Measurement of the Higgs boson total decay width using the $H \to WW \to e\nu\mu\nu$ decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

(Received 8 January 2026; accepted 17 March 2026; published 26 May 2026)

The Higgs boson (H) decay width is determined from the ratio of off- and on-shell production of $H \to WW \to e\nu\mu\nu$ using proton–proton collision data corresponding to an integrated luminosity of 138 fb^{-1} collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the Large Hadron Collider. The off-shell signal strength is measured as $\mu_{\text{off-shell}} = 1.2^{+0.8}_{-0.7}$. The Higgs boson total decay width is $\Gamma_H = 3.9^{+2.7}_{-2.2}$ MeV, in agreement with the standard model prediction. The uncertainty in this result represents a factor of 3 improvement over the previous CMS result in this decay channel.

DOI: 10.1103/rny9-zby1

I. INTRODUCTION

The standard model (SM) is a relativistic quantum field theory that describes the constituents of matter via fields and their associated particle interactions [1–3]. One of the accomplishments of the SM is the prediction of the Higgs field and related Higgs boson (H) [2,4–7], which was discovered in 2012 [8,9]. Since its discovery, a campaign to study its properties has been underway at the CERN Large Hadron Collider (LHC) [10,11], a key property being its decay width, Γ_H.

The theoretical prediction of Γ_H for a SM Higgs boson with a mass of 125 GeV is 4.1 MeV with a relative uncertainty of $\pm 3.9\%$ [12]. Since the value of Γ_H is much smaller than the invariant mass resolution of the LHC detectors, precise direct measurements of the decay width are not feasible; instead, it can be constrained through the use of off-shell production modes. The CMS Collaboration has previously determined the width to be $\Gamma_H = 3.0^{+2.0}_{-1.5}$ MeV [13] using off-shell Higgs boson decays to ZZ with subsequent decays to four charged leptons and to two charged leptons and two neutrinos ($H \to ZZ \to 4\ell$ and $2\ell 2\nu$, respectively, with ℓ referring to electrons or muons) using data collected in 2016–2018 at $\sqrt{s} = 13$ TeV. The ATLAS Collaboration has reported a width value of $\Gamma_H = 4.3^{+2.7}_{-1.9}$ MeV [14] in the same $H \to ZZ$ decay channels, $\Gamma_H = 0.9^{+3.4}_{-0.9}$ MeV using $H \to WW \to 2\ell 2\nu$ [15], and $\Gamma_H < 450$ MeV at 95% confidence level from $t\bar{t}t\bar{t}$ production measurements [16].

To complement previous results, we report the measurement of Γ_H from the ratio of its off- and on-shell production in the $H \to WW \to e\nu\mu\nu$ decay mode, using CMS data collected in 2016–2018 at $\sqrt{s} = 13$ TeV. In this paper, the off-shell contribution is defined using a requirement on the WW invariant mass at the generator level of $m_{WW} > 160$ GeV. The previous CMS result using this channel, $\Gamma_H < 26$ MeV [17], was performed with $\sqrt{s} = 7$ and 8 TeV data collected in 2011–2012. The increased center-of-mass energy and integrated luminosity, together with reduced experimental and theoretical uncertainties, motivate this study. Deviations of Γ_H from its SM expectation could point to physics beyond the SM, such as anomalous couplings, since the decay width is determined by all known particle couplings to the Higgs boson.

Given that the width of the Higgs boson is narrow compared to its mass, the narrow-width approximation can be applied [18–21], and its on-shell production cross section $\sigma_{\text{on-shell}}$ reduces to

$$\sigma_{\text{on-shell}} \approx \frac{g_{\mathrm{p}}^2 g_{\mathrm{d}}^2}{(p^2 - M_H^2) + M_H \Gamma_H} \approx \frac{g_{\mathrm{p}}^2 g_{\mathrm{d}}^2}{M_H \Gamma_H}, \qquad (1)$$

where p is the four-momentum of the Higgs boson, M_H its mass, and g_{p} and g_{d} the respective production and decay mode couplings being considered. At center-of-mass energies well above the WW production threshold, there is no significant dependence of the corresponding off-shell cross section $\sigma_{\text{off-shell}}$ on Γ_H and M_H, so we simply have

$$\mu_{\text{off-shell}} \propto \sigma_{\text{off-shell}} = g_{\mathrm{p}}^2 g_{\mathrm{d}}^2, \qquad (2)$$

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

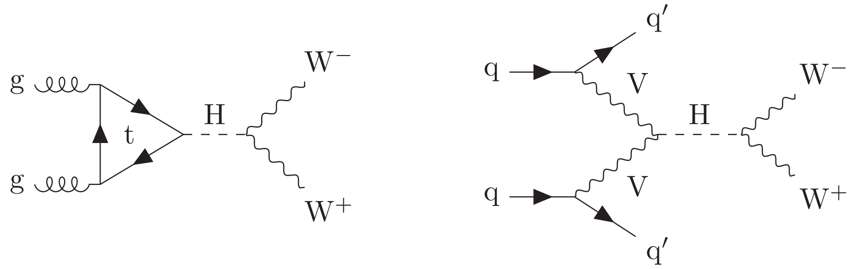

FIG. 1. Feynman diagrams illustrating Higgs boson production and decays to WW in ggF (left) and VBF (right) modes, where H refers to an on- or off-shell Higgs boson.

$$\mu_{\text{on-shell}} \propto \sigma_{\text{on-shell}} \propto \frac{g_{\text{p}}^2 g_{\text{d}}^2}{\Gamma_H}, \tag{3}$$

where μ is the signal strength, defined as the ratio of the measured cross section to the SM prediction for either on- or off-shell production, both of which are equal to unity in the SM. Hence,

$$\Gamma_H \propto \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}. \tag{4}$$

Thus, it is possible to determine the decay width of the Higgs boson by measuring the relative rates of off- to on-shell Higgs boson production.

The two largest Higgs boson production modes, gluon–gluon fusion (ggF) and vector boson fusion (VBF, where $V = W$ or Z), illustrated by the Feynman diagrams in Fig. 1, are used in this analysis. The $WW \to e\nu\mu\nu$ final state is chosen, where the different lepton flavors are required to remove the large Drell–Yan (DY) background in the same-flavor final state. Neutrinos present a challenge because they are electrically neutral, weakly interacting particles, which makes them impossible to directly detect. Their presence can only be inferred from missing transverse momentum, $\vec{p}_{\text{T}}^{\text{miss}}$, as defined in Sec. II.

There are several background physics processes that contribute to the $H \to WW$ channel. At large m_{WW}, the most relevant ones for this measurement are the gluon-induced continuum $gg \to WW$ and electroweak $qq \to qqWW$ production, which interfere destructively with off-shell ggF and VBF, respectively, because of the identical initial and final states. The destructive interference prevents the cross section of scattered W bosons from diverging to infinity, thereby preserving unitarity in the electroweak theory. In this paper, the off-shell contribution is defined as the signal, seen in Fig. 1, plus interference, and it accounts for only a few percent of the total expected event yield once all backgrounds are included, especially the on-shell contributions, $t\bar{t}$, and nonresonant WW production. As a result, the analysis effectively searches for a small shape distortion in the high-mass tail of the m_{WW} distribution on top of sizeable backgrounds, and relies on a precise modeling of off-shell $H \to WW$, the nonresonant WW continuum, and their interference.

The structure of this paper is as follows. Section II provides a short overview of the CMS detector. Details of the data samples and the simulated events are presented in Sec. III. The strategy for event selection and the categorization procedure are outlined in Sec. IV. Section V discusses the background estimation, while Sec. VI summarizes the treatment of systematic uncertainties. The statistical procedure and final results are reported in Secs. VII and VIII, respectively, and the final summary is given in Sec. IX. Tabulated results are provided in the HEPData record for this analysis [22].

II. THE CMS DETECTOR AND EVENT RECONSTRUCTION

The CMS apparatus [23,24] is a multipurpose, nearly hermetic detector, designed to trigger on [25–27] and identify electrons, muons, photons, and (charged and neutral) hadrons [28–30]. Its central feature 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 (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity η coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [23,24].

Events of interest are selected using a two-tiered trigger system. 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 with a fixed latency of 4 μs [25]. 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 a few kHz before data storage [26,27].

The particle-flow (PF) global event reconstruction [31] combines information from the tracking system, calorimeters, and muon detectors to reconstruct and identify individual particles (photons, electrons, muons, charged and neutral hadrons). Electrons are reconstructed from ECAL energy clusters matched to tracks in the silicon tracker, with an explicit treatment of bremsstrahlung along the trajectory, and are accepted within $|\eta| < 2.5$. Muons are reconstructed by matching tracks in the silicon tracker to compatible hits or segments in the muon system within $|\eta| < 2.4$. Tracks not identified as electrons or muons are assigned to charged hadrons, while neutral hadrons are reconstructed from HCAL energy deposits not associated with any charged particle track, or from a combined ECAL + HCAL excess over the expected charged-hadron response.

The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The momentum (energy) of muons is obtained from the corresponding curvature of the track. Only the sum of the transverse momentum (p_{T}) carried away by the neutrinos can be reconstructed using missing transverse momentum. The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as $p_{\mathrm{T}}^{\mathrm{miss}}$ [32]. Additional proton–proton interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction [33] is applied to correct for remaining contributions. The value of $p_{\mathrm{T}}^{\mathrm{miss}}$ is defined using the pileup per particle identification (PUPPI) algorithm [32] along with specific filters to mitigate the effects of the detector noise, and is required to exceed 20 GeV. Anomalous high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events can be due to a variety of reconstruction failures, detector malfunctions, or noncollision backgrounds. Such events are rejected by event filters that are designed to identify more than 85%–90% of the spurious high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events with a mistagging rate less than 0.1% [32].

For each event, hadronic jets with a minimum p_{T} of 20 GeV are clustered from reconstructed particles using the infrared and collinear safe anti-k_{T} algorithm [34,35] with a distance parameter of 0.4, within $|\eta| < 4.7$. Jet momentum is determined as the vectorial sum of all particle momenta in the jet and is found from simulation to be, on average, within 5%–10% of the true momentum over the entire p_{T} spectrum and detector acceptance. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle-level jets on average. *In situ* measurements of the momentum balance in multijet events are used to account for any residual differences in the jet energy scale between data and simulation. The jet energy resolution amounts typically to 15%–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [36]. Additional selection criteria [33] are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures.

III. DATA AND SIMULATED SAMPLES

In this analysis, we use proton–proton collision data samples collected by the CMS experiment in 2016–2018, with a total integrated luminosity of 138 fb^{-1} [37–39].

Each event is required to pass HLT selections, which involve reconstruction of leptons (e, μ) passing specific isolation and identification criteria [27]. The single-lepton trigger selects either one electron with $p_{\mathrm{T}} > 25$, 35, and 32 GeV for the 2016, 2017, and 2018 datasets, respectively, or one muon with $p_{\mathrm{T}} > 24(27)$ GeV for the 2016 and 2018 (2017) datasets. For the combined electron–muon trigger, the highest transverse momentum (leading) lepton must have $p_{\mathrm{T}} > 23$ GeV with the requisite second-highest transverse momentum (subleading) lepton having $p_{\mathrm{T}} > 12$ GeV. The average trigger efficiency, stable across all years to within about 1%, for a single (double) lepton trigger is 87 (95)% [27].

Simulated events are used for modeling signal and background processes. Event samples for the 2016, 2017, and 2018 datasets are simulated separately to account for differences in the detector and pileup conditions.

The VBF off-shell Higgs boson simulations are handled following the procedure described in Ref. [40], which combines several Higgs boson samples to reproduce the expected line shape for signal (S), the $qq \to qqWW$ continuum background (B), shown in Fig. 2, and the combination of signal, background, and interference ($S + B + I$). Higgs boson production is generated with POWHEG v2 [41–43] at next-to-leading order (NLO), while the decay to a pair of W bosons and subsequently to leptons is performed using JHUgen v7.1.4 [44]. The VBF samples are generated for m_{WW} values ranging from 125–3000 GeV, with sufficient event counts to cover both the on- and off-shell regions. The simulated Higgs bosons are treated within the complex pole scheme (CPS) [45], and reweighted to the SM expectation at $M_H = 125$ GeV using the matrix-element likelihood approach (MELA) [46,47]. These samples are combined, resulting in a consistent set of off-shell VBF samples with high number of entries per mass bin in the off-shell tail.

Off-shell ggF samples are generated using the MCFM v7.0 [48–50] generator, which can handle leading-order (LO) generation for the ggF S, the $gg \to WW$ B, and $S + B + I$. The use of MCFM in this analysis differs from the procedure recommended in Ref. [40] because matrix-element reweighting of quark-mediated box diagrams, such as those for the $gg \to WW$ background, illustrated in Fig. 2, yields divergent results. The MCFM generator does not use the

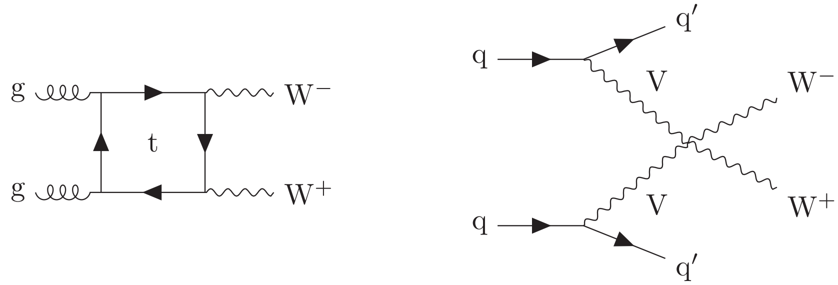

FIG. 2. Feynman diagrams for nonresonant WW production: $gg \to WW$ (left) and one example of $qq \to qqWW$ (right).

reweighting procedure and naturally accounts for the impact of the top quark loop on the Higgs boson amplitude. Off-shell ggF samples are first normalized to next-to-NLO (NNLO) precision via a K-factor [51], differential in m_{WW}, and then normalized at next-to-NNLO (N^3LO) [12,52].

A requirement of $m_{WW} > 160$ GeV is set at the generator level to define the ggF and VBF off-shell events in the simulated samples, as this value corresponds to the threshold above which the Higgs boson can decay into two on-shell W bosons. The selection is inverted for on-shell events, where at least one W boson is off-shell. Generated events where at least one W boson decays into a τ lepton, which subsequently decays leptonically, are treated as signal. These leptonic τ decays contribute approximately 3%–5% to the signal yield in the on-shell regions and 10%–15% in the off-shell regions.

The ggF and VBF on-shell Higgs boson samples are simulated using POWHEG+JHUGEN. The ggF events are reweighted to match the parton shower (PS) model at NNLO + PS [53,54], and further scaled with a K-factor to N^3LO [12,52]. Simulated samples for the associated production (mainly WH and $t\bar{t}H$) are also considered, as described in Ref. [55], although their contribution in the analysis phase space is negligible. The background processes are simulated using several different generators. The production of W^+W^- pairs via quark–antiquark annihilation, $qq \to WW$, is simulated at NNLO + PS with POWHEG. For this sample, a discrepancy between data and simulation is observed in the p_T^{WW} distribution. This particular kinematic variable is difficult to model for WW processes, especially at low p_T^{WW} values around 1 GeV. To improve the Monte Carlo (MC) modeling, a correction factor is derived in the inclusive phase space for WW production. After subtracting all non-$qq \to WW$ backgrounds from the data, the ratio of the resulting p_T^{WW} distribution to the $qq \to WW$ MC prediction is fitted with a second-order polynomial, which is then applied as an event weight. The overall $qq \to WW$ normalization before and after applying the correction is preserved. The DY production of Z/γ^* and multiboson processes, such as $W\gamma$, ZZ, and VVV, are generated at NLO using MadGraph5_aMC@NLO v2.4.2 [56]. Single top quark, $t\bar{t}$, WZ, and $W\gamma^*$ background processes are simulated at NLO with POWHEG v2. The measured top quark p_T distribution from $t\bar{t}$ events in data is softer [57] than that predicted by simulation. This discrepancy is due to missing higher-order quantum chromodynamic (QCD) and electroweak corrections. A paramaterized weight correction [58] is applied in simulation as a function of the generator-level top quark p_T distribution ratio (from NNLO calculations and NLO samples) to improve the modeling in the NLO $t\bar{t}$ MC simulation.

The Pythia8 generator [59] with the CP5 underlying event (UE) tune [60] is used for PS, hadronization, and UE simulation. Parton distribution functions (PDFs) are modeled with the NNPDF3.1 [61] set at NNLO precision for all samples. For all processes, the detector response is simulated using a detailed description of the CMS detector, based on the Geant4 toolkit [62]. The distribution of the number of pileup interactions in the simulation is adjusted to match that observed in data for each year. Additional corrections are applied to the MC simulated samples to match the experimental response in data for the trigger selection, lepton reconstruction, identification, isolation, and momentum scale, jet energy scale, and resolution, missing transverse energy scale, b tagging selection, and L1 trigger corrections for events that are identified with an incorrect bunch crossing [25] (a "prefiring" correction).

