

Observation of Same-Sign WW Production from Double Parton Scattering in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Tumasyan *et al.**
(CMS Collaboration)

 (Received 6 June 2022; accepted 18 August 2022; published 1 September 2023)

The first observation of the production of $W^\pm W^\pm$ bosons from double parton scattering processes using same-sign electron-muon and dimuon events in proton-proton collisions is reported. The data sample corresponds to an integrated luminosity of 138 fb^{-1} recorded at a center-of-mass energy of 13 TeV using the CMS detector at the CERN LHC. Multivariate discriminants are used to distinguish the signal process from the main backgrounds. A binned maximum likelihood fit is performed to extract the signal cross section. The measured cross section for production of same-sign W bosons decaying leptonically is $80.7 \pm 11.2(\text{stat})_{-8.6}^{+9.5}(\text{syst}) \pm 12.1(\text{model}) \text{ fb}$, whereas the measured fiducial cross section is $6.28 \pm 0.81(\text{stat}) \pm 0.69(\text{syst}) \pm 0.37(\text{model}) \text{ fb}$. The observed significance of the signal is 6.2 standard deviations above the background-only hypothesis.

DOI: [10.1103/PhysRevLett.131.091803](https://doi.org/10.1103/PhysRevLett.131.091803)

Double parton scattering (DPS) events, in which two hard parton-parton interactions occur in a single proton-proton (pp) collision, have been proposed and studied since the advent of the parton model and hadron colliders [1–9]. The study of such events sheds light on the internal structure of the colliding protons. Primarily, the study of DPS processes provides information on the transverse profile of the proton and its energy evolution, information that is otherwise not accessible in single parton scattering (SPS) events. In addition, processes with two or more hard parton-parton scatterings allow the study of correlations among the partons from the same proton in terms of momentum, flavor, color, and spin.

In the simplest theoretical model [10], the two parton-parton interactions in DPS can be considered entirely uncorrelated, and the expected DPS cross section can be written as the (normalized) product of the SPS cross sections to produce processes A and B independently, as

$$\sigma_{AB}^{\text{DPS}} = \frac{n \sigma_A \sigma_B}{2 \sigma_{\text{eff}}}, \quad (1)$$

where n is a combinatorial factor that takes a value of unity if $A = B$ and two otherwise. The denominator σ_{eff} can be interpreted as being proportional to the average squared transverse distance between the interacting partons, and it

serves as a useful quantity to compare DPS processes in different production modes. Its experimental value ranges between 2 and 10 mb for gluon-initiated and 10 and 25 mb for quark-initiated DPS production processes [11–29].

As the center-of-mass energy of pp collisions increases, so does the density of sea quarks and gluons, which, in turn, leads to increased DPS contributions to many final states where pairs of heavy particles are produced. These additional DPS contributions can limit the precision of searches for new physics [30] and the accuracy of high-precision standard model analyses [31]. Therefore, it is important to study DPS processes in different production modes and final states. Theoretical advancements [8] have improved upon the simple “geometric” approach on which Eq. (1) is based. The introduction of interparton correlations via double parton distribution functions (dPDF) [32–35], which include parton splitting effects and impact parameter dependence, has led to the first dPDF-based Monte Carlo (MC) event generator for DPS events, *ashower* [36].

The production of leptonically decaying same-sign (SS) W boson pairs is a promising process to study DPS [37]. Its experimental signature is rather clean and easy to trigger on, and the SPS $W^\pm W^\pm$ production is highly suppressed because of two additional partons produced in the final state compared with the opposite-sign configuration. Figure 1 illustrates the production of $W^\pm W^\pm$ via the DPS and SPS processes at leading order (LO) accuracy in electroweak and perturbative quantum chromodynamics (QCD). The DPS $W^\pm W^\pm$ production has not been observed experimentally, and the existing searches for the process are not statistically significant due to the size of the available data samples [25,38].

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

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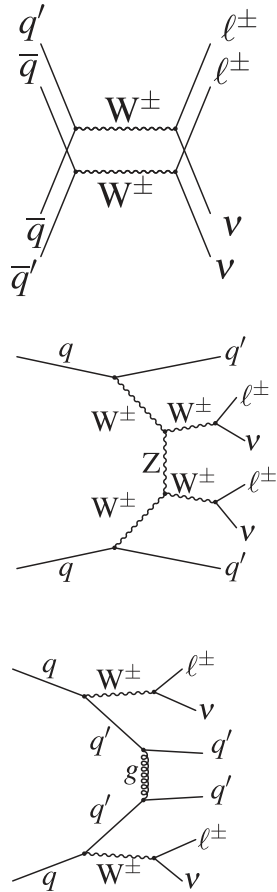


FIG. 1. Example Feynman diagrams for leptonically decaying $W^\pm W^\pm$ bosons produced via DPS (upper) and SPS (middle and lower) processes.

