,⁹ A. Moraes,⁹ W. L. Aldá Júnior,¹⁰ E. Belchior Batista Das Chagas,¹⁰ H. BRANDAO MALBOISSON,¹⁰ W. Carvalho,¹⁰ J. Chinellato,^{10,f} E. Coelho,¹⁰ E. M. Da Costa,¹⁰ G. G. Da Silveira,^{10,g} D. De Jesus Damiao,¹⁰ S. Fonseca De Souza,¹⁰ J. Martins,^{10,h} D. Matos Figueiredo,¹⁰ M. Medina Jaime,^{10,i} M. Melo De Almeida,¹⁰ C. Mora Herrera,¹⁰ L. Mundim,¹⁰ H. Nogima,¹⁰ P. Rebello Teles,¹⁰ L. J. Sanchez Rosas,¹⁰ A. Santoro,¹⁰ S. M. Silva Do Amaral,¹⁰ A. Sznajder,¹⁰ M. Thiel,¹⁰ E. J. Tonelli Manganote,^{10,f} F. Torres Da Silva De Araujo,¹⁰ A. Vilela Pereira,¹⁰ C. A. Bernardes,^{11a} L. Calligaris,^{11a} T. R. Fernandez Perez Tomei,^{11a} E. M. Gregores,^{11a,11b} D. S. Lemos,^{11a} P. G. Mercadante,^{11a,11b} S. F. Novaes,^{11a} Sandra S. Padula,^{11a} A. Aleksandrov,¹² G. Antchev,¹² I. Atanasov,¹² R. Hadjiiska,¹² P. Iaydjiev,¹² M. Misheva,¹² M. Rodozov,¹² M. Shopova,¹² G. Sultanov,¹² M. Bonchev,¹³ A. Dimitrov,¹³ T. Ivanov,¹³ L. Litov,¹³ B. Pavlov,¹³ P. Petkov,¹³ A. Petrov,¹³ W. Fang,^{14,d} Q. Guo,¹⁴ H. Wang,¹⁴ L. Yuan,¹⁴ M. Ahmad,¹⁵ Z. Hu,¹⁵ Y. Wang,¹⁵ E. Chapon,¹⁶ G. M. Chen,^{16,j} H. S. Chen,^{16,j} M. Chen,¹⁶ D. Leggat,¹⁶ H. Liao,¹⁶ Z. Liu,¹⁶ R. Sharma,¹⁶ A. Spiezia,¹⁶ J. Tao,¹⁶ J. Thomas-wilsker,¹⁶ J. Wang,¹⁶ H. Zhang,¹⁶ S. Zhang,^{16,j} J. Zhao,¹⁶ A. Agapitos,¹⁷ Y. Ban,¹⁷ C. Chen,¹⁷ A. Levin,¹⁷ Q. Li,¹⁷ M. Lu,¹⁷ X. Lyu,¹⁷ Y. Mao,¹⁷ S. J. Qian,¹⁷ D. Wang,¹⁷ Q. Wang,¹⁷ J. Xiao,¹⁷ Z. You,¹⁸ X. Gao,^{19,d} M. Xiao,²⁰ C. Avila,²¹ A. Cabrera,²¹ C. Florez,²¹ J. Fraga,²¹ A. Sarkar,²¹ M. A. Segura Delgado,²¹ J. Jaramillo,²² J. Mejia Guisao,²² F. Ramirez,²² J. D. Ruiz Alvarez,²² C. A. Salazar González,²² N. Vanegas Arbelaez,²² D. Giljanovic,²³ N. Godinovic,²³ D. Lelas,²³ I. Puljak,²³ T. Sculac,²³ Z. Antunovic,²⁴ M. Kovac,²⁴ V. Brigljevic,²⁵ D. Ferencek,²⁵ D. Majumder,²⁵ M. Roguljic,²⁵ A. Starodumov,^{25,k} T. Susa,²⁵ M. W. Ather,²⁶ A. Attikis,²⁶ E. Erodotou,²⁶ A. Ioannou,²⁶ G. Kole,²⁶ M. Kolosova,²⁶ S. Konstantinou,²⁶

G. Mavromanolakis,²⁶ J. Mousa,²⁶ C. Nicolaou,²⁶ F. Ptochos,²⁶ P. A. Razis,²⁶ H. Rykaczewski,²⁶ H. Saka,²⁶ D. Tsiakkouri,²⁶ M. Finger,^{27,1} M. Finger Jr.,^{27,1} A. Kveton,²⁷ J. Tomsa,²⁷ E. Ayala,²⁸ E. Carrera Jarrin,²⁹ E. Salama,^{30,m,n} M. A. Mahmoud,³¹ Y. Mohammed,^{31,o} S. Bhowmik,³² A. Carvalho Antunes De Oliveira,³² R. K. Dewanjee,³² K. Ehataht,³² M. Kadastik,³² M. Raidal,³² C. Veelken,³² P. Eerola,³³ L. Forthomme,³³ H. Kirschenmann,³³ K. Osterberg,³³ M. Voutilainen,³³ E. Brücken,³⁴ F. Garcia,³⁴ J. Havukainen,³⁴ V. Karimäki,³⁴ M. S. Kim,³⁴ R. Kinnunen,³⁴ T. Lampén,³⁴ K. Lassila-Perini,³⁴ S. Laurila,³⁴ S. Lehti,³⁴ T. Lindén,³⁴ H. Siikonen,³⁴ E. Tuominen,³⁴ J. Tuominiemi,³⁴ P. Luukka,³⁵ T. Tuuva,³⁵ C. Amendola,³⁶ M. Besancon,³⁶ F. Couderc,³⁶ M. Dejardin,³⁶ D. Denegri,³⁶ J. L. Faure,³⁶ F. Ferri,³⁶ S. Ganjour,³⁶ A. Givernaud,³⁶ P. Gras,³⁶ G. Hamel de Monchenault,³⁶ P. Jarry,³⁶ B. Lenzi,³⁶ E. Locci,³⁶ J. Malcles,³⁶ J. Rander,³⁶ A. Rosowsky,³⁶ M. Ö. Sahin,³⁶ A. Savoy-Navarro,^{36,p} M. Titov,³⁶ G. B. Yu,³⁶ S. Ahuja,³⁷ F. Beaudette,³⁷ M. Bonanomi,³⁷ A. Buchot Perraguin,³⁷ P. Busson,³⁷ C. Charlot,³⁷ O. Davignon,³⁷ B. Diab,³⁷ G. Falmagne,³⁷ R. Granier de Cassagnac,³⁷ A. Hakimi,³⁷ I. Kucher,³⁷ A. Lobanov,³⁷ C. Martin Perez,³⁷ M. Nguyen,³⁷ C. Ochando,³⁷ P. Paganini,³⁷ J. Rembser,³⁷ R. Salerno,³⁷ J. B. Sauvan,³⁷ Y. Sirois,³⁷ A. Zabi,³⁷ A. Zghiche,³⁷ J.-L. Agram,^{38,q} J. Andrea,³⁸ D. Bloch,³⁸ G. Bourgatte,³⁸ J.-M. Brom,³⁸ E. C. Chabert,³⁸ C. Collard,³⁸ J.-C. Fontaine,^{38,q} D. Gelé,³⁸ U. Goerlach,³⁸ C. Grimault,³⁸ A.-C. Le Bihan,³⁸ P. Van Hove,³⁸ E. Asilar,³⁹ S. Beauceron,³⁹ C. Bernet,³⁹ G. Boudoul,³⁹ C. Camen,³⁹ A. Carle,³⁹ N. Chanon,³⁹ D. Contardo,³⁹ P. Depasse,³⁹ H. El Mamouni,³⁹ J. Fay,³⁹ S. Gascon,³⁹ M. Gouzevitch,³⁹ B. Ille,³⁹ Sa. Jain,³⁹ I. B. Laktineh,³⁹ H. Lattaud,³⁹ A. Lesauvage,³⁹ M. Lethuillier,³⁹ L. Mirabito,³⁹ L. Torterotot,³⁹ G. Touquet,³⁹ M. Vander Donckt,³⁹ S. Viret,³⁹ A. Khvedelidze,^{40,1} Z. Tsamalaidze,^{40,1} L. Feld,⁴¹ K. Klein,⁴¹ M. Lipinski,⁴¹ D. Meuser,⁴¹ A. Pauls,⁴¹ M. Preuten,⁴¹ M. P. Rauch,⁴¹ J. Schulz,⁴¹ M. Teroerde,⁴¹ D. Eliseev,⁴² M. Erdmann,⁴² P. Fackeldey,⁴² B. Fischer,⁴² S. Ghosh,⁴² T. Hebbeker,⁴² K. Hoepfner,⁴² H. Keller,⁴² L. Mastrolorenzo,⁴² M. Merschmeyer,⁴² A. Meyer,⁴² P. Millet,⁴² G. Mocellin,⁴² S. Mondal,⁴² S. Mukherjee,⁴² D. Noll,⁴² A. Novak,⁴² T. Pook,⁴² A. Pozdnyakov,⁴² T. Quast,⁴² M. Radziej,⁴² Y. Rath,⁴² H. Reithler,⁴² J. Roemer,⁴² A. Schmidt,⁴² S. C. Schuler,⁴² A. Sharma,⁴² S. Wiedenbeck,⁴² S. Zaleski,⁴² C. Dziwok,⁴³ G. Flügge,⁴³ W. Haj Ahmad,^{43,r} O. Hlushchenko,⁴³ T. Kress,⁴³ A. Nowack,⁴³ C. Pistone,⁴³ O. Pooth,⁴³ D. Roy,⁴³ H. Sert,⁴³ A. Stahl,^{43,s} T. Ziemons,⁴³ H. Aarup Petersen,⁴⁴ M. Aldaya Martin,⁴⁴ P. Asmuss,⁴⁴ I. Babounikau,⁴⁴ S. Baxter,⁴⁴ O. Behnke,⁴⁴ A. Bermúdez Martínez,⁴⁴ A. A. Bin Anuar,⁴⁴ K. Borras,^{44,t} V. Botta,⁴⁴ D. Brunner,⁴⁴ A. Campbell,⁴⁴ A. Cardini,⁴⁴ P. Connor,⁴⁴ S. Consuegra Rodríguez,⁴⁴ V. Danilov,⁴⁴ A. De Wit,⁴⁴ M. M. Defranchis,⁴⁴ L. Didikh,⁴⁴ D. Domínguez Damiani,⁴⁴ G. Eckerlin,⁴⁴ D. Eckstein,⁴⁴ T. Eichhorn,⁴⁴ L. I. Estevez Banos,⁴⁴ E. Gallo,^{44,u} A. Geiser,⁴⁴ A. Giralardi,⁴⁴ A. Grohsjean,⁴⁴ M. Guthoff,⁴⁴ A. Harb,⁴⁴ A. Jafari,^{44,v} N. Z. Jomhari,⁴⁴ H. Jung,⁴⁴ A. Kasem,^{44,t} M. Kasemann,⁴⁴ H. Kaveh,⁴⁴ C. Kleinwort,⁴⁴ J. Knolle,⁴⁴ D. Krücker,⁴⁴ W. Lange,⁴⁴ T. Lenz,⁴⁴ J. Lidrych,⁴⁴ K. Lipka,⁴⁴ W. Lohmann,^{44,w} R. Mankel,⁴⁴ I.-A. Melzer-Pellmann,⁴⁴ J. Metwally,⁴⁴ A. B. Meyer,⁴⁴ M. Meyer,⁴⁴ M. Missiroli,⁴⁴ J. Mnich,⁴⁴ A. Mussgiller,⁴⁴ V. Myronenko,⁴⁴ Y. Otari,⁴⁴ D. Pérez Adán,⁴⁴ S. K. Pflitsch,⁴⁴ D. Pitzl,⁴⁴ A. Raspereza,⁴⁴ A. Saggio,⁴⁴ A. Saibel,⁴⁴ M. Savitskyi,⁴⁴ V. Scheurer,⁴⁴ P. Schütze,⁴⁴ C. Schwanenberger,⁴⁴ A. Singh,⁴⁴ R. E. Sosa Ricardo,⁴⁴ N. Tonon,⁴⁴ O. Turkot,⁴⁴ A. Vagnerini,⁴⁴ M. Van De Klundert,⁴⁴ R. Walsh,⁴⁴ D. Walter,⁴⁴ Y. Wen,⁴⁴ K. Wichmann,⁴⁴ C. Wissing,⁴⁴ S. Wuchterl,⁴⁴ O. Zenaiev,⁴⁴ R. Zlebick,⁴⁴ R. Aggleton,⁴⁵ S. Bein,⁴⁵ L. Benato,⁴⁵ A. Benecke,⁴⁵ K. De Leo,⁴⁵ T. Dreyer,⁴⁵ A. Ebrahimi,⁴⁵ M. Eich,⁴⁵ F. Feindt,⁴⁵ A. Fröhlich,⁴⁵ C. Garbers,⁴⁵ E. Garutti,⁴⁵ P. Gunnellini,⁴⁵ J. Haller,⁴⁵ A. Hinzmann,⁴⁵ A. Karavdina,⁴⁵ G. Kasieczka,⁴⁵ R. Klanner,⁴⁵ R. Kogler,⁴⁵ V. Kutzner,⁴⁵ J. Lange,⁴⁵ T. Lange,⁴⁵ A. Malara,⁴⁵ C. E. N. Niemeyer,⁴⁵ A. Nigamova,⁴⁵ K. J. Pena Rodriguez,⁴⁵ O. Rieger,⁴⁵ P. Schleper,⁴⁵ S. Schumann,⁴⁵ J. Schwandt,⁴⁵ D. Schwarz,⁴⁵ J. Sonneveld,⁴⁵ H. Stadie,⁴⁵ G. Steinbrück,⁴⁵ B. Vormwald,⁴⁵ I. Zoi,⁴⁵ M. Baselga,⁴⁶ S. Baur,⁴⁶ J. Bechtel,⁴⁶ T. Berger,⁴⁶ E. Butz,⁴⁶ R. Caspart,⁴⁶ T. Chwalek,⁴⁶ W. De Boer,⁴⁶ A. Dierlamm,⁴⁶ A. Droll,⁴⁶ K. El Morabit,⁴⁶ N. Faltermann,⁴⁶ K. Flöh,⁴⁶ M. Giffels,⁴⁶ A. Gottmann,⁴⁶ F. Hartmann,^{46,s} C. Heidecker,⁴⁶ U. Husemann,⁴⁶ M. A. Iqbal,⁴⁶ I. Katkov,^{46,x} P. Keicher,⁴⁶ R. Koppenhöfer,⁴⁶ S. Maier,⁴⁶ M. Metzler,⁴⁶ S. Mitra,⁴⁶ D. Müller,⁴⁶ Th. Müller,⁴⁶ M. Musich,⁴⁶ G. Quast,⁴⁶ K. Rabbertz,⁴⁶ J. Rauser,⁴⁶ D. Savoie,⁴⁶ D. Schäfer,⁴⁶ M. Schnepf,⁴⁶ M. Schröder,⁴⁶ D. Seith,⁴⁶ I. Shvetsov,⁴⁶ H. J. Simonis,⁴⁶ R. Ulrich,⁴⁶ M. Wassmer,⁴⁶ M. Weber,⁴⁶ R. Wolf,⁴⁶ S. Wozniowski,⁴⁶ G. Anagnostou,⁴⁷ P. Asenov,⁴⁷ G. Daskalakis,⁴⁷ T. Geralis,⁴⁷ A. Kyriakis,⁴⁷ D. Loukas,⁴⁷ G. Paspalaki,⁴⁷ A. Stakia,⁴⁷ M. Diamantopoulou,⁴⁸ D. Karasavvas,⁴⁸ G. Karathanasis,⁴⁸ P. Kontaxakis,⁴⁸ C. K. Koraka,⁴⁸ A. Manousakis-katsikakis,⁴⁸ A. Panagiotou,⁴⁸ I. Papavergou,⁴⁸ N. Saoulidou,⁴⁸ K. Theofilatos,⁴⁸ K. Vellidis,⁴⁸ E. Vourliotis,⁴⁸ G. Bakas,⁴⁹ K. Kousouris,⁴⁹ I. Papakrivopoulos,⁴⁹ G. Tsipolitis,⁴⁹ A. Zacharopoulou,⁴⁹ I. Evangelou,⁵⁰ C. Foudas,⁵⁰ P. Giannelis,⁵⁰ P. Katsoulis,⁵⁰ P. Kokkas,⁵⁰ S. Mallios,⁵⁰ K. Manitaras,⁵⁰ N. Manthos,⁵⁰ I. Papadopoulos,⁵⁰ J. Strologas,⁵⁰ M. Bartók,^{51,y} R. Chudasama,⁵¹ M. Csanad,⁵¹ M. M. A. Gadallah,^{51,z} S. Lökös,^{51,aa} P. Major,⁵¹ K. Mandal,⁵¹ A. Mehta,⁵¹ G. Pasztor,⁵¹ O. Surányi,⁵¹ G. I. Veres,⁵¹ G. Bencze,⁵² C. Hajdu,⁵² D. Horvath,^{52,bb} F. Sikler,⁵² V. Veszpremi,⁵²