IV. EVENT SELECTION AND CATEGORIZATION

The dilepton objects are defined as the oppositely charged electron and muon pair, passing $p_T > 25(20)$ GeV for the leading (subleading) lepton. Several quality requirements are applied to define a muon. We use tight identification and isolation criteria [29]. Additional selections on the distance from the primary interaction vertex (PV) in the transverse and longitudinal planes, $d_{xy} < 0.02$ cm and $d_z < 0.1$ cm, are required to suppress muons from pileup or from heavy-quark hadron decays (nonprompt). To reduce the misidentification rates due to nonprompt leptons not coming from the PV, a multivariate (MVA) discriminant [63] is applied to ensure a maximum separation between prompt and nonprompt leptons. Electrons are identified in a similar fashion, based on a multivariate identification and tight isolation criteria [28,55]. The transverse and longitudinal impact parameter requirements are $d_{xy} < 0.05(0.10)$ cm and $d_z < 0.1(0.2)$ cm for leptons in the pseudorapidity range of the barrel (endcap).

The first selection criterion from the $H \to WW \to e\nu\mu\nu$ decay chain requires $p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV to account for the undetected neutrinos. The dileptons are then required to have an invariant mass $m_{e\mu} > 20$ GeV to suppress nonprompt lepton pairs, and a total transverse momentum magnitude ${p_{\mathrm{T}}}^{e\mu} > 30$ GeV to reduce the contributions from $Z/\gamma^* \to \tau^+\tau^-$ and events in which one of the leptons is nonprompt. The reconstructed transverse mass of the Higgs boson is defined as

$$m_{\mathrm{T}}^{H} = \sqrt{2 p_{\mathrm{T}}^{e\mu} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}, \qquad (5)$$

where $\Delta\phi$ is the difference in azimuthal angle between the dilepton $\vec{p}_{\mathrm{T}}$ and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. To further suppress the DY background, we require $m_{\mathrm{T}}^{H} > 60$ GeV. In order to reduce background from top quark production, the DeepJet b tagging algorithm [64–66] is used on jets of $p_{\mathrm{T}} > 20$ GeV to identify (b tag) those jets, labeled b jets, coming from the hadronization of b quarks. A working point with a misidentification (mistag) rate of 1% and a b jet efficiency of ≈80% versus light-quark-composite jets is selected per year. Events are required to have no b tagged jets.

Events are first categorized based on the number of jets present, using an algorithm that has tight identification and loose pileup mitigation criteria [33], in three different bins: 0, 1, and ≥ 2 jets, where all jets must have $p_{\mathrm{T}} > 30$ GeV to be counted. Events from ggF populate mostly the 0- or 1-jet categories, with the jets coming from QCD radiation, whereas VBF events have at least two high-p_{T} jets at large pseudorapidities.

To better discriminate between signal and background processes and further categorize the events, we used a multiclass fully connected deep neural network (DNN) trained with the Keras library [67] for each of the three jet categories. Four classes are considered in both the 0- and 1-jet categories: off-shell ggF, on-shell ggF, top quark production, and nonresonant WW production, corresponding to the one signal region (SR) and the three largest control regions (CRs), respectively. Six classes are defined for the ≥ 2-jet category: off-shell ggF, off-shell VBF, on-shell ggF, on-shell VBF, top quark production, and nonresonant WW production, corresponding to the two SRs and four CRs.

The DNN inputs and event selection depend on the number of jets in each event. The first-layer DNN variables for the ≥ 2-jet category are defined as follows. For the dileptons, the variables are defined as their invariant mass, the differences in the pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$), ΔR (defined as $\sqrt{\Delta\eta^2 + \Delta\phi^2}$), the total p_{T} of the two leptons, and the p_{T} of the leading and subleading leptons. For dijets, we use the reconstructed transverse mass, $\Delta\eta$, $\Delta\phi$, and the p_{T} and b tagging score of the leading and subleading jets. The $p_{\mathrm{T}}^{\mathrm{miss}}$ and the difference in azimuthal angle $\Delta\phi$ between ${\vec{p}_{\mathrm{T}}}^{e\mu}$ and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ are used as variables to detect the presence of neutrinos in the event. The Higgs boson transverse mass m_{T}^{H} is also included as an input variable. Finally, a proxy invariant mass of the WW system is constructed assuming that the neutrinos from the W boson decays travel in the same direction as their corresponding charged leptons. To compute this variable, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is projected onto the azimuthal direction of each reconstructed lepton. This projected momentum is then added to the transverse momentum of each lepton to form the total transverse momentum of the lepton and neutrino system, whose mass is set to the nominal W boson mass. The final variable is defined as the invariant mass of the sum of these two reconstructed W boson candidates.

The number of nodes in successive layers of the DNN goes from 16 to 60, and then decreases to 30, 15, and 10. This produces the final six event categories: off-shell ggF and VBF, on-shell ggF and VBF, top quark production, and nonresonant WW production. The 0- and 1-jet DNNs are trained separately and are similar to the ≥ 2-jet DNN, with the exception of non-jet or single-jet variables.

The DNN is trained with the Adam optimizer [68], and the output vector is converted into probability distributions via the softmax function, such that the sum of the scores of all classes adds to unity. Events from all MC samples of the processes considered are randomly split such that 50% of the events are used for testing after training, 17.5% for validation during training, and 32.5% for the training itself. To avoid overtraining, an early stopping mechanism is employed that truncates the training if the validation loss submits the same result within 30 epochs. Once trained, a Kolmogorov–Smirnov (KS) [69] test is performed comparing the DNN output distributions for the training and testing datasets. The test determined that no bias was introduced in the training set.

Analysis SRs and CRs are defined by requiring the output DNN score for each training class to be above 0.5. For example, in the off-shell ggF SR category, we demand the corresponding $\mathrm{DNN}_{\text{off-shell}} > 0.5$. The nonresonant WW and $t\bar{t}$ CRs have the same requirement, along with an additional $\mathrm{DNN}_{\mathrm{top}} < 0.2$ or an inverted b quark veto selection, respectively.

V. BACKGROUND ESTIMATION

All background contributions, with the exception of those arising from nonprompt leptons, are estimated using MC simulations.

The nonprompt lepton background is determined directly from data [55] by analyzing events in which the lepton identification criteria are relaxed. Such loosely identified leptons are more likely to originate from jets that have been misclassified as isolated leptons. By evaluating the probability that the leptons selected with these loose criteria pass the SR requirements, together with the efficiency for genuine leptons to be reconstructed and identified, the yield of nonprompt leptons in the SR can be inferred [55]. The reliability of the procedure is verified in a dedicated validation region by requiring a same-sign e-μ pair, while preserving the remaining SR selections.

The overall normalizations of the two main background processes, the nonresonant WW and $t\bar{t}$, are constrained from data simultaneously in the SRs and in the dedicated CRs.

VI. UNCERTAINTIES

All the systematic uncertainties described in Ref. [55] have been considered in this analysis. The experimental systematic uncertainties are estimated from the correlated and uncorrelated integrated luminosity uncertainties; the trigger and lepton isolation and identification efficiencies from the differences between data and MC simulation; the jet energy scale and resolution from variations due to correlated and uncorrelated parameters; the unclustered energy scale; the b tagging selection efficiency using scale factors; the pileup correction; and the MC modeling uncertainties from nonprompt, nonresonant WW, and top quark backgrounds. The nonprompt lepton background is influenced by the jet flavor composition when jets are misidentified as leptons. Such effects contribute an uncertainty of about 5%–10% to the misidentification rate [70]. An additional normalization uncertainty of 30% is assigned to the nonprompt lepton background to cover the maximum discrepancy between data and MC simulation in the same-sign lepton validation region. As a conservative approach, uncertainties equal to the full top quark p_{T} correction for $t\bar{t}$ events and the full p_{T}^{WW} correction for nonresonant WW events are applied.

The theoretical systematic uncertainties arise in the choices of PDFs; renormalization and factorization scales; PS modeling of jet multiplicity; and UE modeling.

Each systematic uncertainty is incorporated into the statistical model using a nuisance parameter, which can either modify the shape or perturb the scale of the DNN output used to derive the final decay width. All of the nuisance parameters are symmetric Gaussian constraints. The contribution of each overall type of uncertainty to the final measurements is given in the summary table of Sec. VIII. The largest systematic uncertainty is from the theoretical components, with the normalization and factorization uncertainties being the most important.

VII. STATISTICAL PROCEDURE

To extract the off-shell signal strength, $\mu_{\text{off-shell}}$, and the Higgs boson total decay width, Γ_H, the CMS statistical analysis tool Combine [71] is used. This framework is based on RooFit [72] and RooStats [73]. Using Combine, we build the likelihood function and perform scans to extract the analysis results. The measurements are made from a profile maximum likelihood fit to different observables depending on the analysis categories: the DNN output distribution is used for the off-shell SRs ($\mathrm{DNN}_{\text{off-shell}}$) and on-shell CRs ($\mathrm{DNN}_{\text{on-shell}}$), while the event yields in the WW and $t\bar{t}$ CRs are accounted for by their normalization factors. In the 0- and 1-jet categories, we include the ggF off-shell SR, ggF on-shell CR, and $t\bar{t}$ CR. The ≥ 2-jet category includes the VBF off-shell SR, VBF on-shell CR, and WW CR, in addition to the other three. Thus, a total of 12 regions are combined per year.

The likelihood fits within Combine take probability density functions as inputs, which are required to be positive-definite. Because the interference contribution can take negative values, the inputs are redefined: signal (S), background (B), and the combined signal + background + interference ($S+B+I$). This ensures positive-definite templates while preserving the correct dependence on the off-shell signal strength. Rewriting the total event yield in terms of the S, B, and I inputs,

$$Y = \sqrt{\mu_{\text{off-shell}}}(S+B+I) + (\mu_{\text{off-shell}} - \sqrt{\mu_{\text{off-shell}}})(S) + (1-\sqrt{\mu_{\text{off-shell}}})(B),$$

where $\mu_{\text{off-shell}}$ is the off-shell signal strength, and each template, e.g., $(S+B+I)$, is its own input. Maximizing the likelihood function then gives us a measurement of $\mu_{\text{off-shell}}$. When extracting the value of Γ_H, a similar procedure is followed. Instead of a direct observation of the width, the ratio of off- and on-shell signal strengths is used:

$$\mathrm{r} = \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}. \tag{6}$$

The ratio r is treated as the parameter of interest, and the yield equation is rewritten using the relationship between r and $\mu_{\text{off-shell}}$, giving

$$Y = \sqrt{\mathrm{r}\mu_{\text{on-shell}}}(S+B+I) + (\mathrm{r}\mu_{\text{on-shell}} - \sqrt{\mathrm{r}\mu_{\text{on-shell}}})(S) + (1-\sqrt{\mathrm{r}\mu_{\text{on-shell}}})(B),$$

where $\mu_{\text{on-shell}}$ is determined from the on-shell CRs. The contamination of on-shell (off-shell) in off-shell (on-shell) regions is negligible, so that we decouple r and $\mu_{\text{on-shell}}$.

The post-fit distributions for the DNN output in the off-shell SR and on-shell CR categories are shown in Figs. 3 and 4, respectively. The binning of the distributions has been optimized to maximize the sensitivity in the last three bins, while avoiding large statistical fluctuations. This is accomplished through fine binning, merging bins from right to left until the relative statistical uncertainty in each of the three highest bins is below 0.1. The chi-square

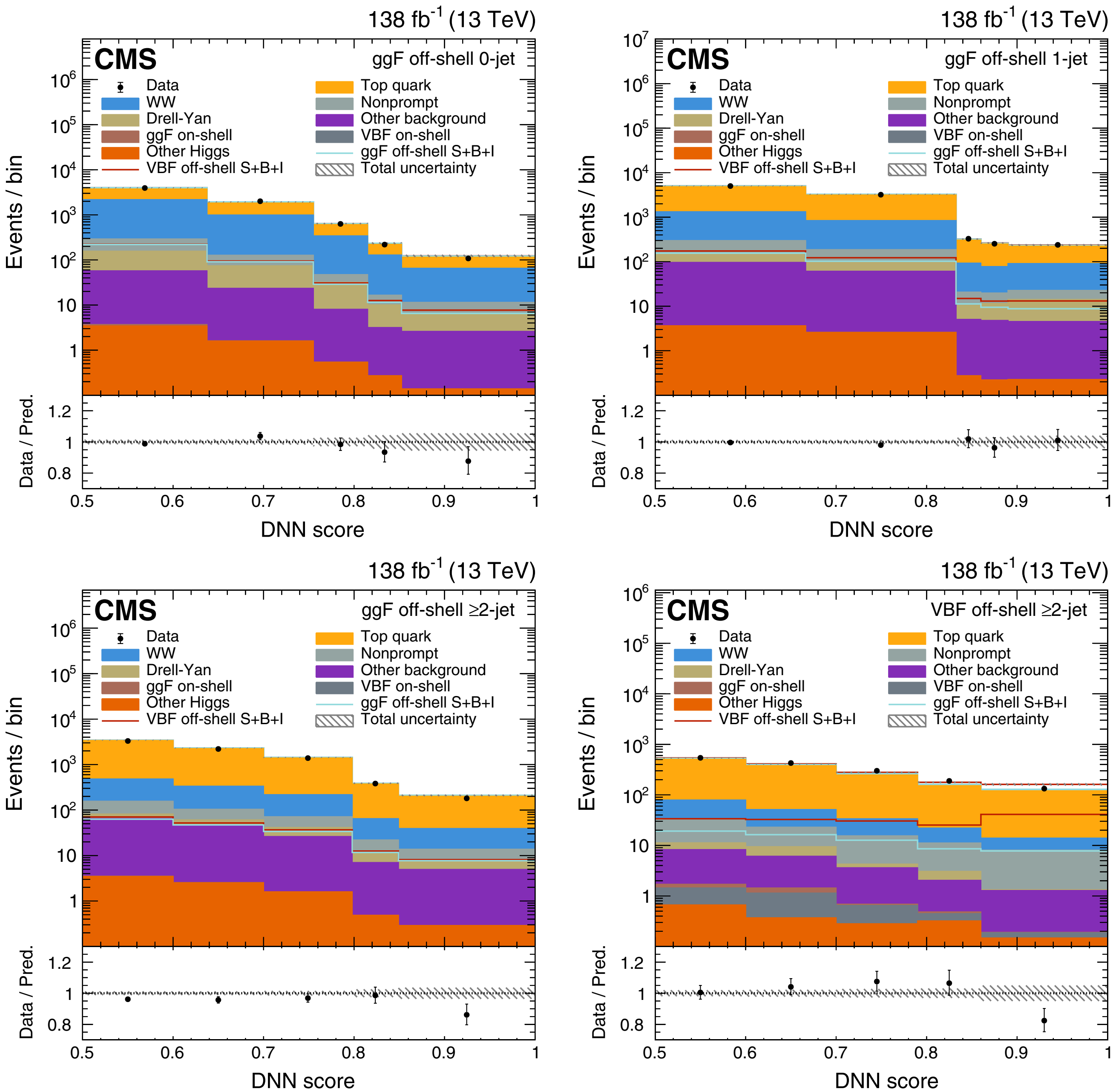

FIG. 3. The off-shell SR post-fit DNN output distributions for the 0-jet (upper left), 1-jet (upper right), and ≥ 2-jet (lower plots) event categories. The data are shown as the black dots, with the vertical bars representing the statistical uncertainties. The predicted signal and background distributions are shown by the various colored histograms. The predicted signal ggF and VBF off-shell $S + B + I$ distributions are displayed both as part of the total stacked histograms, along with all the predicted background distributions, and on top of the stacked background distributions for visibility. The lower portion of the plots gives the ratio of the data to the total predicted yields, including the post-fit signal. The hatched area represents the total uncertainty in the ratio.

goodness-of-fit test with the saturated model [74], used to evaluate how compatible the observed data are with the physics model, returns a p-value [75] of 0.073. This value, while relatively low, indicates that the data are statistically consistent with the model at the 95% CL, and no significant localized tensions are observed.