This Letter presents the first observation of DPS $W^\pm W^\pm$ production using pp collision data at $\sqrt{s} = 13$ TeV. The data sample corresponds to an integrated luminosity of 138 fb^{-1} collected using the CMS detector during the 2016–2018 operation of the LHC. The W bosons are required to decay into final states consisting of two SS leptons ($e^\pm \mu^\pm$ or $\mu^\pm \mu^\pm$), including the contributions from leptonic τ decays. As in Refs. [25,38], the dielectron final state is not considered because of the larger background, but the overall analysis strategy has been reoptimized to enhance the signal sensitivity.

The CMS apparatus [39] is a multipurpose, nearly hermetic detector, designed to trigger on [40,41] and identify electrons, muons, photons, and hadrons [42–45]. A global “particle-flow” (PF) algorithm [46] reconstructs all individual particles in an event, combining information from the silicon tracker and the crystal electromagnetic (ECAL) and the brass-scintillator hadron calorimeters, which all operate within a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Details of the event reconstruction used to define the

primary vertex (PV) and build leptons, jets, hadronically decaying τ leptons (τ_h), and missing transverse momentum (p_T^{miss}) are provided in Refs. [47–52]. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, selects events at a rate of around 100 kHz [40]. The second level, known as the high-level trigger, further reduces the event rate to around 1 kHz before data storage [41].

Charged leptons are required to originate from the primary vertex (PV) to avoid contributions from additional pp interactions in the same and nearby bunch crossings (pileup). Electrons are identified using a multivariate analysis (MVA) discriminant that combines observables sensitive to the matching of charged-particle tracks in the tracker to the energy deposits in the ECAL and the number of bremsstrahlung photons emitted along their trajectory [42,53]. The identification of muons is based on linking track segments reconstructed in the silicon tracker to hits in the muon detectors [43]. Further selection criteria are applied to ensure the correct assignment of the electric charge of the leptons in the reconstruction [42]. Lepton isolation requirements are imposed following the same approach as in Ref. [54]. The electron (muon) candidates are required to pass minimal kinematic selection criteria of $p_T > 10$ GeV and $|\eta| < 2.5(2.4)$ and are referred to as “loose” leptons. The “tight” lepton selection used in the analysis employs an MVA discriminant to separate prompt leptons coming from the decays of W or Z (V) bosons, or τ leptons and nonprompt leptons [54]. The nonprompt leptons originate from the decays of light- and heavy-flavor hadrons inside jets produced via strong interactions (QCD multijet), hadrons misidentified as leptons, and electrons from photon conversions. The MVA discriminant is trained using a set of observables related to the lepton kinematics, isolation, and identification, as well as variables relating the lepton to the PV and to the nearest reconstructed PF jet [54]. Reconstructed jets must not overlap with identified electrons, muons, or τ_h within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$, where ϕ is the azimuthal angle in radians. The DeepJet b -tagging algorithm [55,56] is used to identify jets originating from the hadronization of b quarks. The chosen working point corresponds to a b -tagging efficiency of 84% and a mistag rate of 11% for light-flavor quark and gluon jets.

Collision events are collected using a combination of single-lepton and dilepton triggers that require the presence of one or two isolated leptons above certain p_T thresholds [41]. The resulting trigger efficiency is above 98% for events passing the subsequent offline selection criteria.

The dominant background contribution arises from the WZ process, in which both bosons decay leptonically and one of the leptons from the Z boson decay either is out of the detector acceptance or does not pass the lepton identification criteria. The nonprompt-lepton backgrounds include predominantly $W + \text{jets}$ and QCD multijet events,

with smaller contributions from $t\bar{t}$ production. Other sources of background include $W\gamma^*$ events, $V\gamma$ events with a photon conversion, and ZZ , as well as rare backgrounds, which include SPS $W^\pm W^\pm$, VVV , and $t\bar{t}V$ production. A minor background contribution stems from Drell-Yan (DY) events when the charge of one lepton is mismeasured. The charge mismeasurement in dimuon events is negligible [43], although it is nonzero for electrons [42]. Hence, the lepton charge misidentification (“charge misid”) background contributes to the $e^\pm\mu^\pm$ channel only. The contribution to the signal yield from the production of two overlapping W bosons from pileup is negligible.

The signal process is characterized by the presence of a SS lepton pair with a moderate amount of p_T^{miss} and little jet activity. The signal region (SR) selection requires events with exactly one pair of $e^\pm\mu^\pm$ or $\mu^\pm\mu^\pm$ with $p_T > 25(20)$ GeV for the leading (subleading) lepton. To reduce the contribution from WZ background, events having either a third loosely identified lepton with $p_T > 10$ GeV or a τ_h candidate with $p_T > 20$ GeV and $|\eta| < 2.3$ are rejected. The contributions from nonprompt-lepton backgrounds are reduced by selecting events with $p_T^{\text{miss}} > 15$ GeV and dilepton invariant mass, $m_{\ell\ell} > 12$ GeV.