G. Vesztegombi,^{52,a,aa} S. Czellar,⁵³ J. Karancsi,^{53,y} J. Molnar,⁵³ Z. Szillasi,⁵³ D. Teyssier,⁵³ P. Raics,⁵⁴ Z. L. Trocsanyi,⁵⁴ G. Zilizi,⁵⁴ T. Csorgo,⁵⁵ F. Nemes,⁵⁵ T. Novak,⁵⁵ S. Choudhury,⁵⁶ J. R. Komaragiri,⁵⁶ D. Kumar,⁵⁶ L. Panwar,⁵⁶ P. C. Tiwari,⁵⁶ S. Bahinipati,^{57,cc} D. Dash,⁵⁷ C. Kar,⁵⁷ P. Mal,⁵⁷ T. Mishra,⁵⁷ V. K. Muraleedharan Nair Bindhu,⁵⁷ A. Nayak,^{57,dd} D. K. Sahoo,^{57,cc} N. Sur,⁵⁷ S. K. Swain,⁵⁷ S. Bansal,⁵⁸ S. B. Beri,⁵⁸ V. Bhatnagar,⁵⁸ S. Chauhan,⁵⁸ N. Dhingra,^{58,ee} R. Gupta,⁵⁸ A. Kaur,⁵⁸ S. Kaur,⁵⁸ P. Kumari,⁵⁸ M. Lohan,⁵⁸ M. Meena,⁵⁸ K. Sandeep,⁵⁸ S. Sharma,⁵⁸ J. B. Singh,⁵⁸ A. K. Virdi,⁵⁸ A. Ahmed,⁵⁹ A. Bhardwaj,⁵⁹ B. C. Choudhary,⁵⁹ R. B. Garg,⁵⁹ M. Gola,⁵⁹ S. Keshri,⁵⁹ A. Kumar,⁵⁹ M. Naimuddin,⁵⁹ P. Priyanka,⁵⁹ K. Ranjan,⁵⁹ A. Shah,⁵⁹ M. Bharti,^{60,ff} R. Bhattacharya,⁶⁰ S. Bhattacharya,⁶⁰ D. Bhowmik,⁶⁰ S. Dutta,⁶⁰ S. Ghosh,⁶⁰ B. Gomer,^{60,gg} M. Maity,^{60,hh} S. Nandan,⁶⁰ P. Palit,⁶⁰ A. Purohit,⁶⁰ P. K. Rout,⁶⁰ G. Saha,⁶⁰ S. Sarkar,⁶⁰ M. Sharan,⁶⁰ B. Singh,^{60,ff} S. Thakur,^{60,ff} P. K. Behera,⁶¹ S. C. Behera,⁶¹ P. Kalbhor,⁶¹ A. Muhammad,⁶¹ R. Pradhan,⁶¹ P. R. Pujahari,⁶¹ A. Sharma,⁶¹ A. K. Sikdar,⁶¹ D. Dutta,⁶² V. Kumar,⁶² K. Naskar,^{62,ii} P. K. Netrakanti,⁶² L. M. Pant,⁶² P. Shukla,⁶² T. Aziz,⁶³ M. A. Bhat,⁶³ S. Dugad,⁶³ R. Kumar Verma,⁶³ G. B. Mohanty,⁶³ U. Sarkar,⁶³ S. Banerjee,⁶⁴ S. Bhattacharya,⁶⁴ S. Chatterjee,⁶⁴ M. Guchait,⁶⁴ S. Karmakar,⁶⁴ S. Kumar,⁶⁴ G. Majumder,⁶⁴ K. Mazumdar,⁶⁴ S. Mukherjee,⁶⁴ D. Roy,⁶⁴ N. Sahoo,⁶⁴ S. Dube,⁶⁵ B. Kansal,⁶⁵ A. Kapoor,⁶⁵ K. Kothekar,⁶⁵ S. Pandey,⁶⁵ A. Rane,⁶⁵ A. Rastogi,⁶⁵ S. Sharma,⁶⁵ H. Bakhshiansohi,^{66,ij} S. Chenarani,^{67,kk} S. M. Etesami,⁶⁷ M. Khakzad,⁶⁷ M. Mohammadi Najafabadi,⁶⁷ M. Felcini,⁶⁸ M. Grunewald,⁶⁸ M. Abbrescia,^{69a,69b} R. Aly,^{69a,69b,ll} C. Aruta,^{69a,69b} A. Colaleo,^{69a} D. Creanza,^{69a,69c} N. De Filippis,^{69a,69c} M. De Palma,^{69a,69b} A. Di Florio,^{69a,69b} A. Di Pilato,^{69a,69b} W. Elmetenawee,^{69a,69b} L. Fiore,^{69a} A. Gelmi,^{69a,69b} M. Gul,^{69a} G. Iaselli,^{69a,69c} M. Ince,^{69a,69b} S. Lezki,^{69a,69b} G. Maggi,^{69a,69c} M. Maggi,^{69a} I. Margjeka,^{69a,69b} V. Mastrapasqua,^{69a,69b} J. A. Merlin,^{69a} S. My,^{69a,69b} S. Nuzzo,^{69a,69b} A. Pompili,^{69a,69b} G. Pugliese,^{69a,69c} A. Ranieri,^{69a} G. Selvaggi,^{69a,69b} L. Silvestris,^{69a} F. M. Simone,^{69a,69b} R. Venditti,^{69a} P. Verwilligen,^{69a} G. Abbiendi,^{70a} C. Battilana,^{70a,70b} D. Bonacorsi,^{70a,70b} L. Borgonovi,^{70a,70b} S. Braibant-Giacomelli,^{70a,70b} R. Campanini,^{70a,70b} P. Capiluppi,^{70a,70b} A. Castro,^{70a,70b} F. R. Cavallo,^{70a} C. Ciocca,^{70a} M. Cuffiani,^{70a,70b} G. M. Dallavalle,^{70a} T. Diotallevi,^{70a,70b} F. Fabbri,^{70a} A. Fanfani,^{70a,70b} E. Fontanesi,^{70a,70b} P. Giacomelli,^{70a} C. Grandi,^{70a} L. Guiducci,^{70a,70b} F. Iemmi,^{70a,70b} S. Lo Meo,^{70a,mm} S. Marcellini,^{70a} G. Masetti,^{70a} F. L. Navarria,^{70a,70b} A. Perrotta,^{70a} F. Primavera,^{70a,70b} A. M. Rossi,^{70a,70b} T. Rovelli,^{70a,70b} G. P. Siroli,^{70a,70b} N. Tosi,^{70a} S. Albergo,^{71a,71b,nn} S. Costa,^{71a,71b} A. Di Mattia,^{71a} R. Potenza,^{71a,71b} A. Tricomi,^{71a,71b,nn} C. Tuve,^{71a,71b} G. Barbagli,^{72a} A. Cassese,^{72a} R. Ceccarelli,^{72a,72b} V. Ciulli,^{72a,72b} C. Civinini,^{72a} R. D'Alessandro,^{72a,72b} F. Fiori,^{72a} E. Focardi,^{72a,72b} G. Latino,^{72a,72b} P. Lenzi,^{72a,72b} M. Lizzo,^{72a,72b} M. Meschini,^{72a} S. Paoletti,^{72a} R. Seidita,^{72a,72b} G. Sguazzoni,^{72a} L. Viliani,^{72a} L. Benussi,⁷³ S. Bianco,⁷³ D. Piccolo,⁷³ M. Bozzo,^{74a,74b} F. Ferro,^{74a} R. Mulargia,^{74a,74b} E. Robutti,^{74a} S. Tosi,^{74a,74b} A. Benaglia,^{75a} A. Beschi,^{75a,75b} F. Brivio,^{75a,75b} F. Ceteorelli,^{75a,75b} V. Ciriolo,^{75a,75b,s} F. De Guio,^{75a,75b} M. E. Dinardo,^{75a,75b} P. Dini,^{75a} S. Gennai,^{75a} A. Ghezzi,^{75a,75b} P. Govoni,^{75a,75b} L. Guzzi,^{75a,75b} M. Malberti,^{75a} S. Malvezzi,^{75a} D. Menasce,^{75a} F. Monti,^{75a,75b} L. Moroni,^{75a} M. Paganoni,^{75a,75b} D. Pedrini,^{75a} S. Ragazzi,^{75a,75b} T. Tabarelli de Fatis,^{75a,75b} D. Valsecchi,^{75a,75b,s} D. Zuolo,^{75a,75b} S. Buontempo,^{76a} N. Cavallo,^{76a,76c} A. De Iorio,^{76a,76b} F. Fabozzi,^{76a,76c} F. Fienga,^{76a} A. O. M. Iorio,^{76a,76b} L. Layer,^{76a,76b} L. Lista,^{76a,76b} S. Meola,^{76a,76d,s} P. Paolucci,^{76a,s} B. Rossi,^{76a} C. Sciacca,^{76a,76b} E. Voevodina,^{76a,76b} P. Azzi,^{77a} N. Bacchetta,^{77a} A. Boletti,^{77a,77b} A. Bragagnolo,^{77a,77b} R. Carlin,^{77a,77b} P. Checchia,^{77a} P. De Castro Manzano,^{77a} T. Dorigo,^{77a} F. Gasparini,^{77a,77b} U. Gasparini,^{77a,77b} S. Y. Hoh,^{77a,77b} M. Margoni,^{77a,77b} A. T. Meneguzzo,^{77a,77b} M. Presilla,^{77a,77b} P. Ronchese,^{77a,77b} R. Rossin,^{77a,77b} F. Simonetto,^{77a,77b} G. Strong,^{77a} A. Tiko,^{77a} M. Tosi,^{77a,77b} H. YARAR,^{77a,77b} M. Zanetti,^{77a,77b} P. Zotto,^{77a,77b} A. Zucchetta,^{77a,77b} G. Zumerle,^{77a,77b} C. Aime,^{78a,78b} A. Braghieri,^{78a} S. Calzaferri,^{78a,78b} D. Fiorina,^{78a,78b} P. Montagna,^{78a,78b} S. P. Ratti,^{78a,78b} V. Re,^{78a} M. Ressegotti,^{78a,78b} C. Riccardi,^{78a,78b} P. Salvini,^{78a} I. Vai,^{78a} P. Vitulo,^{78a,78b} M. Biasini,^{79a,79b} G. M. Bilei,^{79a} D. Cianggottini,^{79a,79b} L. Fanò,^{79a,79b} P. Lariccia,^{79a,79b} G. Mantovani,^{79a,79b} V. Mariani,^{79a,79b} M. Menichelli,^{79a} F. Moscatelli,^{79a} A. Rossi,^{79a,79b} A. Santocchia,^{79a,79b} D. Spiga,^{79a} T. Tedeschi,^{79a,79b} K. Androsov,^{80a} P. Azzurri,^{80a} G. Bagliesi,^{80a} V. Bertacchi,^{80a,80c} L. Bianchini,^{80a} T. Boccali,^{80a} R. Castaldi,^{80a} M. A. Ciocci,^{80a,80b} R. Dell'Orso,^{80a} M. R. Di Domenico,^{80a,80b} S. Donato,^{80a} L. Giannini,^{80a,80c} A. Giassi,^{80a} M. T. Grippo,^{80a} F. Ligabue,^{80a,80c} E. Manca,^{80a,80c} G. Mandorli,^{80a,80c} A. Messineo,^{80a,80b} F. Palla,^{80a} G. Ramirez-Sanchez,^{80a,80c} A. Rizzi,^{80a,80b} G. Rolandi,^{80a,80c} S. Roy Chowdhury,^{80a,80c} A. Scribano,^{80a} N. Shafiei,^{80a,80b} P. Spagnolo,^{80a} R. Tenchini,^{80a} G. Tonelli,^{80a,80b} N. Turini,^{80a} A. Venturi,^{80a} P. G. Verdini,^{80a} F. Cavallari,^{81a} M. Cipriani,^{81a,81b} D. Del Re,^{81a,81b} E. Di Marco,^{81a} M. Diemoz,^{81a} E. Longo,^{81a,81b} P. Meridiani,^{81a} G. Organtini,^{81a,81b} F. Pandolfi,^{81a} R. Paramatti,^{81a,81b} C. Quaranta,^{81a,81b} S. Rahatlou,^{81a,81b} C. Rovelli,^{81a} F. Santanastasio,^{81a,81b} L. Soffi,^{81a,81b} R. Tramontano,^{81a,81b} N. Amapane,^{82a,82b} R. Arcidiacono,^{82a,82c} S. Argiro,^{82a,82b} M. Arneodo,^{82a,82c} N. Bartosik,^{82a} R. Bellan,^{82a,82b} A. Bellora,^{82a,82b} C. Biino,^{82a} A. Cappati,^{82a,82b} N. Cartiglia,^{82a} S. Cometti,^{82a} M. Costa,^{82a,82b}