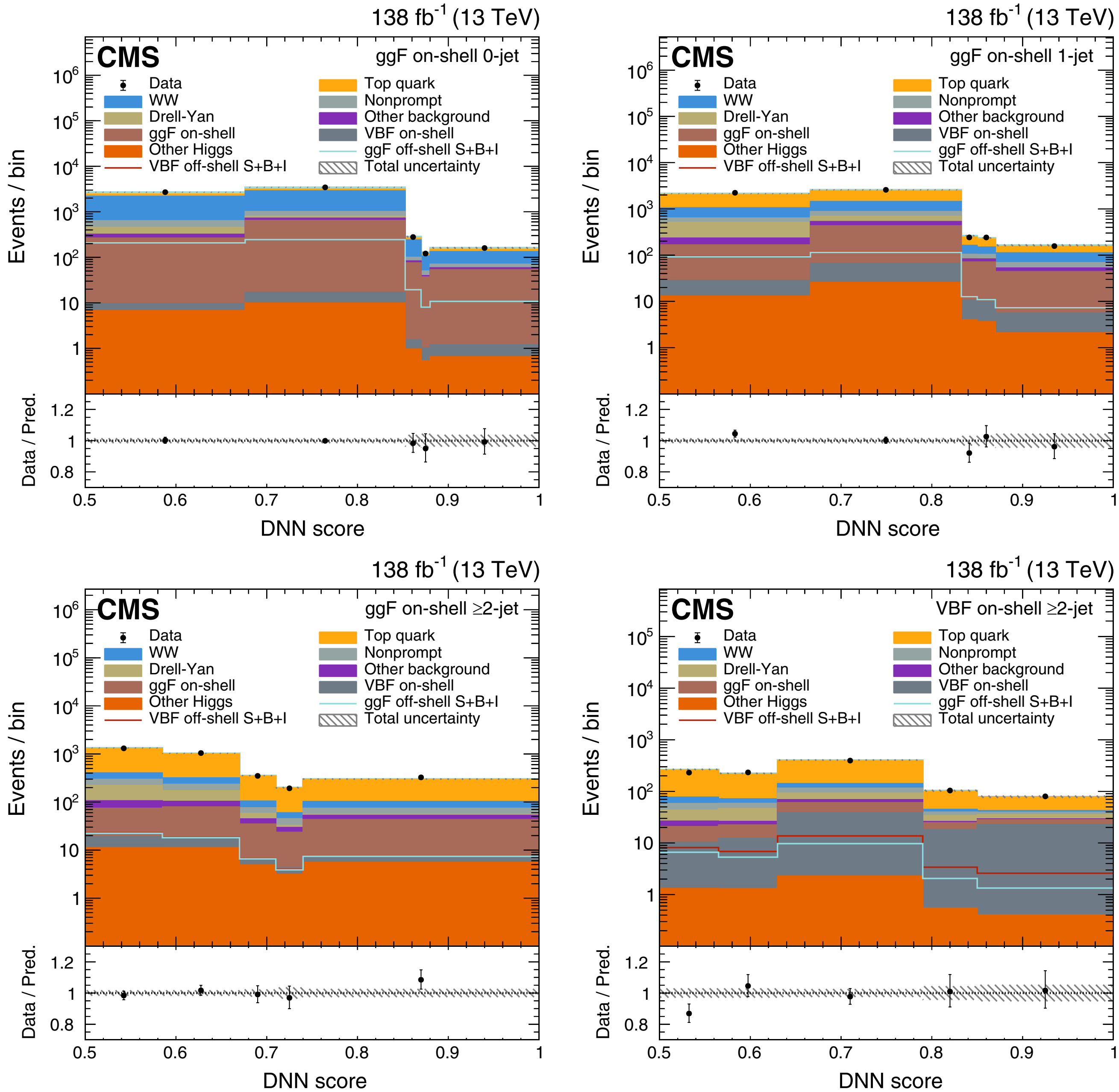

FIG. 4. The on-shell CR post-fit DNN output distributions for the 0-jet (upper left), 1-jet (upper right), and ≥ 2-jet (lower plots) event categories. The data are shown as the black dots, with the vertical bars representing the statistical uncertainties. The predicted signal and background distributions are shown by the various colored histograms. The predicted signal ggF and VBF off-shell $S+B+I$ distributions are displayed both as part of the total stacked histograms, along with all the predicted background distributions, and on top of the stacked background distributions for visibility. The lower portion of the plots gives the ratio of the data to the total predicted yields, including the post-fit signal. The hatched area represents the total uncertainty in the ratio.

VIII. RESULTS

The likelihood scans for the combined off-shell signal strength (left) and the Higgs boson width (right) are shown in Fig. 5.

Table I gives an overview of the analysis results. The derived value of Γ_H is $3.9^{+2.7}_{-2.2}$ MeV, where the uncertainties include both the statistical and systematic components, in agreement with the SM prediction of 4.1 MeV. The best fit value for $\mu_{\text{off-shell}}$ is $1.2^{+0.8}_{-0.7}$. The central value of the $\mu_{\text{off-shell}}$ result is larger than 1 even though the highest bins in both plots of Fig. 3 have a slight deficit below the predicted values. This is because the interference between the off-shell signal and the continuum background is destructive, so a $\mu_{\text{off-shell}}$ value that exceeds unity does not necessarily

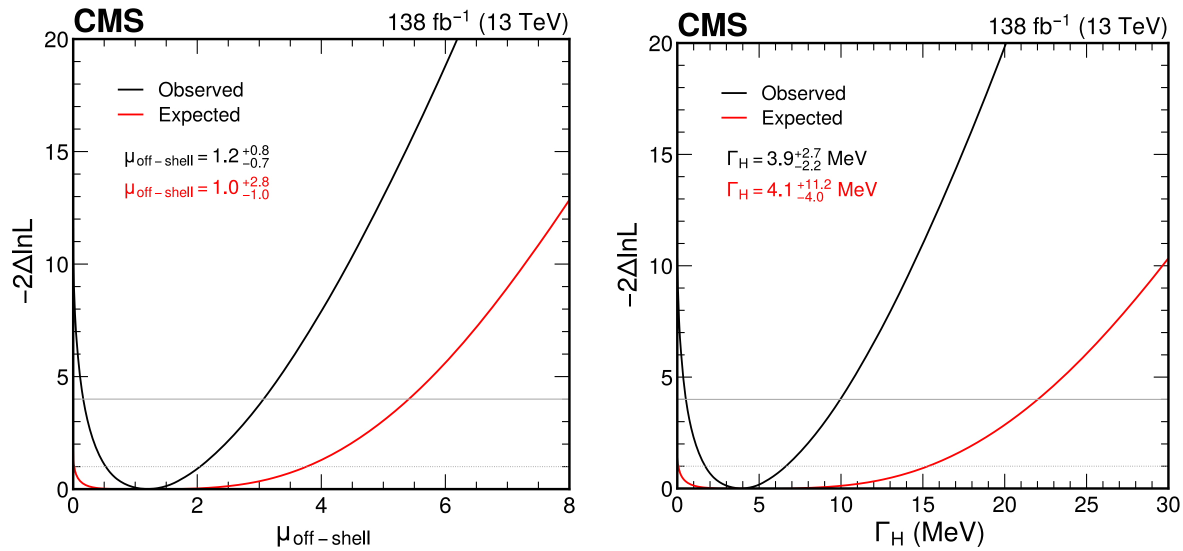

FIG. 5. The observed (black curve) and expected (red curve) likelihood function scans for the off-shell signal strength $\mu_{\text{off-shell}}$ (left) and the Higgs boson decay width Γ_H (right). The resulting best-fit observed and expected values are also given, along with their uncertainties. The 68% and 95% confidence level intervals are shown by the intersection of the likelihood function curves with the dotted and solid horizontal lines, respectively.

TABLE I. Measurements of the ggF and VBF off-shell signal strengths $\mu^{\text{ggF}}_{\text{off-shell}}$ and $\mu^{\text{VBF}}_{\text{off-shell}}$, the overall off-shell signal strength $\mu_{\text{off-shell}}$, the on-shell signal strength $\mu_{\text{on-shell}}$, and the Higgs boson decay width Γ_H. The observed best-fit values are given (Fit), as well as the observed and expected 68% and 95% confidence levels (CLs).

		Observed		Expected	
Parameter	Fit	68% CL	95% CL	68% CL	95% CL
$\mu^{\text{ggF}}_{\text{off-shell}}$	1.19	0.48, 2.15	< 3.40	< 4.31	< 6.21
$\mu^{\text{VBF}}_{\text{off-shell}}$	1.25	0.16, 3.09	< 5.59	< 6.41	< 11.23
$\mu_{\text{off-shell}}$	1.21	0.52, 2.05	0.16, 3.08	0.02, 3.75	< 5.41
$\mu_{\text{on-shell}}$	1.25	1.09, 1.44	0.94, 1.65	0.85, 1.18	0.72, 1.38
Γ_H (MeV)	3.91	1.70, 6.61	0.54, 9.94	0.07, 15.25	< 22.00

imply an excess of signal events. This fact contributes to the observed limits on $\mu_{\text{off-shell}}$ being stronger than the expected limits from the background predictions, as shown in Fig. 5. The deficits in the signal-enriched DNN output bins favor a scenario with more negative signal–background interference.

The statistical and systematic uncertainties in the ratio of the Higgs boson off-shell to on-shell production discussed in Sec. VI are summarized in Table II. It is clear from the table that the total uncertainty in the ratio is dominated by the statistical component. To decompose the total uncertainty in r, nuisance parameters in the model are grouped by categories and likelihood scans are performed by sequentially freezing groups of nuisance parameters and subtracting them in quadrature from the total uncertainty, e.g., the contribution of the statistical uncertainty is obtained by freezing all other nuisance parameters.

The scenario of no off-shell Higgs boson production is excluded at 3.4 standard deviations (1.3 standard deviations expected). This result significantly improves on the previous CMS measurement in the $H \to WW \to 2\ell 2\nu$ channel at $\sqrt{s} = 7$ and 8 TeV of $\Gamma_H < 26$ MeV [17], and is

TABLE II. The sources of systematic uncertainty and their contributions to the total uncertainty in the parameter of interest $r = \mu_{\text{off-shell}}/\mu_{\text{on-shell}}$. The statistical uncertainty is also shown. The values given are the ratios in percent of each uncertainty, divided by the total uncertainty. The last column shows the similar ratios for the uncertainty in $\mu_{\text{off-shell}}$.

Uncertainty	Contribution to r (%)	Contribution to $\mu_{\text{off-shell}}$ (%)
Integrated luminosity	2	3
Theoretical	27	29
Experimental	8	6
Other	4	3
Statistical	56	56

comparable with the CMS $H \to ZZ$ $\sqrt{s} = 13$ TeV measurement of $3.0^{+2.0}_{-1.5}$ MeV [13].

IX. SUMMARY

Measurements of the off- and on-shell signal strengths for the Higgs boson have been performed with the gluon–gluon fusion (ggF) and vector boson fusion (VBF) production modes in the $H \to WW \to e\nu\mu\nu$ decay channel, using proton–proton collision data at $\sqrt{s} = 13$ TeV from the CMS experiment in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. Specific event selection and background discrimination techniques were applied in order to extract the results from maximum likelihood fits to data. The combined off-shell Higgs boson signal strength from ggF and VBF processes is found to be $\mu_{\text{off-shell}} = 1.2^{+0.8}_{-0.7}$, which is used to derive the Higgs boson total decay width of $\Gamma_H = 3.9^{+2.7}_{-2.2}$ MeV, in agreement with the standard model prediction of 4.1 MeV. This measurement represents the first CMS determination of the Higgs boson decay width using the $H \to WW$ channel at $\sqrt{s} = 13$ TeV. This result improves on the analogous CMS analyses at $\sqrt{s} = 7$ and 8 TeV limit by a factor of 3, while complementing the CMS Higgs boson decay width measurement using the $H \to ZZ$ channel at $\sqrt{s} = 13$ 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 and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, CMS detector, and supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, TARISTU24-TK10, and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMFTR, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES, NSC, and NAWA (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI (Thailand); TUBITAK and TENMAK (Türkiye); NASU (Ukraine); STFC (United Kingdom); and 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. 724704, No. 752730, No. 758316, No. 765710, No. 824093, No. 101115353, No. 101002207, and No. 101001205, and COST Action No. CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, Project No. 22rl-037 (Armenia); the Fonds pour la Formation *à la* Recherche dans l'Industrie et dans l'Agriculture (FRIA) and Fonds voor Wetenschappelijk Onderzoek Contract No. 1228724N (Belgium); the Beijing Municipal Science & Technology Commission, No. Z191100007219010, the Fundamental Research Funds for the Central Universities, the Ministry of Science and Technology of China under Grant No. 2023YFA1605804, the Natural Science Foundation of China under Grant No. 12535004, and USTC Research Funds of the Double First-Class Initiative No. YD2030002017 (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, Grant No. FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy—EXC 2121 "Quantum Universe"—390833306, and under Project No. 400140256—GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project No. 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program—ÚNKP, NKFIH Research Grants No. K 131991, No. K 133046, No. K 138136, No. K 143460, No. K 143477, No. K 146913, No. K 146914, No. K 147048, No. 2020-2.2.1-ED-2021-00181, No. TKP2021-NKTA-64, and No. 2025-1.1.5-NEMZ_KI-2025-00004 (Hungary); the Council of Science and Industrial Research, India; ICSC—National Research Center for High Performance Computing, Big Data and Quantum Computing, FAIR—Future Artificial Intelligence Research, and CUP I53D23001070006 (Mission 4 Component 1), funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, Project No. 2022/WK/14, and the National Science Center, Contracts Opus No. 2021/41/B/ST2/01369, No. 2021/43/B/ST2/01552, and No. 2023/49/B/ST2/03273, and the NAWA Contract No. BPN/PPO/2021/1/00011 (Poland); the Fundação para a Ciência e a Tecnologia, Grant No. CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MICIU/AEI/10.13039/501100011033, ERDF/EU, "European Union NextGenerationEU/PRTR", and

Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, the National Science, Research and Innovation Fund Program No. IND_FF_68_369_2300_097, and the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, Grant No. B39G680009 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, Contract No. C-1845; and the Weston Havens Foundation (USA).

DATA AVAILABILITY

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, reuse and open access policy [76].

[1] S. Weinberg, A model of leptons, Phys. Rev. Lett. **19**, 1264 (1967).

[2] S. L. Glashow, Partial-symmetries of weak interactions, Nucl. Phys. **22**, 579 (1961).

[3] A. Salam, Weak and electromagnetic interactions, Conf. Proc. C **680519**, 367 (1968).

[4] P. W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. **12B**, 132 (1964).

[5] P. W. Higgs, Spontaneous symmetry breakdown without massless bosons, Phys. Rev. **145**, 1156 (1966).

[6] F. Englert and R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett. **13**, 321 (1964).

[7] P. W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. **13**, 508 (1964).

[8] 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).

[9] 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).

[10] ATLAS Collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, Nature (London) **607**, 52 (2022); Nature (London) **612**, E24 (2022).

[11] CMS Collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery, Nature (London) **607**, 60 (2022); [Corrigendum: Nature **623**, (2023)], 10.1038/s41586-023-06164-8.

[12] D. de Florian *et al.*, Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, CERN Yellow Rep. Monogr. **2**, 1 (2017).

[13] CMS Collaboration, Measurement of the Higgs boson mass and width using the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D **111**, 092014 (2025).

[14] ATLAS Collaboration, Measurement of off-shell Higgs boson production in the $H^* \to ZZ \to 4\ell$ decay channel using a neural simulation-based inference technique in 13 TeV pp collisions with the ATLAS detector, Rep. Prog. Phys. **88**, 057803 (2025).

[15] ATLAS Collaboration, Constraining off-shell Higgs boson production and the Higgs boson total width using $WW \to \ell\nu\ell\nu$ final states with the ATLAS detector, Phys. Lett. B **870**, 139898 (2025).

[16] ATLAS Collaboration, Constraint on the total width of the Higgs boson from Higgs boson and four-top-quark measurements in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B **861**, 139277 (2025).

[17] CMS Collaboration, Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width, J. High Energy Phys. 09 (2016) 051.

[18] N. Kauer and G. Passarino, Inadequacy of zero-width approximation for a light Higgs boson signal, J. High Energy Phys. 08 (2012) 116.

[19] D. A. Dicus and S. S. D. Willenbrock, Photon pair production and the intermediate mass Higgs boson, Phys. Rev. D **37**, 1801 (1988).

[20] L. J. Dixon and Y. Li, Bounding the Higgs boson width through interferometry, Phys. Rev. Lett. **111**, 111802 (2013).

[21] J. M. Campbell, R. K. Ellis, and C. Williams, Gluon-gluon contributions to W^+W^- production and Higgs interference effects, J. High Energy Phys. 10 (2011) 005.

[22] HEPData record for this analysis (2025), 10.17182/hepdata.165422.

[23] CMS Collaboration, The CMS Experiment at the CERN LHC, J. Instrum. **3**, S08004 (2008).

[24] CMS Collaboration, Development of the CMS detector for the CERN LHC run 3, J. Instrum. **19**, P05064 (2023).

[25] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **15**, P10017 (2020).

[26] CMS Collaboration, The CMS trigger system, J. Instrum. **12**, P01020 (2016).

[27] CMS Collaboration, Performance of the CMS high-level trigger during LHC run 2, J. Instrum. **19**, P11021 (2024).

[28] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. **16**, P05014 (2020).

[29] 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).

[30] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. **9**, P10009 (2014).

[31] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. **12**, P10003 (2017).