Events are required to have at most one jet with $p_T^{\text{jet}} > 30$ GeV within $|\eta_{\text{jet}}| < 2.4$. Events with a b -tagged jet having $p_T^{b,\text{jet}} > 25$ GeV and $|\eta_{b,\text{jet}}| < 2.4$ are vetoed to reject top quark events. For the $e^\pm\mu^\pm$ channel, the dilepton transverse momentum should satisfy $p_T^{\ell\ell} > 20$ GeV to suppress contributions from $V\gamma$ and DY processes. To increase the signal sensitivity, events in the SR are split into four lepton flavor and charge categories: $e^+\mu^+$, $e^-\mu^-$, $\mu^+\mu^+$, and $\mu^-\mu^-$.

The normalization of the WZ (ZZ) background is estimated using $WZ \rightarrow 3\ell\nu$ ($ZZ \rightarrow 4\ell$) lepton control regions (CR) by means of a maximum likelihood (ML) fit to the invariant mass of the three- (four-) lepton system. The $WZ \rightarrow 3\ell\nu$ CR is defined by requiring three tight leptons including at least one opposite-sign same-flavor (OSSF) lepton pair with $|m_{\ell\ell} - m_Z| < 10$ GeV. The invariant mass of the three-lepton system must be > 100 GeV. The leading lepton is required to have $p_T > 25$ GeV, and trailing leptons with $p_T > 15$ GeV are selected. The p_T^{miss} threshold is raised to 50 GeV for this CR, and the rest of the selection requirements are taken from the SR. The $ZZ \rightarrow 4\ell$ CR requires an additional fourth tight lepton with $p_T > 10$ GeV without any requirement on jets and p_T^{miss} . Both the OSSF lepton pairs should have $m_{\ell\ell}$ compatible with the Z boson mass.

Various MC event generators are used to simulate the signal and background processes. The signal process is simulated at LO using the PYTHIA [57], HERWIG [58], and dShower [36] generators. The PYTHIA sample, with leptonically decaying W bosons, is taken as the nominal signal sample, and it predicts a signal cross section value of

$\sigma_{\text{DPS}}^{W^\pm W^\pm} = 86.4$ fb with the tune `cuetp8m1` [14]. The tune dependence of the PYTHIA8 cross section is around 40%, emphasizing the need for an experimental measurement. The sample from HERWIG is used for estimating systematic uncertainties. The PYTHIA v8.226 (8.230) using the NNPDF 2.3 [59] parton distribution functions (PDFs) with the underlying tune `cuetp8m1` (`cp5` [60]) is used for the simulation of the 2016 (2017 and 2018) data-taking periods. The event generator HERWIG++ (v2.7) [58,61] using the CTEQ6L1 [62] PDF set with the tune `CUETHppS1` [14] is used for the 2016 data-taking period, whereas HERWIG7 (v7.1.4) using the NNPDF 3.1 [63] with PDF set `ch3` tune [64] is employed for 2017 and 2018. The dShower generator uses dPDF [33,65] developed using the LO MSTW2008 [65] PDF set. For a given event generator, neither the underlying event tune nor the PDF sets used to simulate the signal samples impact the kinematic observables relevant to the analysis.

The WZ background is simulated at next-to-LO (NLO) in QCD with the `MadGraph5_aMC@NLO` v2.4.2 (2.6.5) generator [66] using the FxFx jet merging scheme [67] for the 2016 (2017 and 2018) data-taking period. The `MadGraph5_aMC@NLO` generator is also used to simulate $V\gamma$, $t\bar{t}V$, and triboson (VVV) production. The POWHEG BOX (v2.0) code [68–70] is used to simulate SPS $W^\pm W^\pm$, ZZ , and $W\gamma^*$ production processes. The simulated samples of backgrounds for the 2016 data-taking period use the NNPDF 3.0 [71,72] PDF set, whereas the NNPDF 3.1 set is used for 2017 and 2018. Background simulations and the dShower event generator are interfaced with PYTHIA8 for modeling of the parton showering, hadronization, and underlying event processes, which have similar versions and tunes as the signal process. The CMS detector response is modeled using GEANT4 [73], and the simulated events are reconstructed with the same algorithms used for the data. Simulated events are weighted to reproduce the pileup distribution measured in the data. The average number of pileup interactions was 23 (32) in 2016 (2017 and 2018). Scale factors are applied to simulated samples to correct for differences in the reconstruction and selection of physics objects and in the trigger efficiencies between simulation and data. These scale factors are measured with the “tag-and-probe” method using DY events [74].

The nonprompt-lepton background is estimated directly from data using the lepton misidentification rate method [54]. The probability for a loose nonprompt lepton to pass the tight lepton selection criteria (f_p) is estimated using a data control sample dominated by nonprompt leptons and is parametrized as a function of p_T and $|\eta|$. Events in a sideband of the SR, with at least one lepton failing the tight lepton selection criteria, are reweighted with f_p to estimate the nonprompt-lepton background contribution. A similar approach is used to estimate the background contribution from “charge misidentification” events by applying the lepton charge misidentification rate to opposite-sign

events in data. The charge misidentification rate is about 0.01% (0.10%) for electrons in the barrel (end cap) regions.