R. Covarelli,^{82a,82b} N. Demaria,^{82a} B. Kiani,^{82a,82b} F. Legger,^{82a} C. Mariotti,^{82a} S. Maselli,^{82a} E. Migliore,^{82a,82b} V. Monaco,^{82a,82b} E. Monteil,^{82a,82b} M. Monteno,^{82a} M. M. Obertino,^{82a,82b} G. Ortona,^{82a} L. Pacher,^{82a,82b} N. Pastrone,^{82a} M. Pelliccioni,^{82a} G. L. Pinna Angioni,^{82a,82b} M. Ruspa,^{82a,82c} R. Salvatico,^{82a,82b} F. Siviero,^{82a,82b} V. Sola,^{82a} A. Solano,^{82a,82b} D. Soldi,^{82a,82b} A. Staiano,^{82a} D. Trocino,^{82a,82b} S. Belforte,^{83a} V. Candelise,^{83a,83b} M. Casarsa,^{83a} F. Cossutti,^{83a} A. Da Rold,^{83a,83b} G. Della Ricca,^{83a,83b} F. Vazzoler,^{83a,83b} S. Dogra,⁸⁴ C. Huh,⁸⁴ B. Kim,⁸⁴ D. H. Kim,⁸⁴ G. N. Kim,⁸⁴ J. Lee,⁸⁴ S. W. Lee,⁸⁴ C. S. Moon,⁸⁴ Y. D. Oh,⁸⁴ S. I. Pak,⁸⁴ B. C. Radburn-Smith,⁸⁴ S. Sekmen,⁸⁴ Y. C. Yang,⁸⁴ H. Kim,⁸⁵ D. H. Moon,⁸⁵ B. Francois,⁸⁶ T. J. Kim,⁸⁶ J. Park,⁸⁶ S. Cho,⁸⁷ S. Choi,⁸⁷ Y. Go,⁸⁷ S. Ha,⁸⁷ B. Hong,⁸⁷ K. Lee,⁸⁷ K. S. Lee,⁸⁷ J. Lim,⁸⁷ J. Park,⁸⁷ S. K. Park,⁸⁷ J. Yoo,⁸⁷ J. Goh,⁸⁸ A. Gurtu,⁸⁸ H. S. Kim,⁸⁹ Y. Kim,⁸⁹ J. Almond,⁹⁰ J. H. Bhyun,⁹⁰ J. Choi,⁹⁰ S. Jeon,⁹⁰ J. Kim,⁹⁰ J. S. Kim,⁹⁰ S. Ko,⁹⁰ H. Kwon,⁹⁰ H. Lee,⁹⁰ K. Lee,⁹⁰ S. Lee,⁹⁰ K. Nam,⁹⁰ B. H. Oh,⁹⁰ M. Oh,⁹⁰ S. B. Oh,⁹⁰ H. Seo,⁹⁰ U. K. Yang,⁹⁰ I. Yoon,⁹⁰ D. Jeon,⁹¹ J. H. Kim,⁹¹ B. Ko,⁹¹ J. S. H. Lee,⁹¹ I. C. Park,⁹¹ Y. Roh,⁹¹ D. Song,⁹¹ I. J. Watson,⁹¹ H. D. Yoo,⁹² Y. Choi,⁹³ C. Hwang,⁹³ Y. Jeong,⁹³ H. Lee,⁹³ Y. Lee,⁹³ I. Yu,⁹³ V. Veckalns,^{94,oo} A. Juodagalvis,⁹⁵ A. Rinkevicius,⁹⁵ G. Tamulaitis,⁹⁵ W. A. T. Wan Abdullah,⁹⁶ M. N. Yusli,⁹⁶ Z. Zolkapli,⁹⁶ J. F. Benitez,⁹⁷ A. Castaneda Hernandez,⁹⁷ J. A. Murillo Quijada,⁹⁷ L. Valencia Palomo,⁹⁷ H. Castilla-Valdez,⁹⁸ E. De La Cruz-Burelo,⁹⁸ I. Heredia-De La Cruz,^{98,pp} R. Lopez-Fernandez,⁹⁸ A. Sanchez-Hernandez,⁹⁸ S. Carrillo Moreno,⁹⁹ C. Oropeza Barrera,⁹⁹ M. Ramirez-Garcia,⁹⁹ F. Vazquez Valencia,⁹⁹ J. Eysermans,¹⁰⁰ I. Pedraza,¹⁰⁰ H. A. Salazar Ibarguen,¹⁰⁰ C. Uribe Estrada,¹⁰⁰ A. Morelos Pineda,¹⁰¹ J. Mijuskovic,^{102,e} N. Raicevic,¹⁰² D. Krofcheck,¹⁰³ S. Bheesette,¹⁰⁴ P. H. Butler,¹⁰⁴ A. Ahmad,¹⁰⁵ M. I. Asghar,¹⁰⁵ M. I. M. Awan,¹⁰⁵ H. R. Hoorani,¹⁰⁵ W. A. Khan,¹⁰⁵ M. A. Shah,¹⁰⁵ M. Shoaib,¹⁰⁵ M. Waqas,¹⁰⁵ V. Avati,¹⁰⁶ L. Grzanka,¹⁰⁶ M. Malawski,¹⁰⁶ H. Bialkowska,¹⁰⁷ M. Bluj,¹⁰⁷ B. Boimska,¹⁰⁷ T. Frueboes,¹⁰⁷ M. Górski,¹⁰⁷ M. Kazana,¹⁰⁷ M. Szleper,¹⁰⁷ P. Traczyk,¹⁰⁷ P. Zalewski,¹⁰⁷ K. Bunkowski,¹⁰⁸ A. Byszuk,^{108,qq} K. Doroba,¹⁰⁸ A. Kalinowski,¹⁰⁸ M. Konecki,¹⁰⁸ J. Krolkowski,¹⁰⁸ M. Olszewski,¹⁰⁸ M. Walczak,¹⁰⁸ M. Araujo,¹⁰⁹ P. Bargassa,¹⁰⁹ D. Bastos,¹⁰⁹ P. Faccioli,¹⁰⁹ M. Gallinaro,¹⁰⁹ J. Hollar,¹⁰⁹ N. Leonardo,¹⁰⁹ T. Niknejad,¹⁰⁹ J. Seixas,¹⁰⁹ K. Shchelina,¹⁰⁹ O. Toldaiev,¹⁰⁹ J. Varela,¹⁰⁹ S. Afanasiev,¹¹⁰ P. Bunin,¹¹⁰ M. Gavrilenko,¹¹⁰ I. Golutvin,¹¹⁰ I. Gorbunov,¹¹⁰ A. Kamenev,¹¹⁰ V. Karjavine,¹¹⁰ A. Lanev,¹¹⁰ A. Malakhov,¹¹⁰ V. Matveev,^{110,rr,ss} P. Moisenz,¹¹⁰ V. Palichik,¹¹⁰ V. Perelygin,¹¹⁰ M. Savina,¹¹⁰ D. Seitova,¹¹⁰ V. Shalaev,¹¹⁰ S. Shmatov,¹¹⁰ S. Shulha,¹¹⁰ V. Smirnov,¹¹⁰ O. Teryaev,¹¹⁰ N. Voytishin,¹¹⁰ A. Zarubin,¹¹⁰ I. Zhizhin,¹¹⁰ G. Gavrillov,¹¹¹ V. Golovtsov,¹¹¹ Y. Ivanov,¹¹¹ V. Kim,^{111,tt} E. Kuznetsova,^{111,uu} V. Murzin,¹¹¹ V. Oreshkin,¹¹¹ I. Smirnov,¹¹¹ D. Sosnov,¹¹¹ V. Sulimov,¹¹¹ L. Uvarov,¹¹¹ S. Volkov,¹¹¹ A. Vorobyev,¹¹¹ Yu. Andreev,¹¹² A. Dermenev,¹¹² S. Gninenko,¹¹² N. Golubev,¹¹² A. Karneyev,¹¹² M. Kirsanov,¹¹² N. Krasnikov,¹¹² A. Pashenkov,¹¹² G. Pivovarov,¹¹² D. Tlisov,^{112,a} A. Toropin,¹¹² V. Epshteyn,¹¹³ V. Gavrillov,¹¹³ N. Lychkovskaya,¹¹³ A. Nikitenko,^{113,vv} V. Popov,¹¹³ G. Safronov,¹¹³ A. Spiridonov,¹¹³ A. Steppenov,¹¹³ M. Toms,¹¹³ E. Vlasov,¹¹³ A. Zhokin,¹¹³ T. Aushev,¹¹⁴ M. Chadeeva,^{115,ww} A. Oskin,¹¹⁵ P. Parygin,¹¹⁵ E. Popova,¹¹⁵ V. Rusinov,¹¹⁵ V. Andreev,¹¹⁶ M. Azarkin,¹¹⁶ I. Dremin,¹¹⁶ M. Kirakosyan,¹¹⁶ A. Terkulov,¹¹⁶ A. Belyaev,¹¹⁷ E. Boos,¹¹⁷ V. Bunichev,¹¹⁷ M. Dubinin,^{117,xx} L. Dudko,¹¹⁷ A. Gribushin,¹¹⁷ V. Klyukhin,¹¹⁷ O. Kodolova,¹¹⁷ I. Lokhtin,¹¹⁷ S. Obraztsov,¹¹⁷ M. Perfilov,¹¹⁷ S. Petrushanko,¹¹⁷ V. Savrin,¹¹⁷ V. Blinov,^{118,yy} T. Dimova,^{118,yy} L. Kardapoltsev,^{118,yy} I. Ovtin,^{118,yy} Y. Skovpen,^{118,yy} I. Azhgirey,¹¹⁹ I. Bayshev,¹¹⁹ V. Kachanov,¹¹⁹ A. Kalinin,¹¹⁹ D. Konstantinov,¹¹⁹ V. Petrov,¹¹⁹ R. Ryutin,¹¹⁹ A. Sobol,¹¹⁹ S. Troshin,¹¹⁹ N. Tyurin,¹¹⁹ A. Uzunian,¹¹⁹ A. Volkov,¹¹⁹ A. Babaev,¹²⁰ A. Iuzhakov,¹²⁰ V. Okhotnikov,¹²⁰ L. Sukhikh,¹²⁰ V. Borchsh,¹²¹ V. Ivanchenko,¹²¹ E. Tcherniaev,¹²¹ P. Adzic,^{122,zz} P. Cirkovic,¹²² M. Dordevic,¹²² P. Milenovic,¹²² J. Milosevic,¹²² M. Aguilar-Benitez,¹²³ J. Alcaraz Maestre,¹²³ A. Álvarez Fernández,¹²³ I. Bachiller,¹²³ M. Barrio Luna,¹²³ Cristina F. Bedoya,¹²³ J. A. Brochero Cifuentes,¹²³ C. A. Carrillo Montoya,¹²³ M. Cepeda,¹²³ M. Cerrada,¹²³ N. Colino,¹²³ B. De La Cruz,¹²³ A. Delgado Peris,¹²³ J. P. Fernández Ramos,¹²³ J. Flix,¹²³ M. C. Fouz,¹²³ A. García Alonso,¹²³ O. Gonzalez Lopez,¹²³ S. Goy Lopez,¹²³ J. M. Hernandez,¹²³ M. I. Josa,¹²³ J. León Holgado,¹²³ D. Moran,¹²³ Á. Navarro Tobar,¹²³ A. Pérez-Calero Yzquierdo,¹²³ J. Puerta Pelayo,¹²³ I. Redondo,¹²³ L. Romero,¹²³ S. Sánchez Navas,¹²³ M. S. Soares,¹²³ A. Triossi,¹²³ L. Urda Gómez,¹²³ C. Willmott,¹²³ C. Albajar,¹²⁴ J. F. de Trocóniz,¹²⁴ R. Reyes-Almanza,¹²⁴ B. Alvarez Gonzalez,¹²⁵ J. Cuevas,¹²⁵ C. Erice,¹²⁵ J. Fernandez Menendez,¹²⁵ S. Folgueras,¹²⁵ I. Gonzalez Caballero,¹²⁵ E. Palencia Cortezon,¹²⁵ C. Ramón Álvarez,¹²⁵ J. Ripoll Sau,¹²⁵ V. Rodríguez Bouza,¹²⁵ S. Sanchez Cruz,¹²⁵ A. Trapote,¹²⁵ I. J. Cabrillo,¹²⁶ A. Calderon,¹²⁶ B. Chazin Quero,¹²⁶ J. Duarte Campderros,¹²⁶ M. Fernandez,¹²⁶ P. J. Fernández Manteca,¹²⁶ G. Gomez,¹²⁶ C. Martinez Rivero,¹²⁶ P. Martinez Ruiz del Arbol,¹²⁶ F. Matorras,¹²⁶ J. Piedra Gomez,¹²⁶ C. Prieels,¹²⁶ F. Ricci-Tam,¹²⁶ T. Rodrigo,¹²⁶ A. Ruiz-Jimeno,¹²⁶ L. Scodellaro,¹²⁶ I. Vila,¹²⁶ J. M. Vizan Garcia,¹²⁶ MK Jayananda,¹²⁷ B. Kailasapathy,^{127,aaa} D. U. J. Sonnadara,¹²⁷ DDC Wickramaratna,¹²⁷ W. G. D. Dharmaratna,¹²⁸ K. Liyanage,¹²⁸ N. Perera,¹²⁸ N. Wickramage,¹²⁸ T. K. Aarrestad,¹²⁹ D. Abbaneo,¹²⁹ B. Akgun,¹²⁹ E. Auffray,¹²⁹ G. Auzinger,¹²⁹