[32] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, J. Instrum. **14**, P07004 (2019).
[33] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, CMS Detector Performance Summary, Report No. CMS-JME-18-001, 2020.
[34] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_T jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.
[35] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, Eur. Phys. J. C **72**, 1896 (2012).
[36] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. **12**, P02014 (2016).
[37] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, Eur. Phys. J. C **81**, 800 (2021).
[38] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-17-004, 2018, https://cds.cern.ch/record/2621960.
[39] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-18-002, 2019, https://cds.cern.ch/record/2676164.
[40] CMS Collaboration, Methods for off-shell Higgs boson production simulation used in CMS analyses, CMS Physics Analysis Summary, Report No. CMS-NOTE-2022-010, 2022, https://cds.cern.ch/record/2826782.
[41] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040.
[42] 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.
[43] 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.
[44] S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, M. Schulze, N. V. Tran, and A. Whitbeck, Spin and parity of a single-produced resonance at the LHC, Phys. Rev. D **86**, 095031 (2012).
[45] S. Goria, G. Passarino, and D. Rosco, The Higgs boson lineshape, Nucl. Phys. **B864**, 530 (2012).
[46] A. V. Gritsan, R. Röntsch, M. Schulze, and M. Xiao, Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques, Phys. Rev. D **94**, 055023 (2016).
[47] A. V. Gritsan, J. Roskes, U. Sarica, M. Schulze, M. Xiao, and Y. Zhou, New features in the JHU generator framework: Constraining Higgs boson properties from on-shell and off-shell production, Phys. Rev. D **102**, 056022 (2020).
[48] J. M. Campbell and R. K. Ellis, An update on vector boson pair production at hadron colliders, Phys. Rev. D **60**, 113006 (1999).
[49] J. M. Campbell, R. K. Ellis, and C. Williams, Vector boson pair production at the LHC, J. High Energy Phys. 07 (2011) 018.
[50] J. M. Campbell, R. K. Ellis, and W. T. Giele, A multi-threaded version of MCFM, Eur. Phys. J. C **75**, 246 (2015).
[51] CMS Collaboration, Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production, Nat. Phys. **18**, 1329 (2022).
[52] C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog, A. Lazopoulos, and B. Mistlberger, High precision determination of the gluon fusion Higgs boson cross-section at the LHC, J. High Energy Phys. 05 (2016) 058.
[53] K. Hamilton, P. Nason, E. Re, and G. Zanderighi, NNLOPS simulation of Higgs boson production, J. High Energy Phys. 10 (2013) 222.
[54] K. Hamilton, P. Nason, and G. Zanderighi, Finite quark-mass effects in the NNLOPS POWHEG + MiNLO Higgs generator, J. High Energy Phys. 05 (2015) 140.
[55] CMS Collaboration, Measurements of the Higgs boson production cross section and couplings in the W boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C **83**, 667 (2023).
[56] 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.
[57] CMS Collaboration, Review of top quark mass measurements in CMS, Phys. Rep. **1115**, 116 (2025).
[58] M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos, and M. Zaro, Top-pair production at the LHC through NNLO QCD and NLO EW, J. High Energy Phys. 10 (2017) 186.
[59] 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 Pythia 8.2, Comput. Phys. Commun. **191**, 159 (2015).
[60] CMS Collaboration, Extraction and validation of a new set of CMS Pythia8 tunes from underlying-event measurements, Eur. Phys. J. C **80**, 4 (2020).
[61] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions from high-precision collider data, Eur. Phys. J. C **77**, 663 (2017).
[62] S. Agostinelli *et al.* (Geant4 Collaboration), Geant4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[63] CMS Collaboration, Evidence for associated production of a Higgs boson with a top quark pair in final states with electrons, muons, and hadronically decaying τ leptons at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 08 (2018) 066.
[64] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, J. Instrum. **13**, P05011 (2017).
[65] E. Bols, J. Kieseler, M. Verzetti, M. Stoye, and A. Stakia, Jet flavour classification using DeepJet, J. Instrum. **15**, P12012 (2020).
[66] CMS Collaboration, Performance summary of AK4 jet b tagging with data from proton-proton collisions at 13 TeV with the CMS detector, CMS Detector Performance Summary, Report No. CMS-DP-2023-005, 2023.
[67] F. Chollet, *Deep Learning with Python*, 2nd ed. (Manning Publications Co., Shelter Island, NY, 2021).

[68] D. P. Kingma and J. Ba, Adam: A method for stochastic optimization, in Proceedings of the 3rd International Conference on Learning Representations (ICLR, San Diego, CA, USA, 2015), arXiv:1412.6980.
[69] W. J. Conover, *Practical Nonparametric Statistics*, 3rd ed. (Wiley, New York, 1999).
[70] CMS Collaboration, Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B **791**, 96 (2019).
[71] A. Hayrapetyan *et al.*, The CMS statistical analysis and combination tool: Combine, Comput. Software. Big Sci. **8**, 18 (2024).
[72] W. Verkerke and D. Kirkby, The RooFit toolkit for data modeling, eConf C **0303241**, MOLT007 (2003).
[73] L. Moneta, K. Belasco, K. S. Cranmer, S. Kreiss, A. Lazzaro, D. Piparo, G. Schott, W. Verkerke, and M. Wolf, The RooStats project, in *Proceedings of the 13th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT 2010)* (IOP Publishing, Bristol, UK, 2010), 10.22323/1.093.0057.
[74] R. D. Cousins, Lectures on statistics in theory: Prelude to statistics in practice, arXiv:1807.05996.
[75] E. Gross and O. Vitells, Trial factors for the look elsewhere effect in high energy physics, Eur. Phys. J. C **70**, 525 (2010).
[76] CMS data availability statement, 10.7483/OPENDATA.CMS.1BNU.8V1W.

A. Hayrapetyan,[1] V. Makarenko,[1] A. Tumasyan,[1,b] W. Adam,[2] L. Benato,[2] T. Bergauer,[2] M. Dragicevic,[2] P. S. Hussain,[2] M. Jeitler,[2,c] N. Krammer,[2] A. Li,[2] D. Liko,[2] M. Matthewman,[2] J. Schieck,[2,c] R. Schöfbeck,[2,c] M. Shooshtari,[2] M. Sonawane,[2] W. Waltenberger,[2] C.-E. Wulz,[2,c] T. Janssen,[3] H. Kwon,[3] D. Ocampo Henao,[3] T. Van Laer,[3] P. Van Mechelen,[3] J. Bierkens,[4] N. Breugelmans,[4] J. D'Hondt,[4] S. Dansana,[4] A. De Moor,[4] M. Delcourt,[4] F. Heyen,[4] Y. Hong,[4] P. Kashko,[4] S. Lowette,[4] I. Makarenko,[4] D. Müller,[4] S. Tavernier,[4] M. Tytgat,[4,d] G. P. Van Onsem,[4] S. Van Putte,[4] D. Vannerom,[4] B. Bilin,[5] B. Clerbaux,[5] A. K. Das,[5] I. De Bruyn,[5] G. De Lentdecker,[5] H. Evard,[5] L. Favart,[5] P. Gianneios,[5] A. Khalilzadeh,[5] F. A. Khan,[5] A. Malara,[5] M. A. Shahzad,[5] A. Sharma,[5] L. Thomas,[5] M. Vanden Bemden,[5] C. Vander Velde,[5] P. Vanlaer,[5] F. Zhang,[5] M. De Coen,[6] D. Dobur,[6] C. Giordano,[6] G. Gokbulut,[6] K. Kaspar,[6] D. Kavtaradze,[6] D. Marckx,[6] K. Skovpen,[6] A. M. Tomaru,[6] N. Van Den Bossche,[6] J. van der Linden,[6] J. Vandenbroeck,[6] H. Aarup Petersen,[7] S. Bein,[7] A. Benecke,[7] A. Bethani,[7] G. Bruno,[7] A. Cappati,[7] J. De Favereau De Jeneret,[7] C. Delaere,[7] F. Gameiro Casalinho,[7] A. Giammanco,[7] A. O. Guzel,[7] V. Lemaitre,[7] J. Lidrych,[7] P. Malek,[7] P. Mastrapasqua,[7] S. Turkcapar,[7] G. A. Alves,[8] M. Barroso Ferreira Filho,[8] E. Coelho,[8] C. Hensel,[8] D. Matos Figueiredo,[8] T. Menezes De Oliveira,[8] C. Mora Herrera,[8] P. Rebello Teles,[8] M. Soeiro,[8] E. J. Tonelli Manganote,[8,e] A. Vilela Pereira,[8] W. L. Aldá Júnior,[9] H. Brandao Malbouisson,[9] W. Carvalho,[9] J. Chinellato,[9,f] M. Costa Reis,[9] E. M. Da Costa,[9] G. G. Da Silveira,[9,g] D. De Jesus Damiao,[9] S. Fonseca De Souza,[9] R. Gomes De Souza,[9] S. S. Jesus,[9] T. Laux Kuhn,[9,g] M. Macedo,[9] K. Mota Amarilo,[9] L. Mundim,[9] H. Nogima,[9] J. P. Pinheiro,[9] A. Santoro,[9] A. Sznajder,[9] M. Thiel,[9] F. Torres Da Silva De Araujo,[9,h] C. A. Bernardes,[10] L. Calligaris,[10] F. Damas,[10] T. R. Fernandez Perez Tomei,[10] E. M. Gregores,[10] B. Lopes Da Costa,[10] I. Maietto Silverio,[10] P. G. Mercadante,[10] S. F. Novaes,[10] Sandra S. Padula,[10] V. Scheurer,[10] A. Aleksandrov,[11] G. Antchev,[11] P. Danev,[11] R. Hadjiiska,[11] P. Iaydjiev,[11] M. Shopova,[11] G. Sultanov,[11] A. Dimitrov,[12] L. Litov,[12] B. Pavlov,[12] P. Petkov,[12] A. Petrov,[12] S. Keshri,[13] D. Laroze,[13] S. Thakur,[13] W. Brooks,[14] T. Cheng,[15] T. Javaid,[15] L. Wang,[15] L. Yuan,[15] Z. Hu,[16] Z. Liang,[16] J. Liu,[16] X. Wang,[16] H. Yang,[16] G. M. Chen,[17,i] H. S. Chen,[17,i] M. Chen,[17,i] Y. Chen,[17] Q. Hou,[17] X. Hou,[17] F. Iemmi,[17] C. H. Jiang,[17] H. Liao,[17] G. Liu,[17] Z.-A. Liu,[17,i] J. N. Song,[17,i] S. Song,[17] J. Tao,[17] C. Wang,[17,i] J. Wang,[17] H. Zhang,[17] J. Zhao,[17] A. Agapitos,[18] Y. Ban,[18] A. Carvalho Antunes De Oliveira,[18] S. Deng,[18] B. Guo,[18] Q. Guo,[18] C. Jiang,[18] A. Levin,[18] C. Li,[18] Q. Li,[18] Y. Mao,[18] S. Qian,[18] S. J. Qian,[18] X. Qin,[18] C. Quaranta,[18] X. Sun,[18] D. Wang,[18] J. Wang,[18] M. Zhang,[18] Y. Zhao,[18] C. Zhou,[18] S. Yang,[19] Z. You,[20] N. Lu,[21] G. Bauer,[22,j,k] Z. Cui,[22,k] B. Li,[22,l] H. Wang,[22] K. Yi,[22,m] J. Zhang,[22] Y. Li,[23] Y. Zhou,[23,n] Z. Lin,[24] C. Lu,[24] M. Xiao,[24,o] C. Avila,[25] D. A. Barbosa Trujillo,[25] A. Cabrera,[25] C. Florez,[25] J. Fraga,[25] J. A. Reyes Vega,[25] C. Rendón,[26] M. Rodriguez,[26] A. A. Ruales Barbosa,[26] J. D. Ruiz Alvarez,[26] N. Godinovic,[27] D. Lelas,[27] A. Sculac,[27] M. Kovac,[28] A. Petkovic,[28] T. Sculac,[28] P. Bargassa,[29] V. Brigljevic,[29] B. K. Chitroda,[29] D. Ferencek,[29] K. Jakovcic,[29] A. Starodumov,[29] T. Susa,[29] A. Attikis,[30] K. Christoforou,[30] S. Konstantinou,[30] C. Leonidou,[30] L. Paizanos,[30] F. Ptochos,[30] P. A. Razis,[30] H. Rykaczewski,[30] H. Saka,[30] A. Stepennov,[30] M. Finger,[31,a] M. Finger Jr.,[31] E. Ayala,[32] E. Carrera Jarrin,[33]

A. A. Abdelalim,[34,p,q] B. El-mahdy,[34,r] A. Hussein,[35] H. Mohammed,[35] K. Jaffel,[36] M. Kadastik,[36] T. Lange,[36] C. Nielsen,[36] J. Pata,[36] M. Raidal,[36] N. Seeba,[36] L. Tani,[36] E. Brücken,[37] A. Milieva,[37] K. Osterberg,[37] M. Voutilainen,[37] F. Garcia,[38] P. Inkaew,[38] K. T. S. Kallonen,[38] R. Kumar Verma,[38] T. Lampén,[38] K. Lassila-Perini,[38] B. Lehtela,[38] S. Lehti,[38] T. Lindén,[38] N. R. Mancilla Xinto,[38] M. Myllymäki,[38] M. m. Rantanen,[38] S. Saariokari,[38] N. T. Toikka,[38] J. Tuominiemi,[38] N. Bin Norjoharuddeen,[39] H. Kirschenmann,[39] P. Luukka,[39] H. Petrow,[39] M. Besancon,[40] F. Couderc,[40] M. Dejardin,[40] D. Denegri,[40] P. Devouge,[40] J. L. Faure,[40] F. Ferri,[40] P. Gaigne,[40] S. Ganjour,[40] P. Gras,[40] F. Guilloux,[40] G. Hamel de Monchenault,[40] M. Kumar,[40] V. Lohezic,[40] Y. Maidannyk,[40] J. Malcles,[40] F. Orlandi,[40] L. Portales,[40] S. Ronchi,[40] M. Ö. Sahin,[40] A. Savoy-Navarro,[40,s] P. Simkina,[40] M. Titov,[40] M. Tornago,[40] R. Amella Ranz,[41] F. Beaudette,[41] G. Boldrini,[41] P. Busson,[41] C. Charlot,[41] M. Chiusi,[41] T. D. Cuisset,[41] O. Davignon,[41] A. De Wit,[41] T. Debnath,[41] I. T. Ehle,[41] S. Ghosh,[41] A. Gilbert,[41] R. Granier de Cassagnac,[41] L. Kalipoliti,[41] M. Manoni,[41] M. Nguyen,[41] S. Obraztsov,[41] C. Ochando,[41] R. Salerno,[41] J. B. Sauvan,[41] Y. Sirois,[41] G. Sokmen,[41] Y. Song,[41] L. Urda Gómez,[41] A. Zabi,[41] A. Zghiche,[41] J.-L. Agram,[42,t] J. Andrea,[42] D. Bloch,[42] J.-M. Brom,[42] E. C. Chabert,[42] C. Collard,[42] G. Coulon,[42] S. Falke,[42] U. Goerlach,[42] R. Haeberle,[42] A.-C. Le Bihan,[42] M. Meena,[42] O. Poncet,[42] G. Saha,[42] P. Vaucelle,[42] A. Di Florio,[43] B. Orzari,[43] D. Amram,[44] S. Beauceron,[44] B. Blancon,[44] G. Boudoul,[44] N. Chanon,[44] D. Contardo,[44] P. Depasse,[44] H. El Mamouni,[44] J. Fay,[44] E. Fillaudeau,[44] S. Gascon,[44] M. Gouzevitch,[44] C. Greenberg,[44] G. Grenier,[44] B. Ille,[44] E. Jourd'Huy,[44] M. Lethuillier,[44] B. Massoteau,[44] L. Mirabito,[44] A. Purohit,[44] M. Vander Donckt,[44] J. Xiao,[44] G. Adamov,[45] I. Lomidze,[45] Z. Tsamalaidze,[45,u] V. Botta,[46] S. Consuegra Rodríguez,[46] L. Feld,[46] K. Klein,[46] M. Lipinski,[46] P. Nattland,[46] V. Oppenländer,[46] A. Pauls,[46] D. Pérez Adán,[46] N. Röwert,[46] C. Daumann,[47] S. Diekmann,[47] N. Eich,[47] D. Eliseev,[47] F. Engelke,[47] J. Erdmann,[47] M. Erdmann,[47] B. Fischer,[47] T. Hebbeker,[47] K. Hoepfner,[47] F. Ivone,[47] A. Jung,[47] N. Kumar,[47] M. y. Lee,[47] F. Mausolf,[47] M. Merschmeyer,[47] A. Meyer,[47] A. Pozdnyakov,[47] W. Redjeb,[47] H. Reithler,[47] U. Sarkar,[47] V. Sarkisovi,[47] A. Schmidt,[47] C. Seth,[47] A. Sharma,[47] J. L. Spah,[47] V. Vaulin,[47] S. Zaleski,[47] M. R. Beckers,[48] C. Dziwok,[48] G. Flügge,[48] N. Hoeflich,[48] T. Kress,[48] A. Nowack,[48] O. Pooth,[48] A. Stahl,[48] A. Zotz,[48] A. Abel,[49] M. Aldaya Martin,[49] J. Alimena,[49] S. Amoroso,[49] Y. An,[49] I. Andreev,[49] J. Bach,[49] S. Baxter,[49] H. Becerril Gonzalez,[49] O. Behnke,[49] A. Belvedere,[49] F. Blekman,[49,v] K. Borras,[49,w] A. Campbell,[49] S. Chatterjee,[49] L. X. Coll Saravia,[49] G. Eckerlin,[49] D. Eckstein,[49] E. Gallo,[49,v] A. Geiser,[49] M. Guthoff,[49] A. Hinzmann,[49] L. Jeppe,[49] M. Kasemann,[49] C. Kleinwort,[49] R. Kogler,[49] M. Komm,[49] D. Krücker,[49] W. Lange,[49] D. Leyva Pernia,[49] K.-Y. Lin,[49] K. Lipka,[49,x] W. Lohmann,[49,y] J. Malvaso,[49] R. Mankel,[49] I.-A. Melzer-Pellmann,[49] M. Mendizabal Morentin,[49] A. B. Meyer,[49] G. Milella,[49] K. Moral Figueroa,[49] A. Mussgiller,[49] L. P. Nair,[49] J. Niedziela,[49] A. Nürnberg,[49] J. Park,[49] E. Ranken,[49] A. Raspereza,[49] D. Rastorguev,[49] L. Rygaard,[49] M. Scham,[49,z,w] S. Schnake,[49,w] P. Schütze,[49] C. Schwanenberger,[49,v] D. Schwarz,[49] D. Selivanova,[49] K. Sharko,[49] M. Shchedrolosiev,[49] D. Stafford,[49] M. Torkian,[49] A. Ventura Barroso,[49] R. Walsh,[49] D. Wang,[49] Q. Wang,[49] K. Wichmann,[49] L. Wiens,[49,w] C. Wissing,[49] Y. Yang,[49] S. Zakharov,[49] A. Zimermmane Castro Santos,[49] A. R. Alves Andrade,[50] M. Antonello,[50] S. Bollweg,[50] M. Bonanomi,[50] L. Ebeling,[50] K. El Morabit,[50] Y. Fischer,[50] M. Frahm,[50] E. Garutti,[50] A. Grohsjean,[50] A. A. Guvenli,[50] J. Haller,[50] D. Hundhausen,[50] G. Kasieczka,[50] P. Keicher,[50] R. Klanner,[50] W. Korcari,[50] T. Kramer,[50] C. c. Kuo,[50] F. Labe,[50] J. Lange,[50] A. Lobanov,[50] J. Matthiesen,[50] L. Moureaux,[50] K. Nikolopoulos,[50] A. Paasch,[50] K. J. Pena Rodriguez,[50] N. Prouvost,[50] B. Raciti,[50] M. Rieger,[50] D. Savoiu,[50] P. Schleper,[50] M. Schröder,[50] J. Schwandt,[50] M. Sommerhalder,[50] H. Stadie,[50] G. Steinbrück,[50] R. Ward,[50] B. Wiederspan,[50] M. Wolf,[50] C. Yede,[50] S. Brommer,[51] A. Brusamolino,[51] E. Butz,[51] Y. M. Chen,[51] T. Chwalek,[51] A. Dierlamm,[51] G. G. Dincer,[51] D. Druzhkin,[51] U. Elicabuk,[51] N. Faltermann,[51] M. Giffels,[51] A. Gottmann,[51] F. Hartmann,[51,aa] M. Horzela,[51] F. Hummer,[51] U. Husemann,[51] J. Kieseler,[51] M. Klute,[51] J. Knolle,[51] R. Kunnilan Muhammed Rafeek,[51] O. Lavoryk,[51] J. M. Lawhorn,[51] S. Maier,[51] A. A. Monsch,[51] M. Mormile,[51] Th. Müller,[51] E. Pfeffer,[51] M. Presilla,[51] G. Quast,[51] K. Rabbertz,[51] B. Regnery,[51] R. Schmieder,[51] N. Shadskiy,[51] I. Shvetsov,[51] H. J. Simonis,[51] L. Sowa,[51] L. Stockmeier,[51] K. Tauqeer,[51] M. Toms,[51] B. Topko,[51] N. Trevisani,[51] C. Verstege,[51] T. Voigtländer,[51] R. F. Von Cube,[51] J. Von Den Driesch,[51] C. Winter,[51] R. Wolf,[51] W. D. Zeuner,[51] X. Zuo,[51] G. Anagnostou,[52] G. Daskalakis,[52] A. Kyriakis,[52] G. Melachroinos,[53] Z. Painesis,[53] I. Paraskevas,[53] N. Saoulidou,[53] K. Theofilatos,[53] E. Tziaferi,[53] E. Tzovara,[53]