Because of the topological differences between the dominant WZ and nonprompt-lepton backgrounds, two separate boosted decision tree (BDT) discriminants [75] are trained to distinguish the signal from these background components. Addition of the BDT discriminant trained against the nonprompt-lepton backgrounds improves the signal sensitivity by 13%. The BDT training against the WZ sample is done using its simulated sample, whereas the training against nonprompt leptons is carried out using a “tight-loose” control sample in data. Kinematic differences between the signal and these backgrounds are explored to define a set of input variables for the training of two discriminants, which are optimized based on their discriminating power. These input variables include transverse momenta of the two leptons; p_T^{miss} ; product and absolute sum of the η of the two leptons; separation in ϕ between the leptons; separation in ϕ between the subleading lepton and p_T^{miss} ; separation in ϕ between the dilepton system and the subleading lepton; transverse mass of the two leptons; transverse mass of the leading lepton and p_T^{miss} ; and the “stransverse mass” of the dilepton and p_T^{miss} system [76,77]. The two BDT scores are mapped into a two-dimensional (2D) plane in both discriminants. Further, the 2D plane is divided into 13 contiguous regions on which the final fit is performed. This division into regions is performed through optimization of the expected signal significance.

The integrated luminosities for the 2016–2018 data-taking years have individual uncertainties of 1.2%–2.5% [78–80], while the overall uncertainty for the 2016–2018 period is 1.6%. The simulation of pileup events assumes an inelastic pp cross section of 69.2 mb, with an associated uncertainty of 5% [81], which impacts the expected signal and background yields by 1%. The uncertainties in data to simulation scale factors corresponding to the lepton trigger, reconstruction, and identification result in an uncertainty of 3.3% (2.8%) for the $e^\pm\mu^\pm$ ($\mu^\pm\mu^\pm$) final states. This also includes an uncertainty in the scale factors applied to account for the $L1$ trigger inefficiency observed in the $|\eta| > 2.0$ region for the 2016 and 2017 data-taking periods [40]. The jet energy scale uncertainties affect the expected event yields by 3%. Uncertainties in the p_T^{miss} are calculated by varying the momenta of unclustered particles that are identified neither as a jet nor as a lepton and affect the expected event yields by $\approx 2\%$. The uncertainty in the b -tagging efficiency has an effect of $\approx 1.8\%$ on the expected event yields.

For the $e^\pm\mu^\pm$ ($\mu^\pm\mu^\pm$) channels, a normalization uncertainty of 30% (25%) in the nonprompt-lepton background accounts for the observed variations in the background estimation method when applied to simulated samples. The dependence of f_p on the kinematics of the event sample in which it is measured is included as a shape uncertainty [54].

A normalization uncertainty of 20% is applied to the “charge misid” background, covering the differences in the measurement of the charge misidentification rate in data and simulation. The data-to-MC normalization factors of the $V\gamma$ background, measured using a dedicated CR [82], are close to unity.

A 50% normalization uncertainty is applied to all other small simulated backgrounds, accounting for the theoretical uncertainties in the predicted cross sections. The theoretical uncertainties associated with the choice of the renormalization and factorization scales and the variations in the PDFs and the strong coupling constant [83,84] affect the simulated background yields by $\approx 1\%$. The effect of variation in PDF sets is negligible for the signal simulations. Any residual model dependence of the signal process is estimated by allowing the shape of the final BDT discriminant to vary between the PYTHIA and HERWIG simulations, and the resulting effect is small. The statistical uncertainties due to the limited size of the MC samples are treated according to the Barlow-Beeston-lite method [85,86].

The yield of the DPS $W^\pm W^\pm$ process in the SR is obtained by performing a binned ML fit simultaneously in the SR and in the two CRs [87–89]; i.e., the normalization factors for the WZ and ZZ backgrounds are included as free parameters in the fit together with the signal process. The fit is performed after combining all the background and signal processes in the aforementioned lepton flavor and charge categories, resulting in four independent distributions of the final BDT discriminant per data-taking year. An excess of events with respect to the background-only hypothesis is observed, which is quantified by calculating the p value using a profile likelihood ratio test statistic [87]. Figure 2 shows the BDT discriminant distribution after the ML fit (postfit) for the four lepton flavor and sign categories. The contributions from different backgrounds and the signal processes are stacked on top of each other, and the associated postfit uncertainties are also shown. The distributions of the kinematic variables used to train the BDT discriminants along with the two BDT discriminants are shown in Supplemental Material [90].