J. Baechler,¹²⁹ P. Baillon,¹²⁹ A. H. Ball,¹²⁹ D. Barney,¹²⁹ J. Bendavid,¹²⁹ N. Beni,¹²⁹ M. Bianco,¹²⁹ A. Bocci,¹²⁹ P. Bortignon,¹²⁹ E. Bossini,¹²⁹ E. Brondolin,¹²⁹ T. Camporesi,¹²⁹ G. Cerminara,¹²⁹ L. Cristella,¹²⁹ D. d'Enterria,¹²⁹ A. Dabrowski,¹²⁹ N. Daci,¹²⁹ V. Daponte,¹²⁹ A. David,¹²⁹ A. De Roeck,¹²⁹ M. Deile,¹²⁹ R. Di Maria,¹²⁹ M. Dobson,¹²⁹ M. Dünser,¹²⁹ N. Dupont,¹²⁹ A. Elliott-Peisert,¹²⁹ N. Emriskova,¹²⁹ F. Fallavollita,^{129,bbb} D. Fasanella,¹²⁹ S. Fiorendi,¹²⁹ G. Franzoni,¹²⁹ J. Fulcher,¹²⁹ W. Funk,¹²⁹ S. Giani,¹²⁹ D. Gigi,¹²⁹ K. Gill,¹²⁹ F. Glege,¹²⁹ L. Gouskos,¹²⁹ M. Guilbaud,¹²⁹ D. Gulhan,¹²⁹ M. Haranko,¹²⁹ J. Hegeman,¹²⁹ Y. Iiyama,¹²⁹ V. Innocente,¹²⁹ T. James,¹²⁹ P. Janot,¹²⁹ J. Kaspar,¹²⁹ J. Kieseler,¹²⁹ M. Komm,¹²⁹ N. Kratochwil,¹²⁹ C. Lange,¹²⁹ P. Lecoq,¹²⁹ K. Long,¹²⁹ C. Lourenço,¹²⁹ L. Malgeri,¹²⁹ M. Mannelli,¹²⁹ A. Massironi,¹²⁹ F. Meijers,¹²⁹ S. Mersi,¹²⁹ E. Meschi,¹²⁹ F. Moortgat,¹²⁹ M. Mulders,¹²⁹ J. Ngadiuba,¹²⁹ J. Niedziela,¹²⁹ S. Orfanelli,¹²⁹ L. Orsini,¹²⁹ F. Pantaleo,^{129,s} L. Pape,¹²⁹ E. Perez,¹²⁹ M. Peruzzi,¹²⁹ A. Petrilli,¹²⁹ G. Petrucciani,¹²⁹ A. Pfeiffer,¹²⁹ M. Pierini,¹²⁹ D. Rabady,¹²⁹ A. Racz,¹²⁹ M. Rieger,¹²⁹ M. Rovere,¹²⁹ H. Sakulin,¹²⁹ J. Salfeld-Nebgen,¹²⁹ S. Scarfi,¹²⁹ C. Schäfer,¹²⁹ C. Schwick,¹²⁹ M. Selvaggi,¹²⁹ A. Sharma,¹²⁹ P. Silva,¹²⁹ W. Snoeys,¹²⁹ P. Sphicas,^{129,ccc} J. Steggemann,¹²⁹ S. Summers,¹²⁹ V. R. Tavolaro,¹²⁹ D. Treille,¹²⁹ A. Tsirou,¹²⁹ G. P. Van Onsem,¹²⁹ A. Vartak,¹²⁹ M. Verzetti,¹²⁹ K. A. Wozniak,¹²⁹ W. D. Zeuner,¹²⁹ L. Caminada,^{130,ddd} W. Erdmann,¹³⁰ R. Horisberger,¹³⁰ Q. Ingram,¹³⁰ H. C. Kaestli,¹³⁰ D. Kotlinski,¹³⁰ U. Langenegger,¹³⁰ T. Rohe,¹³⁰ M. Backhaus,¹³¹ P. Berger,¹³¹ A. Calandri,¹³¹ N. Chernyavskaya,¹³¹ A. De Cosa,¹³¹ G. Dissertori,¹³¹ M. Dittmar,¹³¹ M. Donegà,¹³¹ C. Dorfer,¹³¹ T. Gadek,¹³¹ T. A. Gómez Espinosa,¹³¹ C. Grab,¹³¹ D. Hits,¹³¹ W. Lustermann,¹³¹ A.-M. Lyon,¹³¹ R. A. Manzoni,¹³¹ M. T. Meinhard,¹³¹ F. Micheli,¹³¹ F. Nessi-Tedaldi,¹³¹ F. Pauss,¹³¹ V. Perovic,¹³¹ G. Perrin,¹³¹ L. Perrozzi,¹³¹ S. Pigazzini,¹³¹ M. G. Ratti,¹³¹ M. Reichmann,¹³¹ C. Reissel,¹³¹ T. Reitenspiess,¹³¹ B. Ristic,¹³¹ D. Ruini,¹³¹ D. A. Sanz Becerra,¹³¹ M. Schönenberger,¹³¹ V. Stampf,¹³¹ M. L. Vesterbacka Olsson,¹³¹ R. Wallny,¹³¹ D. H. Zhu,¹³¹ C. AMSler,^{132,eee} C. Botta,¹³² D. Brzhechko,¹³² M. F. Canelli,¹³² R. Del Burgo,¹³² J. K. Heikkilä,¹³² M. Huwiler,¹³² A. Jofrehei,¹³² B. Kilminster,¹³² S. Leontsinis,¹³² A. Macchiolo,¹³² P. Meiring,¹³² V. M. Mikuni,¹³² U. Molinatti,¹³² I. Neutelings,¹³² G. Raucó,¹³² A. Reimers,¹³² P. Robmann,¹³² K. Schweiger,¹³² Y. Takahashi,¹³² S. Wertz,¹³² C. Adloff,^{133,fff} C. M. Kuo,¹³³ W. Lin,¹³³ A. Roy,¹³³ T. Sarkar,^{133,hh} S. S. Yu,¹³³ L. Ceard,¹³⁴ P. Chang,¹³⁴ Y. Chao,¹³⁴ K. F. Chen,¹³⁴ P. H. Chen,¹³⁴ W.-S. Hou,¹³⁴ Y. y. Li,¹³⁴ R.-S. Lu,¹³⁴ E. Paganis,¹³⁴ A. Psallidas,¹³⁴ A. Steen,¹³⁴ E. Yazgan,¹³⁴ B. Asavapibhop,¹³⁵ C. Asawatangtrakuldee,¹³⁵ N. Srimanobhas,¹³⁵ F. Boran,¹³⁶ S. Damarseekin,^{136,ggg} Z. S. Demiroglu,¹³⁶ F. Dolek,¹³⁶ C. Dozen,^{136,hhh} I. Dumanoglu,^{136,iii} E. Eskut,¹³⁶ G. Gokbulut,¹³⁶ Y. Guler,¹³⁶ E. Gурpinar Guler,^{136,jjj} I. Hos,^{136,kkk} C. Isik,¹³⁶ E. E. Kangal,^{136,lll} O. Kara,¹³⁶ A. Kayis Topaksu,¹³⁶ U. Kiminsu,¹³⁶ G. Onengut,¹³⁶ K. Ozdemir,^{136,mmm} A. Polatoz,¹³⁶ A. E. Simsek,¹³⁶ B. Tali,^{136,nnn} U. G. Tok,¹³⁶ S. Turkcapar,¹³⁶ I. S. Zorbakir,¹³⁶ C. Zorbilmez,¹³⁶ B. Isildak,^{137,ooo} G. Karapinar,^{137,ppp} K. Ocalan,^{137,qqq} M. Yalvac,^{137,rrr} I. O. Atakisi,¹³⁸ E. Gülmez,¹³⁸ M. Kaya,^{138,sss} O. Kaya,^{138,ttt} Ö. Özçelik,¹³⁸ S. Tekten,^{138,uuu} E. A. Yetkin,^{138,vvv} A. Cakir,¹³⁹ K. Cankocak,^{139,iii} Y. Komurcu,¹³⁹ S. Sen,^{139,www} F. Aydogmus Sen,¹⁴⁰ S. Cerci,^{140,nnn} B. Kaynak,¹⁴⁰ S. Ozkorucuklu,¹⁴⁰ D. Sunar Cerci,^{140,nnn} B. Grynyov,¹⁴¹ L. Levchuk,¹⁴² E. Bhal,¹⁴³ S. Bologna,¹⁴³ J. J. Brooke,¹⁴³ E. Clement,¹⁴³ D. Cussans,¹⁴³ H. Flacher,¹⁴³ J. Goldstein,¹⁴³ G. P. Heath,¹⁴³ H. F. Heath,¹⁴³ L. Kreczko,¹⁴³ B. Krikler,¹⁴³ S. Paramesvaran,¹⁴³ T. Sakuma,¹⁴³ S. Seif El Nasr-Storey,¹⁴³ V. J. Smith,¹⁴³ J. Taylor,¹⁴³ A. Titterton,¹⁴³ K. W. Bell,¹⁴⁴ A. Belyaev,^{144,xxx} C. Brew,¹⁴⁴ R. M. Brown,¹⁴⁴ D. J. A. Cockerill,¹⁴⁴ K. V. Ellis,¹⁴⁴ K. Harder,¹⁴⁴ S. Harper,¹⁴⁴ J. Linacre,¹⁴⁴ K. Manolopoulos,¹⁴⁴ D. M. Newbold,¹⁴⁴ E. Olaiya,¹⁴⁴ D. Petyt,¹⁴⁴ T. Reis,¹⁴⁴ T. Schuh,¹⁴⁴ C. H. Shepherd-Themistocleous,¹⁴⁴ A. Thea,¹⁴⁴ I. R. Tomalin,¹⁴⁴ T. Williams,¹⁴⁴ R. Bainbridge,¹⁴⁵ P. Bloch,¹⁴⁵ S. Bonomally,¹⁴⁵ J. Borg,¹⁴⁵ S. Breeze,¹⁴⁵ O. Buchmuller,¹⁴⁵ A. Bundock,¹⁴⁵ V. Cepaitis,¹⁴⁵ G. S. Chahal,^{145,yyy} D. Colling,¹⁴⁵ P. Dauncey,¹⁴⁵ G. Davies,¹⁴⁵ M. Della Negra,¹⁴⁵ G. Fedi,¹⁴⁵ G. Hall,¹⁴⁵ G. Iles,¹⁴⁵ J. Langford,¹⁴⁵ L. Lyons,¹⁴⁵ A.-M. Magnan,¹⁴⁵ S. Malik,¹⁴⁵ A. Martelli,¹⁴⁵ V. Milosevic,¹⁴⁵ J. Nash,^{145,zzz} V. Palladino,¹⁴⁵ M. Pesaresi,¹⁴⁵ D. M. Raymond,¹⁴⁵ A. Richards,¹⁴⁵ A. Rose,¹⁴⁵ E. Scott,¹⁴⁵ C. Seez,¹⁴⁵ A. Shtipliyski,¹⁴⁵ M. Stoye,¹⁴⁵ A. Tapper,¹⁴⁵ K. Uchida,¹⁴⁵ T. Virdee,^{145,s} N. Wardle,¹⁴⁵ S. N. Webb,¹⁴⁵ D. Winterbottom,¹⁴⁵ A. G. Zecchinelli,¹⁴⁵ J. E. Cole,¹⁴⁶ P. R. Hobson,¹⁴⁶ A. Khan,¹⁴⁶ P. Kyberd,¹⁴⁶ C. K. Mackay,¹⁴⁶ I. D. Reid,¹⁴⁶ L. Teodorescu,¹⁴⁶ S. Zahid,¹⁴⁶ A. Brinkerhoff,¹⁴⁷ K. Call,¹⁴⁷ B. Caraway,¹⁴⁷ J. Dittmann,¹⁴⁷ K. Hatakeyama,¹⁴⁷ A. R. Kanuganti,¹⁴⁷ C. Madrid,¹⁴⁷ B. McMaster,¹⁴⁷ N. Pastika,¹⁴⁷ S. Sawant,¹⁴⁷ C. Smith,¹⁴⁷ R. Bartek,¹⁴⁸ A. Dominguez,¹⁴⁸ R. Uniyal,¹⁴⁸ A. M. Vargas Hernandez,¹⁴⁸ A. Buccilli,¹⁴⁹ O. Charaf,¹⁴⁹ S. I. Cooper,¹⁴⁹ S. V. Gleyzer,¹⁴⁹ C. Henderson,¹⁴⁹ P. Rumerio,¹⁴⁹ C. West,¹⁴⁹ A. Akpinar,¹⁵⁰ A. Albert,¹⁵⁰ D. Arcaro,¹⁵⁰ C. Cosby,¹⁵⁰ Z. Demiragli,¹⁵⁰ D. Gastler,¹⁵⁰ C. Richardson,¹⁵⁰ J. Rohlf,¹⁵⁰ K. Salyer,¹⁵⁰ D. Sperka,¹⁵⁰ D. Spitzbart,¹⁵⁰ I. Suarez,¹⁵⁰ S. Yuan,¹⁵⁰ D. Zou,¹⁵⁰ G. Benelli,¹⁵¹ B. Burkley,¹⁵¹ X. Coubez,^{151,t} D. Cutts,¹⁵¹ Y. t. Duh,¹⁵¹ M. Hadley,¹⁵¹ U. Heintz,¹⁵¹ J. M. Hogan,^{151,aaaa} K. H. M. Kwok,¹⁵¹ E. Laird,¹⁵¹ G. Landsberg,¹⁵¹ K. T. Lau,¹⁵¹ J. Lee,¹⁵¹ M. Narain,¹⁵¹ S. Sagir,^{151,bbbb} R. Syarif,¹⁵¹ E. Usai,¹⁵¹ W. Y. Wong,¹⁵¹ D. Yu,¹⁵¹ W. Zhang,¹⁵¹ R. Band,¹⁵²