K. Vellidis,[53] I. Zisopoulos,[53] T. Chatzistavrou,[54] G. Karapostoli,[54] K. Kousouris,[54] E. Siamarkou,[54] G. Tsipolitis,[54] I. Bestintzanos,[55] I. Evangelou,[55] C. Foudas,[55] P. Katsoulis,[55] P. Kokkas,[55] P. G. Kosmoglou Kioseoglou,[55] N. Manthos,[55] I. Papadopoulos,[55] J. Strologas,[55] C. Hajdu,[56] D. Horvath,[56,bb,cc] Á. Kadlecsik,[56] K. Márton,[56] A. J. Rádl,[56,dd] F. Sikler,[56] V. Veszpremi,[56] M. Csanád,[57] K. Farkas,[57] A. Fehérkuti,[57,ee] M. M. A. Gadallah,[57,ff] M. León Coello,[57] G. Pásztor,[57] G. I. Veres,[57] B. Ujvari,[58] G. Zilizi,[58] G. Bencze,[59] S. Czellar,[59] J. Molnar,[59] Z. Szillasi,[59] T. Csorgo,[60,ee] F. Nemes,[60,ee] T. Novak,[60] I. Szanyi,[60,gg] S. Bahinipati,[61] S. Nayak,[61] R. Raturi,[61] S. Bansal,[62] S. B. Beri,[62] V. Bhatnagar,[62] S. Chauhan,[62] N. Dhingra,[62,hh] A. Kaur,[62] H. Kaur,[62] M. Kaur,[62] S. Kumar,[62] T. Sheokand,[62] J. B. Singh,[62] A. Singla,[62] A. Bhardwaj,[63] A. Chhetri,[63] B. C. Choudhary,[63] A. Kumar,[63] A. Kumar,[63] M. Naimuddin,[63] S. Phor,[63] K. Ranjan,[63] M. K. Saini,[63] P. Palni,[64] S. Acharya,[65,ii] B. Gomber,[65] S. Mukherjee,[66] S. Bhattacharya,[67] S. Das Gupta,[67] S. Dutta,[67] S. Dutta,[67] S. Sarkar,[67] M. M. Ameen,[68] P. K. Behera,[68] S. Chatterjee,[68] G. Dash,[68] A. Dattamunsi,[68] P. Jana,[68] P. Kalbhor,[68] S. Kamble,[68] J. R. Komaragiri,[68,jj] T. Mishra,[68] P. R. Pujahari,[68] A. K. Sikdar,[68] R. K. Singh,[68] P. Verma,[68] S. Verma,[68] A. Vijay,[68] B. K. Sirasva,[69] L. Bhatt,[70] S. Dugad,[70] G. B. Mohanty,[70] M. Shelake,[70] P. Suryadevara,[70] A. Bala,[71] S. Banerjee,[71] S. Barman,[71,kk] R. M. Chatterjee,[71] M. Guchait,[71] Sh. Jain,[71] A. Jaiswal,[71] S. Kumar,[71] M. Maity,[71,kk] G. Majumder,[71] K. Mazumdar,[71] S. Parolia,[71] R. Saxena,[71] A. Thachayath,[71] D. Maity,[72,ll] P. Mal,[72] K. Naskar,[72,ll] A. Nayak,[72,ll] K. Pal,[72] P. Sadangi,[72] S. K. Swain,[72] S. Varghese,[72,ll] D. Vats,[72,ll] S. Dube,[73] P. Hazarika,[73] B. Kansal,[73] A. Laha,[73] R. Sharma,[73] S. Sharma,[73] K. Y. Vaish,[73] S. Ghosh,[74] H. Bakhshiansohi,[75,mm] A. Jafari,[75,nn] V. Sedighzadeh Dalavi,[75] M. Zeinali,[75,oo] S. Bashiri,[76] S. Chenarani,[76,pp] S. M. Etesami,[76] Y. Hosseini,[76] M. Khakzad,[76] E. Khazaie,[76] M. Mohammadi Najafabadi,[76] S. Tizchang,[76,qq] M. Felcini,[77] M. Grunewald,[77] M. Abbrescia,[78a,78b] M. Barbieri,[78a,78b] M. Buonsante,[78a,78b] A. Colaleo,[78a,78b] D. Creanza,[78a,78c] N. De Filippis,[78a,78c] M. De Palma,[78a,78b] W. Elmetenawee,[78a,78b,p] N. Ferrara,[78a,78c] L. Fiore,[78a] L. Generoso,[78a,78b] L. Longo,[78a] M. Louka,[78a,78b] G. Maggi,[78a,78c] M. Maggi,[78a] I. Margjeka,[78a] V. Mastrapasqua,[78a,78b] S. My,[78a,78b] F. Nenna,[78a,78b] S. Nuzzo,[78a,78b] A. Pellecchia,[78a,78b] A. Pompili,[78a,78b] G. Pugliese,[78a,78c] R. Radogna,[78a,78b] D. Ramos,[78a] A. Ranieri,[78a] L. Silvestris,[78a] F. M. Simone,[78a,78c] Ü. Sözbilir,[78a] A. Stamerra,[78a,78b] D. Troiano,[78a,78b] R. Venditti,[78a,78b] P. Verwilligen,[78a] A. Zaza,[78a,78b] G. Abbiendi,[79a] C. Battilana,[79a,79b] D. Bonacorsi,[79a,79b] P. Capiluppi,[79a,79b] F. R. Cavallo,[79a] G. M. Dallavalle,[79a] T. Diotalevi,[79a,79b] F. Fabbri,[79a] A. Fanfani,[79a,79b] R. Farinelli,[79a] D. Fasanella,[79a] P. Giacomelli,[79a] C. Grandi,[79a] L. Guiducci,[79a,79b] S. Lo Meo,[79a,rr] M. Lorusso,[79a,79b] L. Lunerti,[79a] G. Masetti,[79a] F. L. Navarria,[79a,79b] G. Paggi,[79a,79b] A. Perrotta,[79a] A. M. Rossi,[79a,79b] S. Rossi Tisbeni,[79a,79b] T. Rovelli,[79a,79b] G. P. Siroli,[79a,79b] S. Costa,[80a,80b,ss] A. Di Mattia,[80a] A. Lapertosa,[80a] R. Potenza,[80a,80b] A. Tricomi,[80a,80b,ss] J. Altork,[81a,81b] P. Assiouras,[81a] G. Barbagli,[81a] G. Bardelli,[81a] M. Bartolini,[81a,81b] A. Calandri,[81a,81b] B. Camaiani,[81a,81b] A. Cassese,[81a] R. Ceccarelli,[81a] V. Ciulli,[81a,81b] C. Civinini,[81a] R. D'Alessandro,[81a,81b] L. Damenti,[81a,81b] E. Focardi,[81a,81b] T. Kello,[81a] G. Latino,[81a,81b] P. Lenzi,[81a,81b] M. Lizzo,[81a] M. Meschini,[81a] S. Paoletti,[81a] A. Papanastassiou,[81a,81b] G. Sguazzoni,[81a] L. Viliani,[81a] L. Benussi,[82] S. Bianco,[82] S. Meola,[82,tt] D. Piccolo,[82] M. Alves Gallo Pereira,[83a] F. Ferro,[83a] E. Robutti,[83a] S. Tosi,[83a,83b] A. Benaglia,[84a] F. Brivio,[84a] V. Camagni,[84a,84b] F. Cetorelli,[84a,84b] F. De Guio,[84a,84b] M. E. Dinardo,[84a,84b] P. Dini,[84a] S. Gennai,[84a] R. Gerosa,[84a,84b] A. Ghezzi,[84a,84b] P. Govoni,[84a,84b] L. Guzzi,[84a] M. R. Kim,[84a] G. Lavizzari,[84a,84b] M. T. Lucchini,[84a,84b] M. Malberti,[84a] S. Malvezzi,[84a] A. Massironi,[84a] D. Menasce,[84a] L. Moroni,[84a] M. Paganoni,[84a,84b] S. Palluotto,[84a,84b] D. Pedrini,[84a] A. Perego,[84a,84b] G. Pizzati,[84a,84b] T. Tabarelli de Fatis,[84a,84b] S. Buontempo,[85a] C. Di Fraia,[85a,85b] F. Fabozzi,[85a,85c] L. Favilla,[85a,85d] A. O. M. Iorio,[85a,85b] L. Lista,[85a,85b,uu] P. Paolucci,[85a,aa] B. Rossi,[85a] P. Azzi,[86a] N. Bacchetta,[86a,vv] M. Biasotto,[86a,ww] D. Bisello,[86a,86b] L. Borella,[86a] P. Bortignon,[86a,86c] G. Bortolato,[86a,86b] A. C. M. Bulla,[86a,86c] R. Carlin,[86a,86b] P. Checchia,[86a] T. Dorigo,[86a,xx] F. Gasparini,[86a,86b] U. Gasparini,[86a,86b] S. Giorgetti,[86a] E. Lusiani,[86a] M. Margoni,[86a,86b] A. T. Meneguzzo,[86a,86b] J. Pazzini,[86a,86b] F. Primavera,[86a,86b] P. Ronchese,[86a,86b] R. Rossin,[86a,86b] F. Simonetto,[86a,86b] M. Tosi,[86a,86b] A. Triossi,[86a,86b] M. Zanetti,[86a,86b] P. Zotto,[86a,86b] A. Zucchetta,[86a,86b] A. Braghieri,[87a] M. Brunoldi,[87a,87b] S. Calzaferri,[87a,87b] P. Montagna,[87a,87b] M. Pelliccioni,[87a,87b] V. Re,[87a] C. Riccardi,[87a,87b] P. Salvini,[87a] I. Vai,[87a,87b] P. Vitulo,[87a,87b] S. Ajmal,[88a,88b] M. E. Ascioti,[88a,88b] G. M. Bilei,[88a,a] C. Carrivale,[88a,88b] D. Ciangottini,[88a,88b] L. Della Penna,[88a,88b] L. Fanò,[88a,88b] V. Mariani,[88a,88b] M. Menichelli,[88a] F. Moscatelli,[88a,yy] A. Rossi,[88a,88b] A. Santocchia,[88a,88b] D. Spiga,[88a]