The measured value of $\sigma_{\text{DPS}}^{W^\pm W^\pm}$ is $80.7 \pm 11.2(\text{stat})_{-8.6}^{+9.5}(\text{syst}) \pm 12.1(\text{model})$ fb, where the model uncertainty accounts for the difference in cross sections obtained in the experimental acceptance region with the PYTHIA and HERWIG simulations. The observed statistical significance of the signal is 6.2 standard deviations above the background-only hypothesis. Separate fits to the $e^\pm\mu^\pm$ and $\mu^\pm\mu^\pm$ channels indicate that the two measurements agree within 1.7 standard deviations. The DPS $W^\pm W^\pm$ production cross section is also measured in a fiducial volume, defined using two generator-level SS “dressed” leptons ($e^\pm\mu^\pm$ or $\mu^\pm\mu^\pm$) from W boson decays excluding the events with leptonically decaying τ leptons. The leptons are dressed by adding the momenta of generator-level

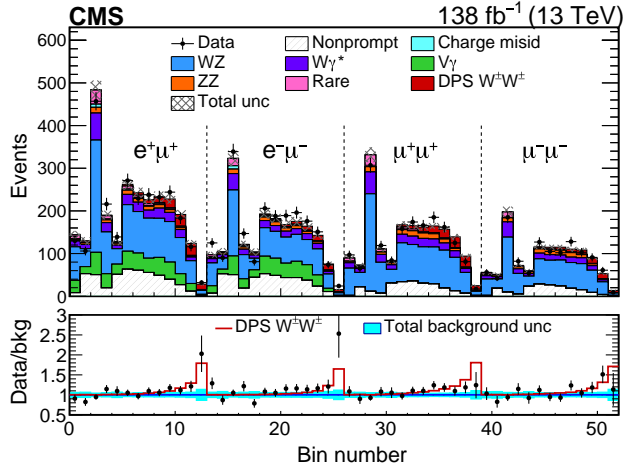


FIG. 2. Postfit distribution of the final BDT discriminant output for the four lepton flavor and sign categories. The SPS $W^\pm W^\pm$, $t\bar{t}V$, and VVV contributions are grouped as the “rare” background. The total postfit uncertainty in the signal and background predictions is shown as the hatched band. The bottom panels show the ratio of data to the sum of all background contributions as the black data points along with the extracted signal shown by the red line. The vertical error bars on the data points represent the statistical uncertainty of the data.

photons within a cone of $\Delta R(\ell, \gamma) < 0.1$ to their momenta and are required to pass kinematic requirements on the p_T , η , $m_{\ell\ell}$, and $p_T^{\ell\ell}$ variables from the SR selection. The measured fiducial cross section is $6.28 \pm 0.81(\text{stat}) \pm 0.69(\text{syst}) \pm 0.37(\text{model})$ fb, where the model uncertainty represents the observed difference in reconstruction efficiencies within the fiducial region obtained using the PYTHIA and HERWIG simulations. The measured value of the inclusive (fiducial) cross section is in agreement with the predicted value of 86.4 (6.74) fb by PYTHIA8 with the tune `cuetp8m1` and `dShower`. A value of σ_{eff} is extracted from Eq. (1), using the measured $\sigma_{\text{DPS}}^{W^\pm W^\pm}$ value and the next-to-NLO prediction for the single W^+ (W^-) production cross section including leptonic decays of $35.4 \pm 1.4(26.0 \pm 1.0)$ nb [91,92]. This procedure results in a value of $12.2^{+2.9}_{-2.2}$ mb, consistent with previous measurements of this quantity from final states with vector bosons [19,26]. Tabulated results are provided in HEPData [93].

In summary, the first observation of $W^\pm W^\pm$ production from double parton scattering processes in proton-proton collisions at $\sqrt{s} = 13$ TeV has been reported. The analyzed dataset corresponds to an integrated luminosity of 138 fb^{-1} collected in 2016–2018 using the CMS detector at the LHC. Events are selected by requiring same-sign electron-muon or dimuon pairs with moderate missing transverse momentum and low jet multiplicity. Boosted decision trees are used to discriminate between the signal and the dominant background processes. A fiducial cross section of $6.28 \pm 0.81(\text{stat}) \pm 0.69(\text{syst}) \pm 0.37(\text{model})$ fb is extracted, and an inclusive cross section of $80.7 \pm 11.2(\text{stat})^{+9.5}_{-8.6}(\text{syst}) \pm 12.1(\text{model})$ fb is measured. This corresponds to an

observed significance of the signal above the background-only hypothesis of 6.2 standard deviations. A value of the DPS effective cross section, characterizing the transverse distribution of partons in the proton, $\sigma_{\text{eff}} = 12.2^{+2.9}_{-2.2}$ mb is extracted.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); and DOE and NSF (USA).