C. Brainerd,¹⁵² R. Breedon,¹⁵² M. Calderon De La Barca Sanchez,¹⁵² M. Chertok,¹⁵² J. Conway,¹⁵² R. Conway,¹⁵² P. T. Cox,¹⁵² R. Erbacher,¹⁵² C. Flores,¹⁵² G. Funk,¹⁵² F. Jensen,¹⁵² W. Ko,^{152,a} O. Kukral,¹⁵² R. Lander,¹⁵² M. Mulhearn,¹⁵² D. Pellett,¹⁵² J. Pilot,¹⁵² M. Shi,¹⁵² D. Taylor,¹⁵² K. Tos,¹⁵² M. Tripathi,¹⁵² Y. Yao,¹⁵² F. Zhang,¹⁵² M. Bachtis,¹⁵³ R. Cousins,¹⁵³ A. Dasgupta,¹⁵³ A. Florent,¹⁵³ D. Hamilton,¹⁵³ J. Hauser,¹⁵³ M. Ignatenko,¹⁵³ T. Lam,¹⁵³ N. Mccoll,¹⁵³ W. A. Nash,¹⁵³ S. Regnard,¹⁵³ D. Saltzberg,¹⁵³ C. Schnaible,¹⁵³ B. Stone,¹⁵³ V. Valuev,¹⁵³ K. Burt,¹⁵⁴ Y. Chen,¹⁵⁴ R. Clare,¹⁵⁴ J. W. Gary,¹⁵⁴ S. M. A. Ghiasi Shirazi,¹⁵⁴ G. Hanson,¹⁵⁴ G. Karapostoli,¹⁵⁴ O. R. Long,¹⁵⁴ N. Manganeli,¹⁵⁴ M. Olmedo Negrete,¹⁵⁴ M. I. Paneva,¹⁵⁴ W. Si,¹⁵⁴ S. Wimpenny,¹⁵⁴ Y. Zhang,¹⁵⁴ J. G. Branson,¹⁵⁵ P. Chang,¹⁵⁵ S. Cittolin,¹⁵⁵ S. Cooperstein,¹⁵⁵ N. Deelen,¹⁵⁵ M. Derdzinski,¹⁵⁵ J. Duarte,¹⁵⁵ R. Gerosa,¹⁵⁵ D. Gilbert,¹⁵⁵ B. Hashemi,¹⁵⁵ V. Krutelyov,¹⁵⁵ J. Letts,¹⁵⁵ M. Masciovecchio,¹⁵⁵ S. May,¹⁵⁵ S. Padhi,¹⁵⁵ M. Pieri,¹⁵⁵ V. Sharma,¹⁵⁵ M. Tadel,¹⁵⁵ F. Würthwein,¹⁵⁵ A. Yagil,¹⁵⁵ N. Amin,¹⁵⁶ C. Campagnari,¹⁵⁶ M. Citron,¹⁵⁶ A. Dorsett,¹⁵⁶ V. Dutta,¹⁵⁶ J. Incandela,¹⁵⁶ B. Marsh,¹⁵⁶ H. Mei,¹⁵⁶ A. Ovcharova,¹⁵⁶ H. Qu,¹⁵⁶ M. Quinnan,¹⁵⁶ J. Richman,¹⁵⁶ U. Sarica,¹⁵⁶ D. Stuart,¹⁵⁶ S. Wang,¹⁵⁶ D. Anderson,¹⁵⁷ A. Bornheim,¹⁵⁷ O. Cerri,¹⁵⁷ I. Dutta,¹⁵⁷ J. M. Lawhorn,¹⁵⁷ N. Lu,¹⁵⁷ J. Mao,¹⁵⁷ H. B. Newman,¹⁵⁷ T. Q. Nguyen,¹⁵⁷ J. Pata,¹⁵⁷ M. Spiropulu,¹⁵⁷ J. R. Vlimant,¹⁵⁷ S. Xie,¹⁵⁷ Z. Zhang,¹⁵⁷ R. Y. Zhu,¹⁵⁷ J. Alison,¹⁵⁸ M. B. Andrews,¹⁵⁸ T. Ferguson,¹⁵⁸ T. Mudholkar,¹⁵⁸ M. Paulini,¹⁵⁸ M. Sun,¹⁵⁸ I. Vorobiev,¹⁵⁸ J. P. Cumalat,¹⁵⁹ W. T. Ford,¹⁵⁹ E. MacDonald,¹⁵⁹ T. Mulholland,¹⁵⁹ R. Patel,¹⁵⁹ A. Perloff,¹⁵⁹ K. Stenson,¹⁵⁹ K. A. Ulmer,¹⁵⁹ S. R. Wagner,¹⁵⁹ J. Alexander,¹⁶⁰ Y. Cheng,¹⁶⁰ J. Chu,¹⁶⁰ D. J. Cranshaw,¹⁶⁰ A. Datta,¹⁶⁰ A. Frankenthal,¹⁶⁰ K. Mcdermott,¹⁶⁰ J. Monroy,¹⁶⁰ J. R. Patterson,¹⁶⁰ D. Quach,¹⁶⁰ A. Ryd,¹⁶⁰ W. Sun,¹⁶⁰ S. M. Tan,¹⁶⁰ Z. Tao,¹⁶⁰ J. Thom,¹⁶⁰ P. Wittich,¹⁶⁰ M. Zientek,¹⁶⁰ S. Abdullin,¹⁶¹ M. Albrow,¹⁶¹ M. Alyari,¹⁶¹ G. Apollinari,¹⁶¹ A. Apresyan,¹⁶¹ A. Apyan,¹⁶¹ S. Banerjee,¹⁶¹ L. A. T. Bauerdick,¹⁶¹ A. Beretvas,¹⁶¹ D. Berry,¹⁶¹ J. Berryhill,¹⁶¹ P. C. Bhat,¹⁶¹ K. Burkett,¹⁶¹ J. N. Butler,¹⁶¹ A. Canepa,¹⁶¹ G. B. Cerati,¹⁶¹ H. W. K. Cheung,¹⁶¹ F. Chlebana,¹⁶¹ M. Cremonesi,¹⁶¹ V. D. Elvira,¹⁶¹ J. Freeman,¹⁶¹ Z. Gece,¹⁶¹ E. Gottschalk,¹⁶¹ L. Gray,¹⁶¹ D. Green,¹⁶¹ S. Grünendahl,¹⁶¹ O. Gutsche,¹⁶¹ R. M. Harris,¹⁶¹ S. Hasegawa,¹⁶¹ R. Heller,¹⁶¹ T. C. Herwig,¹⁶¹ J. Hirschauer,¹⁶¹ B. Jayatilaka,¹⁶¹ S. Jindariani,¹⁶¹ M. Johnson,¹⁶¹ U. Joshi,¹⁶¹ P. Klabbers,¹⁶¹ T. Klijsma,¹⁶¹ B. Klima,¹⁶¹ M. J. Kortelainen,¹⁶¹ S. Lammel,¹⁶¹ D. Lincoln,¹⁶¹ R. Lipton,¹⁶¹ M. Liu,¹⁶¹ T. Liu,¹⁶¹ J. Lykken,¹⁶¹ K. Maeshima,¹⁶¹ D. Mason,¹⁶¹ P. McBride,¹⁶¹ P. Merkel,¹⁶¹ S. Mrenna,¹⁶¹ S. Nahn,¹⁶¹ V. O'Dell,¹⁶¹ V. Papadimitriou,¹⁶¹ K. Pedro,¹⁶¹ C. Pena,^{161,xx} O. Prokofyev,¹⁶¹ F. Ravera,¹⁶¹ A. Reinsvold Hall,¹⁶¹ L. Ristori,¹⁶¹ B. Schneider,¹⁶¹ E. Sexton-Kennedy,¹⁶¹ N. Smith,¹⁶¹ A. Soha,¹⁶¹ W. J. Spalding,¹⁶¹ L. Spiegel,¹⁶¹ S. Stoynev,¹⁶¹ J. Strait,¹⁶¹ L. Taylor,¹⁶¹ S. Tkaczyk,¹⁶¹ N. V. Tran,¹⁶¹ L. Uplegger,¹⁶¹ E. W. Vaandering,¹⁶¹ H. A. Weber,¹⁶¹ A. Woodard,¹⁶¹ D. Acosta,¹⁶² P. Avery,¹⁶² D. Bourilkov,¹⁶² L. Cadamuro,¹⁶² V. Cherepanov,¹⁶² F. Errico,¹⁶² R. D. Field,¹⁶² D. Guerrero,¹⁶² B. M. Joshi,¹⁶² M. Kim,¹⁶² J. Konigsberg,¹⁶² A. Korytov,¹⁶² K. H. Lo,¹⁶² K. Matchev,¹⁶² N. Menendez,¹⁶² G. Mitselmakher,¹⁶² D. Rosenzweig,¹⁶² K. Shi,¹⁶² J. Wang,¹⁶² S. Wang,¹⁶² X. Zuo,¹⁶² T. Adams,¹⁶³ A. Askew,¹⁶³ D. Diaz,¹⁶³ R. Habibullah,¹⁶³ S. Hagopian,¹⁶³ V. Hagopian,¹⁶³ K. F. Johnson,¹⁶³ R. Khurana,¹⁶³ T. Kolberg,¹⁶³ G. Martinez,¹⁶³ H. Prosper,¹⁶³ C. Schiber,¹⁶³ R. Yohay,¹⁶³ J. Zhang,¹⁶³ M. M. Baarmand,¹⁶⁴ S. Butalla,¹⁶⁴ T. Elkafrawy,^{164,m} M. Hohmann,¹⁶⁴ D. Noonan,¹⁶⁴ M. Rahmani,¹⁶⁴ M. Saunders,¹⁶⁴ F. Yumiceva,¹⁶⁴ M. R. Adams,¹⁶⁵ L. Apanasevich,¹⁶⁵ H. Becerril Gonzalez,¹⁶⁵ R. Cavanaugh,¹⁶⁵ X. Chen,¹⁶⁵ S. Dittmer,¹⁶⁵ O. Evdokimov,¹⁶⁵ C. E. Gerber,¹⁶⁵ D. A. Hangal,¹⁶⁵ D. J. Hofman,¹⁶⁵ C. Mills,¹⁶⁵ G. Oh,¹⁶⁵ T. Roy,¹⁶⁵ M. B. Tonjes,¹⁶⁵ N. Varelas,¹⁶⁵ J. Viinikainen,¹⁶⁵ X. Wang,¹⁶⁵ Z. Wu,¹⁶⁵ M. Alhousseini,¹⁶⁶ K. Dilsiz,^{166,cccc} S. Durgut,¹⁶⁶ R. P. Gandrajula,¹⁶⁶ M. Haytmyradov,¹⁶⁶ V. Khristenko,¹⁶⁶ O. K. Köseyan,¹⁶⁶ J.-P. Merlo,¹⁶⁶ A. Mestvirishvili,^{166,dddd} A. Moeller,¹⁶⁶ J. Nachtman,¹⁶⁶ H. Ogul,^{166,eeee} Y. Onel,¹⁶⁶ F. Ozok,^{166,ffff} A. Penzo,¹⁶⁶ C. Snyder,¹⁶⁶ E. Tiras,¹⁶⁶ J. Wetzel,¹⁶⁶ K. Yi,^{166,gggg} O. Amram,¹⁶⁷ B. Blumenfeld,¹⁶⁷ L. Corcodilos,¹⁶⁷ M. Eminizer,¹⁶⁷ A. V. Gritsan,¹⁶⁷ S. Kyriacou,¹⁶⁷ P. Maksimovic,¹⁶⁷ C. Mantilla,¹⁶⁷ J. Roskes,¹⁶⁷ M. Swartz,¹⁶⁷ T. Á. Vámi,¹⁶⁷ C. Baldenegro Barrera,¹⁶⁸ P. Baringer,¹⁶⁸ A. Bean,¹⁶⁸ A. Bylinkin,¹⁶⁸ T. Isidori,¹⁶⁸ S. Khalil,¹⁶⁸ J. King,¹⁶⁸ G. Krintiras,¹⁶⁸ A. Kropivnitskaya,¹⁶⁸ C. Lindsey,¹⁶⁸ N. Minafra,¹⁶⁸ M. Murray,¹⁶⁸ C. Rogan,¹⁶⁸ C. Royon,¹⁶⁸ S. Sanders,¹⁶⁸ E. Schmitz,¹⁶⁸ J. D. Tapia Takaki,¹⁶⁸ Q. Wang,¹⁶⁸ J. Williams,¹⁶⁸ G. Wilson,¹⁶⁸ S. Duric,¹⁶⁹ A. Ivanov,¹⁶⁹ K. Kaadze,¹⁶⁹ D. Kim,¹⁶⁹ Y. Maravin,¹⁶⁹ T. Mitchell,¹⁶⁹ A. Modak,¹⁶⁹ A. Mohammadi,¹⁶⁹ F. Rebassoo,¹⁷⁰ D. Wright,¹⁷⁰ E. Adams,¹⁷¹ A. Baden,¹⁷¹ O. Baron,¹⁷¹ A. Belloni,¹⁷¹ S. C. Eno,¹⁷¹ Y. Feng,¹⁷¹ N. J. Hadley,¹⁷¹ S. Jabeen,¹⁷¹ G. Y. Jeng,¹⁷¹ R. G. Kellogg,¹⁷¹ T. Koeth,¹⁷¹ A. C. Mignerey,¹⁷¹ S. Nabili,¹⁷¹ M. Seidel,¹⁷¹ A. Skuja,¹⁷¹ S. C. Tonwar,¹⁷¹ L. Wang,¹⁷¹ K. Wong,¹⁷¹ D. Abercrombie,¹⁷² B. Allen,¹⁷² R. Bi,¹⁷² S. Brandt,¹⁷² W. Busza,¹⁷² I. A. Cali,¹⁷² Y. Chen,¹⁷² M. D'Alfonso,¹⁷² G. Gomez Ceballos,¹⁷² M. Goncharov,¹⁷² P. Harris,¹⁷² D. Hsu,¹⁷² M. Hu,¹⁷² M. Klute,¹⁷² D. Kovalskyi,¹⁷² J. Krupa,¹⁷² Y.-J. Lee,¹⁷² P. D. Luckey,¹⁷² B. Maier,¹⁷² A. C. Marini,¹⁷² C. McGinn,¹⁷² C. Mironov,¹⁷² S. Narayanan,¹⁷² X. Niu,¹⁷² C. Paus,¹⁷² D. Rankin,¹⁷² C. Roland,¹⁷² G. Roland,¹⁷² Z. Shi,¹⁷² G. S. F. Stephens,¹⁷² K. Sumorok,¹⁷² K. Tatar,¹⁷² D. Velicanu,¹⁷² J. Wang,¹⁷² T. W. Wang,¹⁷² Z. Wang,¹⁷² B. Wyslouch,¹⁷²