T. Tedeschi,[88a,88b] C. Aimè,[89a,89b] C. A. Alexe,[89a,89c] P. Asenov,[89a,89b] P. Azzurri,[89a] G. Bagliesi,[89a] L. Bianchini,[89a,89b] T. Boccali,[89a] E. Bossini,[89a] D. Bruschini,[89a,89c] R. Castaldi,[89a] F. Cattafesta,[89a,89c] M. A. Ciocci,[89a,89d] M. Cipriani,[89a,89b] R. Dell'Orso,[89a] S. Donato,[89a,89b] R. Forti,[89a,89b] A. Giassi,[89a] F. Ligabue,[89a,89c] A. C. Marini,[89a,89b] A. Messineo,[89a,89b] S. Mishra,[89a] V. K. Muraleedharan Nair Bindhu,[89a,89b] S. Nandan,[89a] F. Palla,[89a] M. Riggirello,[89a,89c] A. Rizzi,[89a,89b] G. Rolandi,[89a,89c] S. Roy Chowdhury,[89a,zz] T. Sarkar,[89a] A. Scribano,[89a] P. Solanki,[89a,89b] P. Spagnolo,[89a] F. Tenchini,[89a,89b] R. Tenchini,[89a] G. Tonelli,[89a,89b] N. Turini,[89a,89d] F. Vaselli,[89a,89c] A. Venturi,[89a] P. G. Verdini,[89a] P. Akrap,[90a,90b] C. Basile,[90a,90b] S. C. Behera,[90a] F. Cavallari,[90a] L. Cunqueiro Mendez,[90a,90b] F. De Riggi,[90a,90b] D. Del Re,[90a,90b] M. Del Vecchio,[90a,90b] E. Di Marco,[90a] M. Diemoz,[90a] F. Errico,[90a] L. Frosina,[90a,90b] R. Gargiulo,[90a,90b] B. Harikrishnan,[90a,90b] F. Lombardi,[90a,90b] E. Longo,[90a,90b] L. Martikainen,[90a,90b] J. Mijuskovic,[90a,90b] G. Organtini,[90a,90b] N. Palmeri,[90a,90b] R. Paramatti,[90a,90b] T. Pauletto,[90a,90b] S. Rahatlou,[90a,90b] C. Rovelli,[90a] F. Santanastasio,[90a,90b] L. Soffi,[90a] V. Vladimirov,[90a,90b] N. Amapane,[91a,91b] R. Arcidiacono,[91a,91c] S. Argiro,[91a,91b] M. Arneodo,[91a,91c,a] N. Bartosik,[91a,91c] R. Bellan,[91a,91b] A. Bellora,[91a,91b] C. Biino,[91a] C. Borca,[91a,91b] N. Cartiglia,[91a] M. Costa,[91a,91b] R. Covarelli,[91a,91b] N. Demaria,[91a] L. Finco,[91a] M. Grippo,[91a,91b] B. Kiani,[91a,91b] L. Lanteri,[91a,91b] F. Legger,[91a] F. Luongo,[91a,91b] C. Mariotti,[91a] S. Maselli,[91a] A. Mecca,[91a,91b] L. Menzio,[91a,91b] P. Meridiani,[91a] E. Migliore,[91a,91b] M. Monteno,[91a] M. M. Obertino,[91a,91b] G. Ortona,[91a] L. Pacher,[91a,91b] N. Pastrone,[91a] M. Ruspa,[91a,91c] F. Siviero,[91a,91b] V. Sola,[91a,91b] A. Solano,[91a,91b] A. Staiano,[91a] C. Tarricone,[91a,91b] D. Trocino,[91a] G. Umoret,[91a,91b] E. Vlasov,[91a,91b] R. White,[91a,91b] J. Babbar,[92a,92b,zz] S. Belforte,[92a] V. Candelise,[92a,92b] M. Casarsa,[92a] F. Cossutti,[92a] K. De Leo,[92a] G. Della Ricca,[92a,92b] R. Delli Gatti,[92a,92b] S. Dogra,[93] J. Hong,[93] J. Kim,[93] T. Kim,[93] D. Lee,[93] H. Lee,[93] J. Lee,[93] S. W. Lee,[93] C. S. Moon,[93] Y. D. Oh,[93] S. Sekmen,[93] B. Tae,[93] Y. C. Yang,[93] M. S. Kim,[94] G. Bak,[95] P. Gwak,[95] H. Kim,[95] D. H. Moon,[95] J. Seo,[95] E. Asilar,[96] F. Carnevali,[96] J. Choi,[96,aaa] T. J. Kim,[96] Y. Ryou,[96] J. Song,[96] S. Ha,[97] S. Han,[97] B. Hong,[97] J. Kim,[97] K. Lee,[97] K. S. Lee,[97] S. Lee,[97] J. Yoo,[97] J. Goh,[98] J. Shin,[98] S. Yang,[98] Y. Kang,[99] H. S. Kim,[99] Y. Kim,[99] B. Ko,[99] S. Lee,[99] J. Almond,[100] J. H. Bhyun,[100] J. Choi,[100] J. Choi,[100] W. Jun,[100] H. Kim,[100] J. Kim,[100] T. Kim,[100] Y. Kim,[100] Y. W. Kim,[100] S. Ko,[100] H. Lee,[100] J. Lee,[100] J. Lee,[100] B. H. Oh,[100] J. Shin,[100] U. K. Yang,[100] I. Yoon,[100] W. Jang,[101] D. Kim,[101] S. Kim,[101] J. S. H. Lee,[101] Y. Lee,[101] I. C. Park,[101] Y. Roh,[101] I. J. Watson,[101] G. Cho,[102] K. Hwang,[102] B. Kim,[102] S. Kim,[102] K. Lee,[102] H. D. Yoo,[102] Y. Lee,[103] I. Yu,[103] T. Beyrouthy,[104] Y. Gharbia,[104] F. Alazemi,[105] K. Dreimanis,[106] O. M. Eberlins,[106] A. Gaile,[106] C. Munoz Diaz,[106] D. Osite,[106] G. Pikurs,[106] R. Plese,[106] A. Potrebko,[106] M. Seidel,[106] D. Sidiropoulos Kontos,[106] N. R. Strautnieks,[107] M. Ambrozas,[108] A. Juodagalvis,[108] S. Nargelas,[108] A. Rinkevicius,[108] G. Tamulaitis,[108] I. Yusuff,[109,bbb] Z. Zolkapli,[109] J. F. Benitez,[110] A. Castaneda Hernandez,[110] A. Cota Rodriguez,[110] L. E. Cuevas Picos,[110] H. A. Encinas Acosta,[110] L. G. Gallegos Maríñez,[110] J. A. Murillo Quijada,[110] L. Valencia Palomo,[110] G. Ayala,[111] H. Castilla-Valdez,[111] H. Crotte Ledesma,[111] R. Lopez-Fernandez,[111] J. Mejia Guisao,[111] R. Reyes-Almanza,[111] A. Sánchez Hernández,[111] C. Oropeza Barrera,[112] D. L. Ramirez Guadarrama,[112] M. Ramírez García,[112] I. Bautista,[113] F. E. Neri Huerta,[113] I. Pedraza,[113] H. A. Salazar Ibarguen,[113] C. Uribe Estrada,[113] I. Bubanja,[114] N. Raicevic,[114] P. H. Butler,[115] A. Ahmad,[116] M. I. Asghar,[116] A. Awais,[116] M. I. M. Awan,[116] W. A. Khan,[116] V. Avati,[117] L. Forthomme,[117] L. Grzanka,[117] M. Malawski,[117] K. Piotrzkowski,[117] M. Bluj,[118] M. Górski,[118] M. Kazana,[118] M. Szleper,[118] P. Zalewski,[118] K. Bunkowski,[119] K. Doroba,[119] A. Kalinowski,[119] M. Konecki,[119] J. Krolikowski,[119] A. Muhammad,[119] P. Fokow,[120] K. Pozniak,[120] W. Zabolotny,[120] M. Araujo,[121] D. Bastos,[121] C. Beirão Da Cruz E Silva,[121] A. Boletti,[121] M. Bozzo,[121] T. Camporesi,[121] G. Da Molin,[121] M. Gallinaro,[121] J. Hollar,[121] N. Leonardo,[121] G. B. Marozzo,[121] A. Petrilli,[121] M. Pisano,[121] J. Seixas,[121] J. Varela,[121] J. W. Wulff,[121] P. Adzic,[122] L. Markovic,[122] P. Milenovic,[122] V. Milosevic,[122] D. Devetak,[123] M. Dordevic,[123] J. Milosevic,[123] L. Nadderd,[123] V. Rekovic,[123] M. Stojanovic,[123] M. Alcalde Martinez,[124] J. Alcaraz Maestre,[124] Cristina F. Bedoya,[124] J. A. Brochero Cifuentes,[124] Oliver M. Carretero,[124] M. Cepeda,[124] M. Cerrada,[124] N. Colino,[124] B. De La Cruz,[124] A. Delgado Peris,[124] A. Escalante Del Valle,[124] D. Fernández Del Val,[124] J. P. Fernández Ramos,[124] J. Flix,[124] M. C. Fouz,[124] M. Gonzalez Hernandez,[124] O. Gonzalez Lopez,[124] S. Goy Lopez,[124] J. M. Hernandez,[124] M. I. Josa,[124] J. Llorente Merino,[124] C. Martin Perez,[124] E. Martin Viscasillas,[124] D. Moran,[124] C. M. Morcillo Perez,[124] Á. Navarro Tobar,[124] R. Paz Herrera,[124] A. Pérez-Calero Yzquierdo,[124] J. Puerta Pelayo,[124] I. Redondo,[124] J. Vazquez Escobar,[124] J. F. de Trocóniz,[125]

B. Alvarez Gonzalez,[126] J. Ayllon Torresano,[126] A. Cardini,[126] J. Cuevas,[126] J. Del Riego Badas,[126] D. Estrada Acevedo,[126] J. Fernandez Menendez,[126] S. Folgueras,[126] I. Gonzalez Caballero,[126] P. Leguina,[126] M. Obeso Menendez,[126] E. Palencia Cortezon,[126] J. Prado Pico,[126] A. Soto Rodríguez,[126] P. Vischia,[126] S. Blanco Fernández,[127] I. J. Cabrillo,[127] A. Calderon,[127] J. Duarte Campderros,[127] M. Fernandez,[127] G. Gomez,[127] C. Lasaosa García,[127] R. Lopez Ruiz,[127] C. Martinez Rivero,[127] P. Martinez Ruiz del Arbol,[127] F. Matorras,[127] P. Matorras Cuevas,[127] E. Navarrete Ramos,[127] J. Piedra Gomez,[127] C. Quintana San Emeterio,[127] L. Scodellaro,[127] I. Vila,[127] R. Vilar Cortabitarte,[127] J. M. Vizan Garcia,[127] B. Kailasapathy,[128,ccc] D. D. C. Wickramarathna,[128] W. G. D. Dharmaratna,[129,ddd] K. Liyanage,[129] N. Perera,[129] D. Abbaneo,[130] C. Amendola,[130] R. Ardino,[130] E. Auffray,[130] J. Baechler,[130] D. Barney,[130] J. Bendavid,[130] M. Bianco,[130] A. Bocci,[130] L. Borgonovi,[130] C. Botta,[130] A. Bragagnolo,[130] C. E. Brown,[130] C. Caillol,[130] G. Cerminara,[130] P. Connor,[130] K. Cormier,[130] D. d'Enterria,[130] A. Dabrowski,[130] A. David,[130] A. De Roeck,[130] M. M. Defranchis,[130] M. Deile,[130] M. Dobson,[130] P. J. Fernández Manteca,[130] B. A. Fontana Santos Alves,[130] E. Fontanesi,[130] W. Funk,[130] A. Gaddi,[130] S. Giani,[130] D. Gigi,[130] K. Gill,[130] F. Glege,[130] M. Glowacki,[130] A. Gruber,[130] J. Hegeman,[130] J. K. Heikkilä,[130] R. Hofsaess,[130] B. Huber,[130] T. James,[130] P. Janot,[130] O. Kaluzinska,[130] O. Karacheban,[130,y] G. Karathanasis,[130] S. Laurila,[130] P. Lecoq,[130] E. Leutgeb,[130] C. Lourenço,[130] A.-M. Lyon,[130] M. Magherini,[130] L. Malgeri,[130] M. Mannelli,[130] A. Mehta,[130] F. Meijers,[130] J. A. Merlin,[130] S. Mersi,[130] E. Meschi,[130] M. Migliorini,[130] F. Monti,[130] F. Moortgat,[130] M. Mulders,[130] M. Musich,[130] I. Neutelings,[130] S. Orfanelli,[130] F. Pantaleo,[130] M. Pari,[130] G. Petrucciani,[130] A. Pfeiffer,[130] M. Pierini,[130] M. Pitt,[130] H. Qu,[130] D. Rabady,[130] A. Reimers,[130] B. Ribeiro Lopes,[130] F. Riti,[130] P. Rosado,[130] M. Rovere,[130] H. Sakulin,[130] R. Salvatico,[130] S. Sanchez Cruz,[130] S. Scarfi,[130] M. Selvaggi,[130] K. Shchelina,[130] P. Silva,[130] P. Sphicas,[130,eee] A. G. Stahl Leiton,[130] A. Steen,[130] S. Summers,[130] D. Treille,[130] P. Tropea,[130] E. Vernazza,[130] J. Wanczyk,[130,fff] S. Wuchterl,[130] M. Zarucki,[130] P. Zehetner,[130] P. Zejdl,[130] G. Zevi Della Porta,[130] L. Caminada,[131,ggg] W. Erdmann,[131] R. Horisberger,[131] Q. Ingram,[131] H. C. Kaestli,[131] D. Kotlinski,[131] C. Lange,[131] U. Langenegger,[131] A. Nigamova,[131] L. Noehte,[131,ggg] T. Rohe,[131] A. Samalan,[131] T. K. Aarrestad,[132] M. Backhaus,[132] T. Bevilacqua,[132,ggg] G. Bonomelli,[132] C. Cazzaniga,[132] K. Datta,[132] P. De Bryas Dexmiers D'Archiacchiac,[132,fff] A. De Cosa,[132] G. Dissertori,[132] M. Dittmar,[132] M. Donegà,[132] F. Glessgen,[132] C. Grab,[132] N. Härringer,[132] T. G. Harte,[132] W. Lustermann,[132] M. Malucchi,[132] R. A. Manzoni,[132] L. Marchese,[132] A. Mascellani,[132,fff] F. Nessi-Tedaldi,[132] F. Pauss,[132] B. Ristic,[132] R. Seidita,[132] J. Steggemann,[132,fff] A. Tarabini,[132] D. Valsecchi,[132] R. Wallny,[132] C. Amsler,[133,hhh] P. Bärtschi,[133] F. Bilandzija,[133] M. F. Canelli,[133] G. Celotto,[133] V. Guglielmi,[133] A. Jofrehei,[133] B. Kilminster,[133] T. H. Kwok,[133] S. Leontsinis,[133] V. Lukashenko,[133] A. Macchiolo,[133] F. Meng,[133] M. Missiroli,[133] J. Motta,[133] P. Robmann,[133] E. Shokr,[133] F. Stäger,[133] R. Tramontano,[133] P. Viscone,[133] D. Bhowmik,[134] C. M. Kuo,[134] P. K. Rout,[134] S. Taj,[134] P. C. Tiwari,[134,jj] L. Ceard,[135] K. F. Chen,[135] Z. g. Chen,[135] A. De Iorio,[135] W.-S. Hou,[135] T. h. Hsu,[135] Y. w. Kao,[135] S. Karmakar,[135] G. Kole,[135] Y. y. Li,[135] R.-S. Lu,[135] E. Paganis,[135] X. f. Su,[135] J. Thomas-Wilsker,[135] L. s. Tsai,[135] D. Tsionou,[135] H. y. Wu,[135] E. Yazgan,[135] C. Asawatangtrakuldee,[136] N. Srimanobhas,[136] Y. Maghrbi,[137] D. Agyel,[138] F. Dolek,[138] I. Dumanoglu,[138,iii] Y. Guler,[138,jjj] E. Gurpinar Guler,[138,jjj] C. Isik,[138] O. Kara,[138,kkk] A. Kayis Topaksu,[138] Y. Komurcu,[138] G. Onengut,[138] K. Ozdemir,[138,lll] B. Tali,[138,mmm] U. G. Tok,[138] E. Uslan,[138] I. S. Zorbakir,[138] S. Sen,[139] M. Yalvac,[140,nnn] B. Akgun,[141] I. O. Atakisi,[141,ooo] E. Gülmez,[141] M. Kaya,[141,ppp] O. Kaya,[141,qqq] M. A. Sarkisla,[141,rrr] S. Tekten,[141,sss] D. Boncukcu,[142] A. Cakir,[142] K. Cankocak,[142,iii,ttt] B. Hacisahinoglu,[143] I. Hos,[143,uuu] B. Kaynak,[143] S. Ozkorucuklu,[143] O. Potok,[143] H. Sert,[143] C. Simsek,[143] C. Zorbilmez,[143] S. Cerci,[144] C. Dozen,[144,vvv] B. Isildak,[144] E. Simsek,[144] D. Sunar Cerci,[144] T. Yetkin,[144,vvv] A. Boyaryntsev,[145] O. Dadazhanova,[145] B. Grynyov,[145] L. Levchuk,[146] J. J. Brooke,[147] A. Bundock,[147] F. Bury,[147] E. Clement,[147] D. Cussans,[147] D. Dharmender,[147] H. Flacher,[147] J. Goldstein,[147] H. F. Heath,[147] M.-L. Holmberg,[147] L. Kreczko,[147] S. Paramesvaran,[147] L. Robertshaw,[147] M. S. Sanjrani,[147,mm] J. Segal,[147] V. J. Smith,[147] A. H. Ball,[148] K. W. Bell,[148] A. Belyaev,[148,www] C. Brew,[148] R. M. Brown,[148] D. J. A. Cockerill,[148] A. Elliot,[148] K. V. Ellis,[148] J. Gajownik,[148] K. Harder,[148] S. Harper,[148] J. Linacre,[148] K. Manolopoulos,[148] M. Moallemi,[148] D. M. Newbold,[148] E. Olaiya,[148] D. Petyt,[148] T. Reis,[148] A. R. Sahasransu,[148] G. Salvi,[148] T. Schuh,[148] C. H. Shepherd-Themistocleous,[148] I. R. Tomalin,[148] K. C. Whalen,[148] T. Williams,[148] I. Andreou,[149]