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J. Fraga²⁰, J. Mejia Guisao²¹, F. Ramirez²¹, M. Rodriguez²¹, J. D. Ruiz Alvarez²¹, D. Giljanovic²²,
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 A. Savoy-Navarro^{35,q}, P. Simkina³⁵, M. Titov³⁵, C. Baldenegro Barrera³⁶, F. Beaudette³⁶, A. Buchot Perraguin³⁶,
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 A.-C. Le Bihan³⁷, P. Van Hove³⁷, S. Beauceron³⁸, C. Bernet³⁸, B. Blancon³⁸, G. Boudoul³⁸, A. Carle³⁸,
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 L. Torterotot³⁸, M. Vander Donckt³⁸, P. Verdier³⁸, S. Viret³⁸, G. Adamov³⁹, I. Lomidze³⁹, Z. Tsamalaidze^{39,n},
 V. Botta⁴⁰, L. Feld⁴⁰, K. Klein⁴⁰, M. Lipinski⁴⁰, D. Meuser⁴⁰, A. Pauls⁴⁰, N. Röwert⁴⁰, M. Teroerde⁴⁰,
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 O. Pooth⁴², A. Stahl^{42,u}, T. Ziemons⁴², A. Zotz⁴², H. Aarup Petersen⁴³, M. Aldaya Martin⁴³, P. Asmuss⁴³,
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 F. Blekman^{43,v}, K. Borrás^{43,w}, D. Brunner⁴³, A. Campbell⁴³, A. Cardini⁴³, C. Cheng⁴³, F. Colombina⁴³,
 S. Consuegra Rodríguez⁴³, G. Correia Silva⁴³, M. De Silva⁴³, L. Didukh⁴³, G. Eckerlin⁴³, D. Eckstein⁴³,
 L. I. Estevez Banos⁴³, O. Filatov⁴³, E. Gallo^{43,v}, A. Geiser⁴³, A. Giraldi⁴³, G. Greau⁴³, A. Grohsjean⁴³,
 V. Guglielmi⁴³, M. Guthoff⁴³, A. Jafari^{43,x}, N. Z. Jomhari⁴³, B. Kaeck⁴³, A. Kasem^{43,w}, M. Kasemann⁴³,
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 W. Lohmann^{43,y}, R. Mankel⁴³, I.-A. Melzer-Pellmann⁴³, M. Mendizabal Morentin⁴³, J. Metwally⁴³, A. B. Meyer⁴³,
 G. Milella⁴³, M. Mormile⁴³, A. Mussgiller⁴³, A. Nürnberg⁴³, Y. Otari⁴³, D. Pérez Adán⁴³, A. Raspereza⁴³,
 B. Ribeiro Lopes⁴³, J. Rübenach⁴³, A. Saggio⁴³, A. Saibel⁴³, M. Savitskyi⁴³, M. Scham^{43,w,z}, V. Scheurer⁴³,
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 N. Tonon^{43,a}, M. Van De Klundert⁴³, F. Vazzoler⁴³, A. Ventura Barroso⁴³, R. Walsh⁴³, D. Walter⁴³, Q. Wang⁴³,
 Y. Wen⁴³, K. Wichmann⁴³, L. Wiens^{43,w}, C. Wissing⁴³, S. Wuchterl⁴³, Y. Yang⁴³, A. Zimmermann Castro Santos⁴³,
 R. Aggleton⁴⁴, A. Albrecht⁴⁴, S. Albrecht⁴⁴, M. Antonello⁴⁴, S. Bein⁴⁴, L. Benato⁴⁴, M. Bonanomi⁴⁴,
 P. Connor⁴⁴, K. De Leo⁴⁴, M. Eich⁴⁴, K. El Morabit⁴⁴, F. Feindt⁴⁴, A. Fröhlich⁴⁴, C. Garbers⁴⁴, E. Garutti⁴⁴,
 M. Hajheidari⁴⁴, J. Haller⁴⁴, A. Hinzmann⁴⁴, H. R. Jabusch⁴⁴, G. Kasieczka⁴⁴, R. Klanner⁴⁴, W. Korcari⁴⁴,
 T. Kramer⁴⁴, V. Kutzner⁴⁴, J. Lange⁴⁴, A. Lobanov⁴⁴, C. Matthies⁴⁴, A. Mehta⁴⁴, L. Moureaux⁴⁴,
 M. Mrowietz⁴⁴, A. Nigamova⁴⁴, Y. Nissan⁴⁴, A. Paasch⁴⁴, K. J. Pena Rodriguez⁴⁴, M. Rieger⁴⁴, O. Rieger⁴⁴,
 P. Schleper⁴⁴, M. Schröder⁴⁴, J. Schwandt⁴⁴, H. Stadie⁴⁴, G. Steinbrück⁴⁴, A. Tews⁴⁴, M. Wolf⁴⁴, J. Bechtel⁴⁵,
 S. Brommer⁴⁵, M. Burkart⁴⁵, E. Butz⁴⁵, R. Caspart⁴⁵, T. Chwalek⁴⁵, A. Dierlamm⁴⁵, A. Droll⁴⁵, N. Faltermann⁴⁵