R. M. Chatterjee,¹⁷³ A. Evans,¹⁷³ S. Guts,^{173,a} P. Hansen,¹⁷³ J. Hiltbrand,¹⁷³ Sh. Jain,¹⁷³ M. Krohn,¹⁷³ Y. Kubota,¹⁷³ Z. Lesko,¹⁷³ J. Mans,¹⁷³ M. Revering,¹⁷³ R. Rusack,¹⁷³ R. Saradhy,¹⁷³ N. Schroeder,¹⁷³ N. Strobbe,¹⁷³ M. A. Wadud,¹⁷³ J. G. Acosta,¹⁷⁴ S. Oliveros,¹⁷⁴ K. Bloom,¹⁷⁵ S. Chauhan,¹⁷⁵ D. R. Claes,¹⁷⁵ C. Fangmeier,¹⁷⁵ L. Finco,¹⁷⁵ F. Golf,¹⁷⁵ J. R. González Fernández,¹⁷⁵ I. Kravchenko,¹⁷⁵ J. E. Siado,¹⁷⁵ G. R. Snow,^{175,a} B. Stieger,¹⁷⁵ W. Tabb,¹⁷⁵ F. Yan,¹⁷⁵ G. Agarwal,¹⁷⁶ C. Harrington,¹⁷⁶ L. Hay,¹⁷⁶ I. Iashvili,¹⁷⁶ A. Kharchilava,¹⁷⁶ C. McLean,¹⁷⁶ D. Nguyen,¹⁷⁶ J. Pekkanen,¹⁷⁶ S. Rappoccio,¹⁷⁶ B. Roozbahani,¹⁷⁶ G. Alverson,¹⁷⁷ E. Barberis,¹⁷⁷ C. Freer,¹⁷⁷ Y. Haddad,¹⁷⁷ A. Hortiangtham,¹⁷⁷ J. Li,¹⁷⁷ G. Madigan,¹⁷⁷ B. Marzocchi,¹⁷⁷ D. M. Morse,¹⁷⁷ V. Nguyen,¹⁷⁷ T. Orimoto,¹⁷⁷ A. Parker,¹⁷⁷ L. Skinnari,¹⁷⁷ A. Tishelman-Charny,¹⁷⁷ T. Wamorkar,¹⁷⁷ B. Wang,¹⁷⁷ A. Wisecarver,¹⁷⁷ D. Wood,¹⁷⁷ S. Bhattacharya,¹⁷⁸ J. Bueghly,¹⁷⁸ Z. Chen,¹⁷⁸ A. Gilbert,¹⁷⁸ T. Gunter,¹⁷⁸ K. A. Hahn,¹⁷⁸ N. Odell,¹⁷⁸ M. H. Schmitt,¹⁷⁸ K. Sung,¹⁷⁸ M. Velasco,¹⁷⁸ R. Bucci,¹⁷⁹ N. Dev,¹⁷⁹ R. Goldouzian,¹⁷⁹ M. Hildreth,¹⁷⁹ K. Hurtado Anampa,¹⁷⁹ C. Jessop,¹⁷⁹ D. J. Karmgard,¹⁷⁹ K. Lannon,¹⁷⁹ W. Li,¹⁷⁹ N. Loukas,¹⁷⁹ N. Marinelli,¹⁷⁹ I. Mcalister,¹⁷⁹ F. Meng,¹⁷⁹ K. Mohrman,¹⁷⁹ Y. Musienko,^{179,r} R. Ruchti,¹⁷⁹ P. Siddireddy,¹⁷⁹ S. Taroni,¹⁷⁹ M. Wayne,¹⁷⁹ A. Wightman,¹⁷⁹ M. Wolf,¹⁷⁹ L. Zygala,¹⁷⁹ J. Alimena,¹⁸⁰ B. Bylsma,¹⁸⁰ B. Cardwell,¹⁸⁰ L. S. Durkin,¹⁸⁰ B. Francis,¹⁸⁰ C. Hill,¹⁸⁰ A. Lefeld,¹⁸⁰ B. L. Winer,¹⁸⁰ B. R. Yates,¹⁸⁰ P. Das,¹⁸¹ G. Dezoort,¹⁸¹ P. Elmer,¹⁸¹ B. Greenberg,¹⁸¹ N. Haubrich,¹⁸¹ S. Higginbotham,¹⁸¹ A. Kalogeropoulos,¹⁸¹ G. Kopp,¹⁸¹ S. Kwan,¹⁸¹ D. Lange,¹⁸¹ M. T. Lucchini,¹⁸¹ J. Luo,¹⁸¹ D. Marlow,¹⁸¹ K. Mei,¹⁸¹ I. Ojalvo,¹⁸¹ J. Olsen,¹⁸¹ C. Palmer,¹⁸¹ P. Piroué,¹⁸¹ D. Stickland,¹⁸¹ C. Tully,¹⁸¹ S. Malik,¹⁸² S. Norberg,¹⁸² V. E. Barnes,¹⁸³ R. Chawla,¹⁸³ S. Das,¹⁸³ L. Gutay,¹⁸³ M. Jones,¹⁸³ A. W. Jung,¹⁸³ B. Mahakud,¹⁸³ G. Negro,¹⁸³ N. Neumeister,¹⁸³ C. C. Peng,¹⁸³ S. Piperov,¹⁸³ H. Qiu,¹⁸³ J. F. Schulte,¹⁸³ N. Trevisani,¹⁸³ F. Wang,¹⁸³ R. Xiao,¹⁸³ W. Xie,¹⁸³ T. Cheng,¹⁸⁴ J. Dolen,¹⁸⁴ N. Parashar,¹⁸⁴ M. Stojanovic,^{184,p} A. Baty,¹⁸⁵ S. Dildick,¹⁸⁵ K. M. Ecklund,¹⁸⁵ S. Freed,¹⁸⁵ F. J. M. Geurts,¹⁸⁵ M. Kilpatrick,¹⁸⁵ A. Kumar,¹⁸⁵ W. Li,¹⁸⁵ B. P. Padley,¹⁸⁵ R. Redjimi,¹⁸⁵ J. Roberts,^{185,a} J. Rorie,¹⁸⁵ W. Shi,¹⁸⁵ A. G. Stahl Leitner,¹⁸⁵ A. Bodek,¹⁸⁶ P. de Barbaro,¹⁸⁶ R. Demina,¹⁸⁶ J. L. Dulemba,¹⁸⁶ C. Fallon,¹⁸⁶ T. Ferbel,¹⁸⁶ M. Galanti,¹⁸⁶ A. Garcia-Bellido,¹⁸⁶ O. Hindrichs,¹⁸⁶ A. Khukhunaishvili,¹⁸⁶ E. Ranken,¹⁸⁶ R. Taus,¹⁸⁶ B. Chiarito,¹⁸⁷ J. P. Chou,¹⁸⁷ A. Gandrakota,¹⁸⁷ Y. Gershtein,¹⁸⁷ E. Halkiadakis,¹⁸⁷ A. Hart,¹⁸⁷ M. Heindl,¹⁸⁷ E. Hughes,¹⁸⁷ S. Kaplan,¹⁸⁷ O. Karacheban,^{187,w} I. Laflotte,¹⁸⁷ A. Lath,¹⁸⁷ R. Montalvo,¹⁸⁷ K. Nash,¹⁸⁷ M. Osherson,¹⁸⁷ S. Salur,¹⁸⁷ S. Schnetzer,¹⁸⁷ S. Somalwar,¹⁸⁷ R. Stone,¹⁸⁷ S. A. Thayil,¹⁸⁷ S. Thomas,¹⁸⁷ H. Wang,¹⁸⁷ H. Acharya,¹⁸⁸ A. G. Delannoy,¹⁸⁸ S. Spanier,¹⁸⁸ O. Bouhali,^{189,hhh} M. Dalchenko,¹⁸⁹ A. Delgado,¹⁸⁹ R. Eusebi,¹⁸⁹ J. Gilmore,¹⁸⁹ T. Huang,¹⁸⁹ T. Kamon,^{189,iii} H. Kim,¹⁸⁹ S. Luo,¹⁸⁹ S. Malhotra,¹⁸⁹ R. Mueller,¹⁸⁹ D. Overton,¹⁸⁹ L. Perniè,¹⁸⁹ D. Rathjens,¹⁸⁹ A. Safonov,¹⁸⁹ J. Sturdy,¹⁸⁹ N. Akchurin,¹⁹⁰ J. Damgov,¹⁹⁰ V. Hegde,¹⁹⁰ S. Kunori,¹⁹⁰ K. Lamichhane,¹⁹⁰ S. W. Lee,¹⁹⁰ T. Mengke,¹⁹⁰ S. Muthumuni,¹⁹⁰ T. Peltola,¹⁹⁰ S. Undleeb,¹⁹⁰ I. Volobouev,¹⁹⁰ Z. Wang,¹⁹⁰ A. Whitbeck,¹⁹⁰ E. Appelt,¹⁹¹ S. Greene,¹⁹¹ A. Gurrola,¹⁹¹ R. Janjam,¹⁹¹ W. Johns,¹⁹¹ C. Maguire,¹⁹¹ A. Melo,¹⁹¹ H. Ni,¹⁹¹ K. Padeken,¹⁹¹ F. Romeo,¹⁹¹ P. Sheldon,¹⁹¹ S. Tuo,¹⁹¹ J. Velkovska,¹⁹¹ M. Verweij,¹⁹¹ M. W. Arenton,¹⁹² B. Cox,¹⁹² G. Cummings,¹⁹² J. Hakala,¹⁹² R. Hirosky,¹⁹² M. Joyce,¹⁹² A. Ledovskoy,¹⁹² A. Li,¹⁹² C. Neu,¹⁹² B. Tannenwald,¹⁹² Y. Wang,¹⁹² E. Wolfe,¹⁹² F. Xia,¹⁹² P. E. Karchin,¹⁹³ N. Poudyal,¹⁹³ P. Thapa,¹⁹³ K. Black,¹⁹⁴ T. Bose,¹⁹⁴ J. Buchanan,¹⁹⁴ C. Caillol,¹⁹⁴ S. Dasu,¹⁹⁴ I. De Bruyn,¹⁹⁴ P. Everaerts,¹⁹⁴ C. Galloni,¹⁹⁴ H. He,¹⁹⁴ M. Herndon,¹⁹⁴ A. Hervé,¹⁹⁴ U. Hussain,¹⁹⁴ A. Lanaro,¹⁹⁴ A. Loeliger,¹⁹⁴ R. Loveless,¹⁹⁴ J. Madhusudanan Sreekala,¹⁹⁴ A. Mallampalli,¹⁹⁴ D. Pinna,¹⁹⁴ T. Ruggles,¹⁹⁴ A. Savin,¹⁹⁴ V. Shang,¹⁹⁴ V. Sharma,¹⁹⁴ W. H. Smith,¹⁹⁴ D. Teague,¹⁹⁴ S. Trembath-reichert,¹⁹⁴ and W. Vetens¹⁹⁴