R. Bainbridge,[149] P. Bloch,[149] O. Buchmuller,[149] C. A. Carrillo Montoya,[149] D. Colling,[149] I. Das,[149] P. Dauncey,[149] G. Davies,[149] M. Della Negra,[149] S. Fayer,[149] G. Fedi,[149] G. Hall,[149] H. R. Hoorani,[149] A. Howard,[149] G. Iles,[149] C. R. Knight,[149] P. Krueper,[149] J. Langford,[149] K. H. Law,[149] J. León Holgado,[149] L. Lyons,[149] A.-M. Magnan,[149] B. Maier,[149] S. Mallios,[149] A. Mastronikolis,[149] M. Mieskolainen,[149] J. Nash,[149,xxx] M. Pesaresi,[149] P. B. Pradeep,[149] B. C. Radburn-Smith,[149] A. Richards,[149] A. Rose,[149] L. Russell,[149] K. Savva,[149] R. Schmitz,[149] C. Seez,[149] R. Shukla,[149] A. Tapper,[149] K. Uchida,[149] G. P. Uttley,[149] T. Virdee,[149,aa] M. Vojinovic,[149] N. Wardle,[149] D. Winterbottom,[149] J. E. Cole,[150] A. Khan,[150] P. Kyberd,[150] I. D. Reid,[150] S. Abdullin,[151] A. Brinkerhoff,[151] E. Collins,[151] M. R. Darwish,[151] J. Dittmann,[151] K. Hatakeyama,[151] V. Hegde,[151] J. Hiltbrand,[151] B. McMaster,[151] J. Samudio,[151] S. Sawant,[151] C. Sutantawibul,[151] J. Wilson,[151] J. M. Hogan,[152] R. Bartek,[153] A. Dominguez,[153] S. Raj,[153] B. Sahu,[153] A. E. Simsek,[153] S. S. Yu,[153] B. Bam,[154] A. Buchot Perraguin,[154] S. Campbell,[154] R. Chudasama,[154] S. I. Cooper,[154] C. Crovella,[154] G. Fidalgo,[154] S. V. Gleyzer,[154] A. Khukhunaishvili,[154] K. Matchev,[154] E. Pearson,[154] P. Rumerio,[154,yyy] E. Usai,[154] R. Yi,[154] S. Cholak,[155] G. De Castro,[155] Z. Demiragli,[155] C. Erice,[155] C. Fangmeier,[155] C. Fernandez Madrazo,[155] J. Fulcher,[155] F. Golf,[155] S. Jeon,[155] J. O'Cain,[155] I. Reed,[155] J. Rohlf,[155] K. Salyer,[155] D. Sperka,[155] D. Spitzbart,[155] I. Suarez,[155] A. Tsatsos,[155] E. Wurtz,[155] A. G. Zecchinelli,[155] G. Barone,[156] G. Benelli,[156] D. Cutts,[156] S. Ellis,[156] L. Gouskos,[156] M. Hadley,[156] U. Heintz,[156] K. W. Ho,[156] T. Kwon,[156] L. Lambrecht,[156] G. Landsberg,[156] K. T. Lau,[156] J. Luo,[156] S. Mondal,[156] J. Roloff,[156] T. Russell,[156] S. Sagir,[156,zzz] X. Shen,[156] M. Stamenkovic,[156] N. Venkatasubramanian,[156] S. Abbott,[157] S. Baradia,[157] B. Barton,[157] R. Breedon,[157] H. Cai,[157] M. Calderon De La Barca Sanchez,[157] E. Cannaert,[157] M. Chertok,[157] M. Citron,[157] J. Conway,[157] P. T. Cox,[157] F. Eble,[157] R. Erbacher,[157] O. Kukral,[157] G. Mocellin,[157] S. Ostrom,[157] I. Salazar Segovia,[157] J. S. Tafoya Vargas,[157] W. Wei,[157] S. Yoo,[157] K. Adamidis,[158] M. Bachtis,[158] D. Campos,[158] R. Cousins,[158] S. Crossley,[158] G. Flores Avila,[158] J. Hauser,[158] M. Ignatenko,[158] M. A. Iqbal,[158] T. Lam,[158] Y. f. Lo,[158] E. Manca,[158] A. Nunez Del Prado,[158] D. Saltzberg,[158] V. Valuev,[158] R. Clare,[159] J. W. Gary,[159] G. Hanson,[159] A. Aportela,[160] A. Arora,[160] J. G. Branson,[160] S. Cittolin,[160] S. Cooperstein,[160] B. D'Anzi,[160] D. Diaz,[160] J. Duarte,[160] L. Giannini,[160] Y. Gu,[160] J. Guiang,[160] V. Krutelyov,[160] R. Lee,[160] J. Letts,[160] H. Li,[160] M. Masciovecchio,[160] F. Mokhtar,[160] S. Mukherjee,[160] M. Pieri,[160] D. Primosch,[160] M. Quinnan,[160] V. Sharma,[160] M. Tadel,[160] E. Vourliotis,[160] F. Würthwein,[160] A. Yagil,[160] Z. Zhao,[160] A. Barzdukas,[161] L. Brennan,[161] C. Campagnari,[161] S. Carron Montero,[161,aaaa] K. Downham,[161] C. Grieco,[161] M. M. Hussain,[161] J. Incandela,[161] M. W. K. Lai,[161] A. J. Li,[161] P. Masterson,[161] J. Richman,[161] S. N. Santpur,[161] D. Stuart,[161] T. Á. Vámi,[161] X. Yan,[161] D. Zhang,[161] A. Albert,[162] S. Bhattacharya,[162] A. Bornheim,[162] O. Cerri,[162] R. Kansal,[162] H. B. Newman,[162] G. Reales Gutiérrez,[162] T. Sievert,[162] M. Spiropulu,[162] J. R. Vlimant,[162] R. A. Wynne,[162] S. Xie,[162] J. Alison,[163] S. An,[163] M. Cremonesi,[163] V. Dutta,[163] E. Y. Ertorer,[163] T. Ferguson,[163] T. A. Gómez Espinosa,[163] A. Harilal,[163] A. Kallil Tharayil,[163] M. Kanemura,[163] C. Liu,[163] M. Marchegiani,[163] P. Meiring,[163] S. Murthy,[163] P. Palit,[163] K. Park,[163] M. Paulini,[163] A. Roberts,[163] A. Sanchez,[163] W. Terrill,[163] J. P. Cumalat,[164] W. T. Ford,[164] A. Hart,[164] S. Kwan,[164] J. Pearkes,[164] C. Savard,[164] N. Schonbeck,[164] K. Stenson,[164] K. A. Ulmer,[164] S. R. Wagner,[164] N. Zipper,[164] D. Zuolo,[164] J. Alexander,[165] X. Chen,[165] J. Dickinson,[165] A. Duquette,[165] J. Fan,[165] X. Fan,[165] J. Grassi,[165] S. Hogan,[165] P. Kotamnives,[165] J. Monroy,[165] G. Niendorf,[165] M. Oshiro,[165] J. R. Patterson,[165] A. Ryd,[165] J. Thom,[165] P. Wittich,[165] R. Zou,[165] L. Zygala,[165] M. Albrow,[166] M. Alyari,[166] O. Amram,[166] G. Apollinari,[166] A. Apresyan,[166] L. A. T. Bauerdick,[166] D. Berry,[166] J. Berryhill,[166] P. C. Bhat,[166] K. Burkett,[166] J. N. Butler,[166] A. Canepa,[166] G. B. Cerati,[166] H. W. K. Cheung,[166] F. Chlebana,[166] C. Cosby,[166] G. Cummings,[166] I. Dutta,[166] V. D. Elvira,[166] J. Freeman,[166] A. Gandrakota,[166] Z. Gecse,[166] L. Gray,[166] D. Green,[166] A. Grummer,[166] S. Grünendahl,[166] D. Guerrero,[166] O. Gutsche,[166] R. M. Harris,[166] J. Hirschauer,[166] V. Innocente,[166] B. Jayatilaka,[166] S. Jindariani,[166] M. Johnson,[166] U. Joshi,[166] B. Klima,[166] S. Lammel,[166] C. Lee,[166] D. Lincoln,[166] R. Lipton,[166] T. Liu,[166] K. Maeshima,[166] D. Mason,[166] P. McBride,[166] P. Merkel,[166] S. Mrenna,[166] S. Nahn,[166] J. Ngadiuba,[166] D. Noonan,[166] S. Norberg,[166] V. Papadimitriou,[166] N. Pastika,[166] K. Pedro,[166] C. Pena,[166,bbbb] C. E. Perez Lara,[166] V. Perovic,[166] F. Ravera,[166] A. Reinsvold Hall,[166,cccc] L. Ristori,[166] M. Safdari,[166] E. Sexton-Kennedy,[166] E. Smith,[166] N. Smith,[166] A. Soha,[166] L. Spiegel,[166] S. Stoynev,[166] J. Strait,[166] L. Taylor,[166] S. Tkaczyk,[166] N. V. Tran,[166] L. Uplegger,[166]

E. W. Vaandering,[166] C. Wang,[166] I. Zoi,[166] C. Aruta,[167] P. Avery,[167] D. Bourilkov,[167] P. Chang,[167] V. Cherepanov,[167] R. D. Field,[167] C. Huh,[167] E. Koenig,[167] M. Kolosova,[167] J. Konigsberg,[167] A. Korytov,[167] G. Mitselmakher,[167] K. Mohrman,[167] A. Muthirakalayil Madhu,[167] N. Rawal,[167] S. Rosenzweig,[167] V. Sulimov,[167] Y. Takahashi,[167] J. Wang,[167] T. Adams,[168] A. Al Kadhim,[168] A. Askew,[168] S. Bower,[168] R. Goff,[168] R. Hashmi,[168] A. Hassani,[168] R. S. Kim,[168] T. Kolberg,[168] G. Martinez,[168] M. Mazza,[168] H. Prosper,[168] P. R. Prova,[168] R. Yohay,[168] B. Alsufyani,[169] S. Butalla,[169] S. Das,[169] M. Hohlmann,[169] M. Lavinsky,[169] E. Yanes,[169] M. R. Adams,[170] N. Barnett,[170] A. Baty,[170] C. Bennett,[170] R. Cavanaugh,[170] R. Escobar Franco,[170] O. Evdokimov,[170] C. E. Gerber,[170] H. Gupta,[170] M. Hawksworth,[170] A. Hingrajiya,[170] D. J. Hofman,[170] Z. Huang,[170] J. h. Lee,[170] C. Mills,[170] S. Nanda,[170] G. Nigmatkulov,[170] B. Ozek,[170] T. Phan,[170] D. Pilipovic,[170] R. Pradhan,[170] E. Prifti,[170] P. Roy,[170] T. Roy,[170] D. Shekar,[170] N. Singh,[170] A. Thielen,[170] M. B. Tonjes,[170] N. Varelas,[170] M. A. Wadud,[170] J. Yoo,[170] M. Alhusseini,[171] D. Blend,[171] K. Dilsiz,[171,dddd] O. K. Köseyan,[171] A. Mestvirishvili,[171,eeee] O. Neogi,[171] H. Ogul,[171,ffff] Y. Onel,[171] A. Penzo,[171] C. Snyder,[171] E. Tiras,[171,gggg] B. Blumenfeld,[172] J. Davis,[172] A. V. Gritsan,[172] L. Kang,[172] S. Kyriacou,[172] P. Maksimovic,[172] M. Roguljic,[172] S. Sekhar,[172] M. V. Srivastav,[172] M. Swartz,[172] A. Abreu,[173] L. F. Alcerro Alcerro,[173] J. Anguiano,[173] S. Arteaga Escatel,[173] P. Baringer,[173] A. Bean,[173] R. Bhattacharya,[173] Z. Flowers,[173] D. Grove,[173] J. King,[173] G. Krintiras,[173] M. Lazarovits,[173] C. Le Mahieu,[173] J. Marquez,[173] M. Murray,[173] M. Nickel,[173] S. Popescu,[173,hhhh] C. Rogan,[173] C. Royon,[173] S. Rudrabhatla,[173] S. Sanders,[173] C. Smith,[173] G. Wilson,[173] B. Allmond,[174] N. Islam,[174] A. Ivanov,[174] K. Kaadze,[174] Y. Maravin,[174] J. Natoli,[174] G. G. Reddy,[174] D. Roy,[174] G. Sorrentino,[174] A. Baden,[175] A. Belloni,[175] J. Bistany-riebman,[175] S. C. Eno,[175] N. J. Hadley,[175] S. Jabeen,[175] R. G. Kellogg,[175] T. Koeth,[175] B. Kronheim,[175] S. Lascio,[175] P. Major,[175] A. C. Mignerey,[175] C. Palmer,[175] C. Papageorgakis,[175] M. M. Paranjpe,[175] E. Popova,[175,iiii] A. Shevelev,[175] L. Zhang,[175] C. Baldenegro Barrera,[176] H. Bossi,[176] S. Bright-Thonney,[176] I. A. Cali,[176] Y. c. Chen,[176] P. c. Chou,[176] M. D'Alfonso,[176] J. Eysermans,[176] C. Freer,[176] G. Gomez-Ceballos,[176] M. Goncharov,[176] G. Grosso,[176] P. Harris,[176] D. Hoang,[176] G. M. Innocenti,[176] K. Ivanov,[176] G. Kopp,[176] D. Kovalskyi,[176] J. Krupa,[176] L. Lavezzo,[176] Y.-J. Lee,[176] K. Long,[176] C. Mcginn,[176] A. Novak,[176] M. I. Park,[176] C. Paus,[176] C. Reissel,[176] C. Roland,[176] G. Roland,[176] S. Rothman,[176] T. a. Sheng,[176] G. S. F. Stephans,[176] D. Walter,[176] J. Wang,[176] Z. Wang,[176] B. Wyslouch,[176] T. J. Yang,[176] A. Alpana,[177] B. Crossman,[177] W. J. Jackson,[177] C. Kapsiak,[177] M. Krohn,[177] D. Mahon,[177] J. Mans,[177] B. Marzocchi,[177] R. Rusack,[177] O. Sancar,[177] R. Saradhy,[177] N. Strobbe,[177] K. Bloom,[178] D. R. Claes,[178] G. Haza,[178] J. Hossain,[178] C. Joo,[178] I. Kravchenko,[178] K. H. M. Kwok,[178] A. Rohilla,[178] J. E. Siado,[178] W. Tabb,[178] A. Vagnerini,[178] A. Wightman,[178] F. Yan,[178] H. Bandyopadhyay,[179] L. Hay,[179] H. w. Hsia,[179] I. Iashvili,[179] A. Kalogeropoulos,[179] A. Kharchilava,[179] A. Mandal,[179] M. Morris,[179] D. Nguyen,[179] S. Rappoccio,[179] H. Rejeb Sfar,[179] A. Williams,[179] D. Yu,[179] A. Aarif,[180] G. Alverson,[180] E. Barberis,[180] J. Bonilla,[180] B. Bylsma,[180] M. Campana,[180] J. Dervan,[180] Y. Haddad,[180] Y. Han,[180] I. Israr,[180] A. Krishna,[180] M. Lu,[180] N. Manganelli,[180] R. Mccarthy,[180] D. M. Morse,[180] T. Orimoto,[180] L. Skinnari,[180] C. S. Thoreson,[180] E. Tsai,[180] D. Wood,[180] S. Dittmer,[181] K. A. Hahn,[181] M. Mcginnis,[181] Y. Miao,[181] D. G. Monk,[181] M. H. Schmitt,[181] A. Taliercio,[181] M. Velasco,[181] J. Wang,[181] G. Agarwal,[182] R. Band,[182] R. Bucci,[182] S. Castells,[182] A. Das,[182] A. Datta,[182] A. Ehnis,[182] R. Goldouzian,[182] M. Hildreth,[182] K. Hurtado Anampa,[182] T. Ivanov,[182] C. Jessop,[182] A. Karneyeu,[182] K. Lannon,[182] J. Lawrence,[182] N. Loukas,[182] L. Lutton,[182] J. Mariano,[182] N. Marinelli,[182] T. McCauley,[182] C. Mcgrady,[182] C. Moore,[182] Y. Musienko,[182,iiii] H. Nelson,[182] M. Osherson,[182] A. Piccinelli,[182] R. Ruchti,[182] A. Townsend,[182] Y. Wan,[182] M. Wayne,[182] H. Yockey,[182] M. Carrigan,[183] R. De Los Santos,[183] L. S. Durkin,[183] C. Hill,[183] M. Joyce,[183] D. A. Wenzl,[183] B. L. Winer,[183] B. R. Yates,[183] H. Bouchamaoui,[184] G. Dezoort,[184] P. Elmer,[184] A. Frankenthal,[184] M. Galli,[184] B. Greenberg,[184] N. Haubrich,[184] K. Kennedy,[184] Y. Lai,[184] D. Lange,[184] A. Loeliger,[184] D. Marlow,[184] I. Ojalvo,[184] J. Olsen,[184] F. Simpson,[184] D. Stickland,[184] C. Tully,[184] S. Malik,[185] R. Sharma,[185] S. Chandra,[186] A. Gu,[186] L. Gutay,[186] M. Huwiler,[186] M. Jones,[186] A. W. Jung,[186] D. Kondratyev,[186] J. Li,[186] M. Liu,[186] G. Negro,[186] N. Neumeister,[186] G. Paspalaki,[186] S. Piperov,[186] N. R. Saha,[186] J. F. Schulte,[186] F. Wang,[186] A. Wildridge,[186] W. Xie,[186] Y. Yao,[186] Y. Zhong,[186] N. Parashar,[187] A. Pathak,[187] E. Shumka,[187] D. Acosta,[188] A. Agrawal,[188] C. Arbour,[188] T. Carnahan,[188] P. Das,[188] K. M. Ecklund,[188] F. J. M. Geurts,[188] T. Huang,[188] I. Krommydas,[188]