M. Giffels⁴⁵ J. O. Gosewisch⁴⁵ A. Gottmann⁴⁵ F. Hartmann^{45,u} M. Horzela⁴⁵ U. Husemann⁴⁵ P. Keicher⁴⁵
M. Klute⁴⁵ R. Koppenhöfer⁴⁵ S. Maier⁴⁵ S. Mitra⁴⁵ Th. Müller⁴⁵ M. Neukum⁴⁵ G. Quast⁴⁵ K. Rabbertz⁴⁵
J. Rauser⁴⁵ D. Savoio⁴⁵ M. Schnepf⁴⁵ D. Seith⁴⁵ I. Shvetsov⁴⁵ H. J. Simonis⁴⁵ N. Trevisani⁴⁵ R. Ulrich⁴⁵
J. van der Linden⁴⁵ R. F. Von Cube⁴⁵ M. Wassmer⁴⁵ M. Weber⁴⁵ S. Wieland⁴⁵ R. Wolf⁴⁵ S. Wozniowski⁴⁵
S. Wunsch⁴⁵ G. Anagnostou⁴⁶ P. Assiouras⁴⁶ G. Daskalakis⁴⁶ A. Kyriakis⁴⁶ A. Stakia⁴⁶ M. Diamantopoulou⁴⁷
D. Karasavvas⁴⁷ P. Kontaxakis⁴⁷ A. Manousakis-Katsikakis⁴⁷ A. Panagiotou⁴⁷ I. Papavergou⁴⁷ N. Saoulidou⁴⁷
K. Theofilatos⁴⁷ E. Tziaferi⁴⁷ K. Vellidis⁴⁷ E. Vourliotis⁴⁷ I. Zisopoulos⁴⁷ G. Bakas⁴⁸ T. Chatzistavrou⁴⁸
K. Kousouris⁴⁸ I. Papakrivopoulos⁴⁸ G. Tsiopolitis⁴⁸ A. Zacharopoulou⁴⁸ K. Adamidis⁴⁹ I. Bestintzanos⁴⁹
I. Evangelou⁴⁹ C. Foudas⁴⁹ P. Gianneios⁴⁹ C. Kamtsikis⁴⁹ P. Katsoulis⁴⁹ P. Kokkas⁴⁹
P. G. Kosmoglou Kioseoglou⁴⁹ N. Manthos⁴⁹ I. Papadopoulos⁴⁹ J. Strologas⁴⁹ M. Csanád⁵⁰ K. Farkas⁵⁰
M. M. A. Gadallah^{50,aa} C. Komjáti⁵⁰ S. Lökös^{50,bb} P. Major⁵⁰ K. Mandal⁵⁰ G. Pásztor⁵⁰ A. J. Rádl^{50,cc}
O. Surányi⁵⁰ G. I. Veres⁵⁰ M. Bartók^{51,dd} G. Bencze⁵¹ C. Hajdu⁵¹ D. Horvath^{51,ee,ff} F. Sikler⁵¹
V. Veszpremi⁵¹ N. Beni⁵² S. Czellar⁵² J. Karancsi^{52,dd} J. Molnar⁵² Z. Szillasi⁵² D. Teyssier⁵² P. Raics⁵³
B. Ujvari^{53,gg} T. Csorgo^{54,cc} F. Nemes^{54,cc} T. Novak⁵⁴ J. Babbar⁵⁵ S. Bansal⁵⁵ S. B. Beri⁵⁵ V. Bhatnagar⁵⁵
G. Chaudhary⁵⁵ S. Chauhan⁵⁵ N. Dhingra^{55,hh} R. Gupta⁵⁵ A. Kaur⁵⁵ A. Kaur⁵⁵ H. Kaur⁵⁵ M. Kaur⁵⁵
S. Kumar⁵⁵ P. Kumari⁵⁵ M. Meena⁵⁵ K. Sandeep⁵⁵ T. Sheokand⁵⁵ J. B. Singh^{55,ii} A. Singla⁵⁵ A. K. Viridi⁵⁵
A. Ahmed⁵⁶ A. Bhardwaj⁵⁶ B. C. Choudhary⁵⁶ M. Gola⁵⁶ S. Keshri⁵⁶ A. Kumar⁵⁶ M. Naimuddin⁵⁶
P. Priyanka⁵⁶ K. Ranjan⁵⁶ S. Saumya⁵⁶ A. Shah⁵⁶ S. Baradia⁵⁷ S. Barman^{57,ji} S. Bhattacharya⁵⁷
D. Bhowmik⁵⁷ S. Dutta⁵⁷ S. Dutta⁵⁷ B. Gomber^{57,kk} M. Maity^{57,ji} P. Palit⁵⁷ P. K. Rout⁵⁷ G. Saha⁵⁷ B. Sahu⁵⁷
S. Sarkar⁵⁷ P. K. Behera⁵⁸ S. C. Behera⁵⁸ P. Kalbhor⁵⁸ J. R. Komaragiri^{58,ll} D. Kumar^{58,ll} A. Muhammad⁵⁸
L. Panwar^{58,ll} R. Pradhan⁵⁸ P. R. Pujahari⁵⁸ A. Sharma⁵⁸ A. K. Sikdar⁵⁸ P. C. Tiwari^{58,ll} S. Verma⁵⁸
K. Naskar^{59,mm} T. Aziz⁶⁰ I. Das⁶⁰ S. Dugad⁶⁰ M. Kumar⁶⁰ G. B. Mohanty⁶⁰ P. Suryadevara⁶⁰ S. Banerjee⁶¹
R. Chudasama⁶¹ M. Guchait⁶¹ S. Karmakar⁶¹ S. Kumar⁶¹ G. Majumder⁶¹ K. Mazumdar⁶¹ S. Mukherjee⁶¹
A. Thachayath⁶¹ S. Bahinipati^{62,nn} A. K. Das⁶² C. Kar⁶² P. Mal⁶² T. Mishra⁶²
V. K. Muraleedharan Nair Bindhu^{62,oo} A. Nayak^{62,oo} P. Saha⁶² N. Sur⁶² S. K. Swain⁶² D. Vats^{62,oo}
A. Alpana⁶³ S. Dube⁶³ B. Kansal⁶³ A. Laha⁶³ S. Pandey⁶³ A. Rastogi⁶³ S. Sharma⁶³
H. Bakhshiansohi^{64,pp} E. Khazaie⁶⁴ M. Zeinali^{64,qq} S. Chenarani^{65,rr} S. M. Etesami⁶⁵ M. Khakzad⁶⁵
M. Mohammadi Najafabadi⁶⁵ M. Grunewald⁶⁶ M. Abbrescia^{67a,67b} R. Aly^{67a,67c,ss} C. Aruta^{67a,67b}
A. Colaleo^{67a} D. Creanza^{67a,67c} N. De Filippis^{67a,67c} M. De Palma^{67a,67b} A. Di Florio^{67a,67b}
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I. Margjeka^{67a,67b} V. Mastrapasqua^{67a,67b} S. My^{67a,67b} S. Nuzzo^{67a,67b} A. Pellecchia^{67a,67b} A. Pompili^{67a,67b}
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A. Fanfani^{68a,68b} P. Giacomelli^{68a} L. Giommi^{68a,68b} C. Grandi^{68a} L. Guiducci^{68a,68b} S. Lo Meo^{68a,tt}
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N. Bacchetta^{75a,ww} P. Bortignon^{75a} A. Bragagnolo^{75a,75b} R. Carlin^{75a,75b} P. Checchia^{75a} U. Gasparini^{75a,75b}