(CMS Collaboration)

¹*Yerevan Physics Institute, Yerevan, Armenia*²*Institut für Hochenergiephysik, Wien, Austria*³*Institute for Nuclear Problems, Minsk, Belarus*⁴*Universiteit Antwerpen, Antwerpen, Belgium*⁵*Vrije Universiteit Brussel, Brussel, Belgium*⁶*Université Libre de Bruxelles, Bruxelles, Belgium*⁷*Ghent University, Ghent, Belgium*⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*⁹*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*¹⁰*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*^{11a}*Universidade Estadual Paulista, São Paulo, Brazil*^{11b}*Universidade Federal do ABC, São Paulo, Brazil*

- ¹²*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
- ¹³*University of Sofia, Sofia, Bulgaria*
- ¹⁴*Beihang University, Beijing, China*
- ¹⁵*Department of Physics, Tsinghua University, Beijing, China*
- ¹⁶*Institute of High Energy Physics, Beijing, China*
- ¹⁷*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
- ¹⁸*Sun Yat-Sen University, Guangzhou, China*
- ¹⁹*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—
Fudan University, Shanghai, China*
- ²⁰*Zhejiang University, Hangzhou, China*
- ²¹*Universidad de Los Andes, Bogota, Colombia*
- ²²*Universidad de Antioquia, Medellin, Colombia*
- ²³*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture,
Split, Croatia*
- ²⁴*University of Split, Faculty of Science, Split, Croatia*
- ²⁵*Institute Rudjer Boskovic, Zagreb, Croatia*
- ²⁶*University of Cyprus, Nicosia, Cyprus*
- ²⁷*Charles University, Prague, Czech Republic*
- ²⁸*Escuela Politecnica Nacional, Quito, Ecuador*
- ²⁹*Universidad San Francisco de Quito, Quito, Ecuador*
- ³⁰*Academy of Scientific Research and Technology of the Arab Republic of Egypt,
Egyptian Network of High Energy Physics, Cairo, Egypt*
- ³¹*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
- ³²*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
- ³³*Department of Physics, University of Helsinki, Helsinki, Finland*
- ³⁴*Helsinki Institute of Physics, Helsinki, Finland*
- ³⁵*Lappeenranta University of Technology, Lappeenranta, Finland*
- ³⁶*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ³⁷*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique,
Institut Polytechnique de Paris, France*
- ³⁸*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
- ³⁹*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3,
Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
- ⁴⁰*Georgian Technical University, Tbilisi, Georgia*
- ⁴¹*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ⁴²*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ⁴³*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
- ⁴⁴*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ⁴⁵*University of Hamburg, Hamburg, Germany*
- ⁴⁶*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
- ⁴⁷*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
- ⁴⁸*National and Kapodistrian University of Athens, Athens, Greece*
- ⁴⁹*National Technical University of Athens, Athens, Greece*
- ⁵⁰*University of Ioánnina, Ioánnina, Greece*
- ⁵¹*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group,
Eötvös Loránd University, Budapest, Hungary*
- ⁵²*Wigner Research Centre for Physics, Budapest, Hungary*
- ⁵³*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁵⁴*Institute of Physics, University of Debrecen, Debrecen, Hungary*
- ⁵⁵*Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary*
- ⁵⁶*Indian Institute of Science (IISc), Bangalore, India*
- ⁵⁷*National Institute of Science Education and Research, HBNI, Bhubaneswar, India*
- ⁵⁸*Panjab University, Chandigarh, India*
- ⁵⁹*University of Delhi, Delhi, India*
- ⁶⁰*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
- ⁶¹*Indian Institute of Technology Madras, Madras, India*
- ⁶²*Bhabha Atomic Research Centre, Mumbai, India*
- ⁶³*Tata Institute of Fundamental Research-A, Mumbai, India*
- ⁶⁴*Tata Institute of Fundamental Research-B, Mumbai, India*
- ⁶⁵*Indian Institute of Science Education and Research (IISER), Pune, India*