N. Lewis,[188] W. Li,[188] J. Lin,[188] O. Miguel Colin,[188] B. P. Padley,[188] R. Redjimi,[188] J. Rotter,[188] C. Vico Villalba,[188] M. Wulansatiti,[188] E. Yigitbasi,[188] Y. Zhang,[188] O. Bessidskaia Bylund,[189] A. Bodek,[189] P. de Barbaro,[189,a] R. Demina,[189] A. Garcia-Bellido,[189] H. S. Hare,[189] O. Hindrichs,[189] N. Parmar,[189] P. Parygin,[189,iiii] H. Seo,[189] R. Taus,[189] Y. h. Yu,[189] B. Chiarito,[190] J. P. Chou,[190] S. V. Clark,[190] S. Donnelly,[190] D. Gadkari,[190] Y. Gershtein,[190] E. Halkiadakis,[190] C. Houghton,[190] D. Jaroslawski,[190] A. Kobert,[190] I. Laflotte,[190] A. Lath,[190] J. Martins,[190] M. Perez Prada,[190] B. Rand,[190] J. Reichert,[190] P. Saha,[190] S. Salur,[190] S. Somalwar,[190] R. Stone,[190] S. A. Thayil,[190] S. Thomas,[190] J. Vora,[190] D. Ally,[191] A. G. Delannoy,[191] S. Fiorendi,[191] J. Harris,[191] T. Holmes,[191] A. R. Kanuganti,[191] N. Karunarathna,[191] J. Lawless,[191] L. Lee,[191] E. Nibigira,[191] B. Skipworth,[191] S. Spanier,[191] D. Aebi,[192] M. Ahmad,[192] T. Akhter,[192] K. Androsov,[192] A. Basnet,[192] A. Bolshov,[192] O. Bouhali,[192,jjjj] A. Cagnotta,[192] V. D'Amante,[192] R. Eusebi,[192] P. Flanagan,[192] J. Gilmore,[192] Y. Guo,[192] T. Kamon,[192] S. Luo,[192] R. Mueller,[192] A. Safonov,[192] N. Akchurin,[193] J. Damgov,[193] Y. Feng,[193] N. Gogate,[193] W. Jin,[193] S. W. Lee,[193] C. Madrid,[193] A. Mankel,[193] T. Peltola,[193] I. Volobouev,[193] E. Appelt,[194] Y. Chen,[194] S. Greene,[194] A. Gurrola,[194] W. Johns,[194] R. Kunnawalkam Elayavalli,[194] A. Melo,[194] D. Rathjens,[194] F. Romeo,[194] P. Sheldon,[194] S. Tuo,[194] J. Velkovska,[194] J. Viinikainen,[194] J. Zhang,[194] B. Cardwell,[195] H. Chung,[195] B. Cox,[195] J. Hakala,[195] G. Hamilton Ilha Machado,[195] R. Hirosky,[195] M. Jose,[195] A. Ledovskoy,[195] C. Mantilla,[195] C. Neu,[195] C. Ramón Álvarez,[195] Z. Wu,[195] S. Bhattacharya,[196] P. E. Karchin,[196] A. Aravind,[197] S. Banerjee,[197] K. Black,[197] T. Bose,[197] E. Chavez,[197] S. Dasu,[197] P. Everaerts,[197] C. Galloni,[197] H. He,[197] M. Herndon,[197] A. Herve,[197] C. K. Koraka,[197] S. Lomte,[197] R. Loveless,[197] A. Mallampalli,[197] A. Mohammadi,[197] S. Mondal,[197] T. Nelson,[197] G. Parida,[197] L. Pétré,[197] D. Pinna,[197] A. Savin,[197] V. Shang,[197] V. Sharma,[197] W. H. Smith,[197] D. Teague,[197] A. Warden,[197] S. Afanasiev,[198] V. Alexakhin,[198] Yu. Andreev,[198] T. Aushev,[198] D. Budkouski,[198] R. Chistov,[198] M. Danilov,[198] T. Dimova,[198] A. Ershov,[198] S. Gninenko,[198] I. Gorbunov,[198] A. Kamenev,[198] V. Karjavine,[198] M. Kirsanov,[198] V. Klyukhin,[198] O. Kodolova,[198,kkkk] V. Korenkov,[198] I. Korsakov,[198] A. Kozyrev,[198] N. Krasnikov,[198] A. Lanev,[198] A. Malakhov,[198] V. Matveev,[198] A. Nikitenko,[198,llll,kkkk] V. Palichik,[198] V. Perelygin,[198] S. Petrushanko,[198] O. Radchenko,[198] M. Savina,[198] V. Shalaev,[198] S. Shmatov,[198] S. Shulha,[198] Y. Skovpen,[198] K. Slizhevskiy,[198] V. Smirnov,[198] O. Teryaev,[198] I. Tlisova,[198] A. Toropin,[198] N. Voytishin,[198] A. Zarubin,[198] I. Zhizhin,[198] L. Dudko,[199] V. Kim,[199,iiii] V. Murzin,[199] V. Oreshkin,[199] D. Sosnov,[199] E. Boos,[199] V. Bunichev,[199] M. Dubinin,[199,bbbb] A. Gribushin,[199] V. Savrin,[199] and A. Snigirev[199]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Vienna, Austria*
[3]*Universiteit Antwerpen, Antwerpen, Belgium*
[4]*Vrije Universiteit Brussel, Brussel, Belgium*
[5]*Université Libre de Bruxelles, Bruxelles, Belgium*
[6]*Ghent University, Ghent, Belgium*
[7]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[9]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[10]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[11]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[12]*University of Sofia, Sofia, Bulgaria*
[13]*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*
[14]*Universidad Tecnica Federico Santa Maria, Valparaiso, Chile*
[15]*Beihang University, Beijing, China*
[16]*Department of Physics, Tsinghua University, Beijing, China*
[17]*Institute of High Energy Physics, Beijing, China*
[18]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[19]*State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China*
[20]*Sun Yat-Sen University, Guangzhou, China*
[21]*University of Science and Technology of China, Hefei, China*

[22]Nanjing Normal University, Nanjing, China
[23]Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China
[24]Zhejiang University, Hangzhou, Zhejiang, China
[25]Universidad de Los Andes, Bogota, Colombia
[26]Universidad de Antioquia, Medellin, Colombia
[27]University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
[28]University of Split, Faculty of Science, Split, Croatia
[29]Institute Rudjer Boskovic, Zagreb, Croatia
[30]University of Cyprus, Nicosia, Cyprus
[31]Charles University, Prague, Czech Republic
[32]Escuela Politecnica Nacional, Quito, Ecuador
[33]Universidad San Francisco de Quito, Quito, Ecuador
[34]Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
[35]Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
[36]National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
[37]Department of Physics, University of Helsinki, Helsinki, Finland
[38]Helsinki Institute of Physics, Helsinki, Finland
[39]Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
[40]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[41]Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
[42]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
[43]Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
[44]Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[45]Georgian Technical University, Tbilisi, Georgia
[46]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
[47]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[48]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
[49]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[50]University of Hamburg, Hamburg, Germany
[51]Karlsruher Institut fuer Technologie, Karlsruhe, Germany
[52]Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
[53]National and Kapodistrian University of Athens, Athens, Greece
[54]National Technical University of Athens, Athens, Greece
[55]University of Ioánnina, Ioánnina, Greece
[56]HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[57]MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[58]Faculty of Informatics, University of Debrecen, Debrecen, Hungary
[59]HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary
[60]Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
[61]IIT Bhubaneswar, Bhubaneswar, India
[62]Panjab University, Chandigarh, India
[63]University of Delhi, Delhi, India
[64]Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India
[65]University of Hyderabad, Hyderabad, India
[66]Indian Institute of Technology Kanpur, Kanpur, India
[67]Saha Institute of Nuclear Physics, HBNI, Kolkata, India
[68]Indian Institute of Technology Madras, Madras, India
[69]IISER Mohali, India, Mohali, India
[70]Tata Institute of Fundamental Research-A, Mumbai, India
[71]Tata Institute of Fundamental Research-B, Mumbai, India
[72]National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
[73]Indian Institute of Science Education and Research (IISER), Pune, India
[74]Indian Institute of Technology Hyderabad, Telangana, India

[75]Isfahan University of Technology, Isfahan, Iran
[76]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
[77]University College Dublin, Dublin, Ireland
[78a]INFN Sezione di Bari, Bari, Italy
[78b]Università di Bari, Bari, Italy
[78c]Politecnico di Bari, Bari, Italy
[79a]INFN Sezione di Bologna, Bologna, Italy
[79b]Università di Bologna, Bologna, Italy
[80a]INFN Sezione di Catania, Catania, Italy
[80b]Università di Catania, Catania, Italy
[81a]INFN Sezione di Firenze, Firenze, Italy
[81b]Università di Firenze, Firenze, Italy
[82]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[83a]INFN Sezione di Genova, Genova, Italy
[83b]Università di Genova, Genova, Italy
[84a]INFN Sezione di Milano-Bicocca, Milano, Italy
[84b]Università di Milano-Bicocca, Milano, Italy
[85a]INFN Sezione di Napoli, Napoli, Italy
[85b]Università di Napoli "Federico II," Napoli, Italy
[85c]Università della Basilicata, Potenza, Italy
[85d]Scuola Superiore Meridionale (SSM), Napoli, Italy
[86a]INFN Sezione di Padova, Padova, Italy
[86b]Università di Padova, Padova, Italy
[86c]Universita degli Studi di Cagliari, Cagliari, Italy
[87a]INFN Sezione di Pavia, Pavia, Italy
[87b]Università di Pavia, Pavia, Italy
[88a]INFN Sezione di Perugia, Perugia, Italy
[88b]Università di Perugia, Perugia, Italy
[89a]INFN Sezione di Pisa, Pisa, Italy
[89b]Università di Pisa, Pisa, Italy
[89c]Scuola Normale Superiore di Pisa, Pisa, Italy
[89d]Università di Siena, Siena, Italy
[90a]INFN Sezione di Roma, Roma, Italy
[90b]Sapienza Università di Roma, Roma, Italy
[91a]INFN Sezione di Torino, Torino, Italy
[91b]Università di Torino, Torino, Italy
[91c]Università del Piemonte Orientale, Novara, Italy
[92a]INFN Sezione di Trieste, Trieste, Italy
[92b]Università di Trieste, Trieste, Italy
[93]Kyungpook National University, Daegu, Korea
[94]Department of Mathematics and Physics—GWNU, Gangneung, Korea
[95]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[96]Hanyang University, Seoul, Korea
[97]Korea University, Seoul, Korea
[98]Kyung Hee University, Department of Physics, Seoul, Korea
[99]Sejong University, Seoul, Korea
[100]Seoul National University, Seoul, Korea
[101]University of Seoul, Seoul, Korea
[102]Yonsei University, Department of Physics, Seoul, Korea
[103]Sungkyunkwan University, Suwon, Korea
[104]College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
[105]Kuwait University—College of Science—Department of Physics, Safat, Kuwait
[106]Riga Technical University, Riga, Latvia
[107]University of Latvia (LU), Riga, Latvia
[108]Vilnius University, Vilnius, Lithuania
[109]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[110]Universidad de Sonora (UNISON), Hermosillo, Mexico
[111]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[112]Universidad Iberoamericana, Mexico City, Mexico

[113]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[114]*University of Montenegro, Podgorica, Montenegro*
[115]*University of Canterbury, Christchurch, New Zealand*
[116]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[117]*AGH University of Krakow, Krakow, Poland*
[118]*National Centre for Nuclear Research, Swierk, Poland*
[119]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[120]*Warsaw University of Technology, Warsaw, Poland*
[121]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[122]*Faculty of Physics, University of Belgrade, Belgrade, Serbia*
[123]*VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[124]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[125]*Universidad Autónoma de Madrid, Madrid, Spain*
[126]*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
[127]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[128]*University of Colombo, Colombo, Sri Lanka*
[129]*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
[130]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[131]*PSI Center for Neutron and Muon Sciences, Villigen, Switzerland*
[132]*ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
[133]*Universität Zürich, Zurich, Switzerland*
[134]*National Central University, Chung-Li, Taiwan*
[135]*National Taiwan University (NTU), Taipei, Taiwan*
[136]*High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand*
[137]*Tunis El Manar University, Tunis, Tunisia*
[138]*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[139]*Hacettepe University, Ankara, Turkey*
[140]*Middle East Technical University, Physics Department, Ankara, Turkey*
[141]*Bogazici University, Istanbul, Turkey*
[142]*Istanbul Technical University, Istanbul, Turkey*
[143]*Istanbul University, Istanbul, Turkey*
[144]*Yildiz Technical University, Istanbul, Turkey*
[145]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
[146]*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
[147]*University of Bristol, Bristol, United Kingdom*
[148]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[149]*Imperial College, London, United Kingdom*
[150]*Brunel University, Uxbridge, United Kingdom*
[151]*Baylor University, Waco, Texas, USA*
[152]*Bethel University, St. Paul, Minnesota, USA*
[153]*Catholic University of America, Washington, DC, USA*
[154]*The University of Alabama, Tuscaloosa, Alabama, USA*
[155]*Boston University, Boston, Massachusetts, USA*
[156]*Brown University, Providence, Rhode Island, USA*
[157]*University of California, Davis, Davis, California, USA*
[158]*University of California, Los Angeles, California, USA*
[159]*University of California, Riverside, Riverside, California, USA*
[160]*University of California, San Diego, La Jolla, California, USA*
[161]*University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA*
[162]*California Institute of Technology, Pasadena, California, USA*
[163]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[164]*University of Colorado Boulder, Boulder, Colorado, USA*
[165]*Cornell University, Ithaca, New York, USA*
[166]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[167]*University of Florida, Gainesville, Florida, USA*
[168]*Florida State University, Tallahassee, Florida, USA*
[169]*Florida Institute of Technology, Melbourne, Florida, USA*
[170]*University of Illinois Chicago, Chicago, Illinois, USA*

[171]*The University of Iowa, Iowa City, Iowa, USA*
[172]*Johns Hopkins University, Baltimore, Maryland, USA*
[173]*The University of Kansas, Lawrence, Kansas, USA*
[174]*Kansas State University, Manhattan, Kansas, USA*
[175]*University of Maryland, College Park, Maryland, USA*
[176]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[177]*University of Minnesota, Minneapolis, Minnesota, USA*
[178]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[179]*State University of New York at Buffalo, Buffalo, New York, USA*
[180]*Northeastern University, Boston, Massachusetts, USA*
[181]*Northwestern University, Evanston, Illinois, USA*
[182]*University of Notre Dame, Notre Dame, Indiana, USA*
[183]*The Ohio State University, Columbus, Ohio, USA*
[184]*Princeton University, Princeton, New Jersey, USA*
[185]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[186]*Purdue University, West Lafayette, Indiana, USA*
[187]*Purdue University Northwest, Hammond, Indiana, USA*
[188]*Rice University, Houston, Texas, USA*
[189]*University of Rochester, Rochester, New York, USA*
[190]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[191]*University of Tennessee, Knoxville, Tennessee, USA*
[192]*Texas A&M University, College Station, Texas, USA*
[193]*Texas Tech University, Lubbock, Texas, USA*
[194]*Vanderbilt University, Nashville, Tennessee, USA*
[195]*University of Virginia, Charlottesville, Virginia, USA*
[196]*Wayne State University, Detroit, Michigan, USA*
[197]*University of Wisconsin—Madison, Madison, Wisconsin, USA*
[198]*An institute or international laboratory covered by a cooperation agreement with CERN*
[199]*An institute formerly covered by a cooperation agreement with CERN*

[a]Deceased.
[b]Also at Yerevan State University, Yerevan, Armenia.
[c]Also at TU Wien, Vienna, Austria.
[d]Also at Ghent University, Ghent, Belgium.
[e]Also at FACAMP—Faculdades de Campinas, Sao Paulo, Brazil.
[f]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[g]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[h]Also at The University of the State of Amazonas, Manaus, Brazil.
[i]Also at University of Chinese Academy of Sciences, Beijing, China.
[j]Also at School of Physics, Zhengzhou University, Zhengzhou, China.
[k]Also at Henan Normal University, Xinxiang, China.
[l]Also at University of Shanghai for Science and Technology, Shanghai, China.
[m]Also at The University of Iowa, Iowa City, Iowa, USA.
[n]Also at Nanjing Normal University, Nanjing, China.
[o]Also at Center for High Energy Physics, Peking University, Beijing, China.
[p]Also at Helwan University, Cairo, Egypt.
[q]Also at Zewail City of Science and Technology, Zewail, Egypt.
[r]Also at Cairo University, Cairo, Egypt.
[s]Also at Purdue University, West Lafayette, Indiana, USA.
[t]Also at Université de Haute Alsace, Mulhouse, France.
[u]Also at Another institute or international laboratory covered by a cooperation agreement with CERN.
[v]Also at University of Hamburg, Hamburg, Germany.
[w]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[x]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[y]Also at Brandenburg University of Technology, Cottbus, Germany.
[z]Also at Forschungszentrum Jülich, Juelich, Germany.
[aa]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[bb]Also at HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary.
[cc]Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
[dd]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

[ee]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[ff]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[gg]Also at The University of Kansas, Lawrence, Kansas, USA.
[hh]Also at Punjab Agricultural University, Ludhiana, India.
[ii]Also at University of Hyderabad, Hyderabad, India.
[jj]Also at Indian Institute of Science (IISc), Bangalore, India.
[kk]Also at University of Visva-Bharati, Santiniketan, India.
[ll]Also at Institute of Physics, Bhubaneswar, India.
[mm]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[nn]Also at Isfahan University of Technology, Isfahan, Iran.
[oo]Also at Sharif University of Technology, Tehran, Iran.
[pp]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[qq]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
[rr]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[ss]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[tt]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[uu]Also at Scuola Superiore Meridionale, Università di Napoli "Federico II," Napoli, Italy.
[vv]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[ww]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
[xx]Also at Lulea University of Technology, Lulea, Sweden.
[yy]Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
[zz]Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.
[aaa]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France.
[bbb]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[ccc]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[ddd]Also at Saegis Campus, Nugegoda, Sri Lanka.
[eee]Also at National and Kapodistrian University of Athens, Athens, Greece.
[fff]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[ggg]Also at Universität Zürich, Zurich, Switzerland.
[hhh]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[iii]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[jjj]Also at Konya Technical University, Konya, Turkey.
[kkk]Also at Istanbul Topkapi University, Istanbul, Turkey.
[lll]Also at Izmir Bakircay University, Izmir, Turkey.
[mmm]Also at Adiyaman University, Adiyaman, Turkey.
[nnn]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[ooo]Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey.
[ppp]Also at Marmara University, Istanbul, Turkey.
[qqq]Also at Milli Savunma University, Istanbul, Turkey.
[rrr]Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey.
[sss]Also at Kafkas University, Kars, Turkey.
[ttt]Also at Istanbul Okan University, Istanbul, Turkey.
[uuu]Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[vvv]Also at Istinye University, Istanbul, Turkey.
[www]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[xxx]Also at Monash University, Faculty of Science, Clayton, Australia.
[yyy]Also at Università di Torino, Torino, Italy.
[zzz]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[aaaa]Also at California Lutheran University, Thousand Oaks, California, USA.
[bbbb]Also at California Institute of Technology, Pasadena, California, USA.
[cccc]Also at United States Naval Academy, Annapolis, Maryland, USA.
[dddd]Also at Bingol University, Bingol, Turkey.
[eeee]Also at Georgian Technical University, Tbilisi, Georgia.
[ffff]Also at Sinop University, Sinop, Turkey.
[gggg]Also at Erciyes University, Kayseri, Turkey.
[hhhh]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[iiii]Also at Another institute formerly covered by a cooperation agreement with CERN.
[jjjj]Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar.
[kkkk]Also at Yerevan Physics Institute, Yerevan, Armenia.
[llll]Also at Imperial College, London, United Kingdom.