- ⁶⁶*Isfahan University of Technology, Isfahan, Iran*
- ⁶⁷*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁶⁸*University College Dublin, Dublin, Ireland*
- ^{69a}*INFN Sezione di Bari*
- ^{69b}*Università di Bari*
- ^{69c}*Politecnico di Bari*
- ^{70a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{70b}*Università di Bologna, Bologna, Italy*
- ^{71a}*INFN Sezione di Catania, Catania, Italy*
- ^{71b}*Università di Catania, Catania, Italy*
- ^{72a}*INFN Sezione di Firenze, Firenze, Italy*
- ^{72b}*Università di Firenze, Firenze, Italy*
- ⁷³*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{74a}*INFN Sezione di Genova, Genova, Italy*
- ^{74b}*Università di Genova, Genova, Italy*
- ^{75a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{75b}*Università di Milano-Bicocca, Milano, Italy*
- ^{76a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{76b}*Università di Napoli 'Federico II', Napoli, Italy*
- ^{76c}*Università della Basilicata, Potenza, Italy*
- ^{76d}*Università G. Marconi, Roma, Italy*
- ^{77a}*INFN Sezione di Padova, Padova, Italy*
- ^{77b}*Università di Padova, Padova, Italy*
- ^{77c}*Università di Trento, Trento, Italy*
- ^{78a}*INFN Sezione di Pavia*
- ^{78b}*Università di Pavia*
- ^{79a}*INFN Sezione di Perugia, Perugia, Italy*
- ^{79b}*Università di Perugia, Perugia, Italy*
- ^{80a}*INFN Sezione di Pisa, Pisa, Italy*
- ^{80b}*Università di Pisa, Pisa, Italy*
- ^{80c}*Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{81a}*INFN Sezione di Roma, Rome, Italy*
- ^{81b}*Sapienza Università di Roma, Rome, Italy*
- ^{82a}*INFN Sezione di Torino, Torino, Italy*
- ^{82b}*Università di Torino, Torino, Italy*
- ^{82c}*Università del Piemonte Orientale, Novara, Italy*
- ^{83a}*INFN Sezione di Trieste, Trieste, Italy*
- ^{83b}*Università di Trieste, Trieste, Italy*
- ⁸⁴*Kyungpook National University, Daegu, Korea*
- ⁸⁵*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁸⁶*Hanyang University, Seoul, Korea*
- ⁸⁷*Korea University, Seoul, Korea*
- ⁸⁸*Kyung Hee University, Department of Physics, Seoul, Republic of Korea*
- ⁸⁹*Sejong University, Seoul, Korea*
- ⁹⁰*Seoul National University, Seoul, Korea*
- ⁹¹*University of Seoul, Seoul, Korea*
- ⁹²*Yonsei University, Department of Physics, Seoul, Korea*
- ⁹³*Sungkyunkwan University, Suwon, Korea*
- ⁹⁴*Riga Technical University, Riga, Latvia*
- ⁹⁵*Vilnius University, Vilnius, Lithuania*
- ⁹⁶*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
- ⁹⁷*Universidad de Sonora (UNISON), Hermosillo, Mexico*
- ⁹⁸*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
- ⁹⁹*Universidad Iberoamericana, Mexico City, Mexico*
- ¹⁰⁰*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
- ¹⁰¹*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
- ¹⁰²*University of Montenegro, Podgorica, Montenegro*
- ¹⁰³*University of Auckland, Auckland, New Zealand*
- ¹⁰⁴*University of Canterbury, Christchurch, New Zealand*
- ¹⁰⁵*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*

- ¹⁰⁶AGH University of Science and Technology Faculty of Computer Science,
Electronics and Telecommunications, Krakow, Poland
- ¹⁰⁷National Centre for Nuclear Research, Swierk, Poland
- ¹⁰⁸Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
- ¹⁰⁹Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
- ¹¹⁰Joint Institute for Nuclear Research, Dubna, Russia
- ¹¹¹Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
- ¹¹²Institute for Nuclear Research, Moscow, Russia
- ¹¹³Institute for Theoretical and Experimental Physics named
by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
- ¹¹⁴Moscow Institute of Physics and Technology, Moscow, Russia
- ¹¹⁵National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI),
Moscow, Russia
- ¹¹⁶P.N. Lebedev Physical Institute, Moscow, Russia
- ¹¹⁷Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ¹¹⁸Novosibirsk State University (NSU), Novosibirsk, Russia
- ¹¹⁹Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia
- ¹²⁰National Research Tomsk Polytechnic University, Tomsk, Russia
- ¹²¹Tomsk State University, Tomsk, Russia
- ¹²²University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia
- ¹²³Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- ¹²⁴Universidad Autónoma de Madrid, Madrid, Spain
- ¹²⁵Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias
(ICTEA), Oviedo, Spain
- ¹²⁶Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
- ¹²⁷University of Colombo, Colombo, Sri Lanka
- ¹²⁸University of Ruhuna, Department of Physics, Matara, Sri Lanka
- ¹²⁹CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ¹³⁰Paul Scherrer Institut, Villigen, Switzerland
- ¹³¹ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
- ¹³²Universität Zürich, Zurich, Switzerland
- ¹³³National Central University, Chung-Li, Taiwan
- ¹³⁴National Taiwan University (NTU), Taipei, Taiwan
- ¹³⁵Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
- ¹³⁶Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
- ¹³⁷Middle East Technical University, Physics Department, Ankara, Turkey
- ¹³⁸Bogazici University, Istanbul, Turkey
- ¹³⁹Istanbul Technical University, Istanbul, Turkey
- ¹⁴⁰Istanbul University, Istanbul, Turkey
- ¹⁴¹Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
- ¹⁴²National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
- ¹⁴³University of Bristol, Bristol, United Kingdom
- ¹⁴⁴Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹⁴⁵Imperial College, London, United Kingdom
- ¹⁴⁶Brunel University, Uxbridge, United Kingdom
- ¹⁴⁷Baylor University, Waco, Texas, USA
- ¹⁴⁸Catholic University of America, Washington, DC, USA
- ¹⁴⁹The University of Alabama, Tuscaloosa, Alabama, USA
- ¹⁵⁰Boston University, Boston, Massachusetts, USA
- ¹⁵¹Brown University, Providence, Rhode Island, USA
- ¹⁵²University of California, Davis, Davis, California, USA
- ¹⁵³University of California, Los Angeles, California, USA
- ¹⁵⁴University of California, Riverside, Riverside, California, USA
- ¹⁵⁵University of California, San Diego, La Jolla, California, USA
- ¹⁵⁶University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA
- ¹⁵⁷California Institute of Technology, Pasadena, California, USA
- ¹⁵⁸Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
- ¹⁵⁹University of Colorado Boulder, Boulder, Colorado, USA
- ¹⁶⁰Cornell University, Ithaca, New York, USA
- ¹⁶¹Fermi National Accelerator Laboratory, Batavia, Illinois, USA

- ¹⁶²University of Florida, Gainesville, Florida, USA
¹⁶³Florida State University, Tallahassee, Florida, USA
¹⁶⁴Florida Institute of Technology, Melbourne, Florida, USA
¹⁶⁵University of Illinois at Chicago (UIC), Chicago, Illinois, USA
¹⁶⁶The University of Iowa, Iowa City, Iowa, USA
¹⁶⁷Johns Hopkins University, Baltimore, Maryland, USA
¹⁶⁸The University of Kansas, Lawrence, Kansas, USA
¹⁶⁹Kansas State University, Manhattan, Kansas, USA
¹⁷⁰Lawrence Livermore National Laboratory, Livermore, California, USA
¹⁷¹University of Maryland, College Park, Maryland, USA
¹⁷²Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
¹⁷³University of Minnesota, Minneapolis, Minnesota, USA
¹⁷⁴University of Mississippi, Oxford, Mississippi, USA
¹⁷⁵University of Nebraska-Lincoln, Lincoln, Nebraska, USA
¹⁷⁶State University of New York at Buffalo, Buffalo, New York, USA
¹⁷⁷Northeastern University, Boston, Massachusetts, USA
¹⁷⁸Northwestern University, Evanston, Illinois, USA
¹⁷⁹University of Notre Dame, Notre Dame, Indiana, USA
¹⁸⁰The Ohio State University, Columbus, Ohio, USA
¹⁸¹Princeton University, Princeton, New Jersey, USA
¹⁸²University of Puerto Rico, Mayaguez, Puerto Rico, USA
¹⁸³Purdue University, West Lafayette, Indiana, USA
¹⁸⁴Purdue University Northwest, Hammond, Indiana, USA
¹⁸⁵Rice University, Houston, Texas, USA
¹⁸⁶University of Rochester, Rochester, New York, USA
¹⁸⁷Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
¹⁸⁸University of Tennessee, Knoxville, Tennessee, USA
¹⁸⁹Texas A&M University, College Station, Texas, USA
¹⁹⁰Texas Tech University, Lubbock, Texas, USA
¹⁹¹Vanderbilt University, Nashville, Tennessee, USA
¹⁹²University of Virginia, Charlottesville, Virginia, USA
¹⁹³Wayne State University, Detroit, Michigan, USA
¹⁹⁴University of Wisconsin—Madison, Madison, Wisconsin, USA

^aDeceased.

^bAlso at Vienna University of Technology, Vienna, Austria.

^cAlso at Department of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport.

^dAlso at Université Libre de Bruxelles, Bruxelles, Belgium.

^eAlso at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

^fAlso at Universidade Estadual de Campinas, Campinas, Brazil.

^gAlso at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

^hAlso at UFMS.

ⁱAlso at Universidade Federal de Pelotas, Pelotas, Brazil.

^jAlso at University of Chinese Academy of Sciences.

^kAlso at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia.

^lAlso at Joint Institute for Nuclear Research, Dubna, Russia.

^mAlso at Ain Shams University, Cairo, Egypt.

ⁿAlso at British University in Egypt, Cairo, Egypt.

^oAlso at Fayoum University, El-Fayoum, Egypt.

^pAlso at Purdue University, West Lafayette, Indiana, USA.

^qAlso at Université de Haute Alsace, Mulhouse, France.

^rAlso at Erzincan Binali Yildirim University, Erzincan, Turkey.

^sAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

^tAlso at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

^uAlso at University of Hamburg, Hamburg, Germany.

^vAlso at Isfahan University of Technology, Isfahan, Iran.

^wAlso at Brandenburg University of Technology, Cottbus, Germany.

^xAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

- ^y Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- ^z Also at Physics Department, Faculty of Science, Assiut University.
- ^{aa} Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- ^{bb} Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ^{cc} Also at IIT Bhubaneswar, Bhubaneswar, India.
- ^{dd} Also at Institute of Physics, Bhubaneswar, India.
- ^{ee} Also at G.H.G. Khalsa College, Punjab, India.
- ^{ff} Also at Shoolini University, Solan, India.
- ^{gg} Also at University of Hyderabad, Hyderabad, India.
- ^{hh} Also at University of Visva-Bharati, Santiniketan, India.
- ⁱⁱ Also at Indian Institute of Technology (IIT), Mumbai, India.
- ^{jj} Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ^{kk} Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ^{ll} Also at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy.
- ^{mm} Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development.
- ⁿⁿ Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia.
- ^{oo} Also at Riga Technical University, Riga, Latvia.
- ^{pp} Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ^{qq} Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ^{rr} Also at Institute for Nuclear Research, Moscow, Russia.
- ^{ss} Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ^{tt} Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^{uu} Also at University of Florida, Gainesville, Florida, USA.
- ^{vv} Also at Imperial College, London, United Kingdom.
- ^{ww} Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ^{xx} Also at California Institute of Technology, Pasadena, California, USA.
- ^{yy} Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ^{zz} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{aaa} Also at Trincomalee Campus, Eastern University, Sri Lanka.
- ^{bbb} Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ^{ccc} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{ddd} Also at Universität Zürich, Zurich, Switzerland.
- ^{eee} Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ^{fff} Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ^{ggg} Also at Şırnak University.
- ^{hhh} Also at Department of Physics, Tsinghua University, Beijing, China.
- ⁱⁱⁱ Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- ^{jjj} Also at Beykent University, Istanbul, Turkey.
- ^{kkk} Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies).
- ^{lll} Also at Mersin University, Mersin, Turkey.
- ^{mmm} Also at Piri Reis University, Istanbul, Turkey.
- ⁿⁿⁿ Also at Adiyaman University, Adiyaman, Turkey.
- ^{ooo} Also at Ozyegin University, Istanbul, Turkey.
- ^{ppp} Also at Izmir Institute of Technology, Izmir, Turkey.
- ^{qqq} Also at Necmettin Erbakan University, Konya, Turkey.
- ^{rrr} Also at Bozok Universitetesi Rektörlüğü.
- ^{sss} Also at Marmara University, Istanbul, Turkey.
- ^{ttt} Also at Milli Savunma University.
- ^{uuu} Also at Kafkas University, Kars, Turkey.
- ^{vvv} Also at Istanbul Bilgi University, Istanbul, Turkey.
- ^{www} Also at Hacettepe University, Ankara, Turkey.
- ^{xxx} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{yyy} Also at IPPP Durham University.
- ^{zzz} Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{aaaa} Also at Bethel University, St. Paul, Minneapolis, USA.
- ^{bbbb} Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ^{cccc} Also at Bingol University, Bingol, Turkey.
- ^{dddd} Also at Georgian Technical University, Tbilisi, Georgia.

^{eece} Also at Sinop University, Sinop, Turkey.

^{ffff} Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

^{gggg} Also at Nanjing Normal University Department of Physics.

^{hhhh} Also at Texas A&M University at Qatar, Doha, Qatar.

ⁱⁱⁱⁱ Also at Kyungpook National University, Daegu, Korea.