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 J. Pazzini^{75a,75b} P. Ronchese^{75a,75b} R. Rossin^{75a,75b} M. Sgaravatto^{75a} F. Simonetto^{75a,75b} G. Strong^{75a}
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 V. Re^{76a} C. Riccardi^{76a,76b} P. Salvini^{76a} I. Vai^{76a} P. Vitulo^{76a,76b} P. Asenov^{77a,zz} G. M. Bilei^{77a}
 D. Ciangottini^{77a,77b} L. Fanò^{77a,77b} M. Magherini^{77a,77b} G. Mantovani,^{77a,77b} V. Mariani^{77a,77b} M. Menichelli^{77a}
 F. Moscatelli^{77a,zz} A. Piccinelli^{77a,77b} M. Presilla^{77a,77b} A. Rossi^{77a,77b} A. Santocchia^{77a,77b} D. Spiga^{77a}
 T. Tedeschi^{77a,77b} P. Azzurri^{78a} G. Bagliesi^{78a} V. Bertacchi^{78a,78c} R. Bhattacharya^{78a} L. Bianchini^{78a,78b}
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 J. Berenguer Antequera^{80a,80b} C. Biino^{80a} N. Cartiglia^{80a} M. Costa^{80a,80b} R. Covarelli^{80a,80b} N. Demaria^{80a}
 M. Grippo^{80a,80b} B. Kiani^{80a,80b} F. Legger^{80a} C. Mariotti^{80a} S. Maselli^{80a} A. Mecca^{80a,80b} E. Migliore^{80a,80b}
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 A. Staiano^{80a} M. Tornago^{80a,80b} D. Trocino^{80a} G. Umoret^{80a,80b} A. Vagnerini^{80a,80b} S. Belforte^{81a}
 V. Candélise^{81a,81b} M. Casarsa^{81a} F. Cossutti^{81a} A. Da Rold^{81a,81b} G. Della Ricca^{81a,81b} G. Sorrentino^{81a,81b}
 S. Dogra⁸² C. Huh⁸² B. Kim⁸² D. H. Kim⁸² G. N. Kim⁸² J. Kim⁸² J. Lee⁸² S. W. Lee⁸² C. S. Moon⁸²
 Y. D. Oh⁸² S. I. Pak⁸² M. S. Ryu⁸² S. Sekmen⁸² Y. C. Yang⁸² H. Kim⁸³ D. H. Moon⁸³ E. Asilar⁸⁴
 T. J. Kim⁸⁴ J. Park⁸⁴ S. Cho⁸⁵ S. Choi⁸⁵ S. Han⁸⁵ B. Hong⁸⁵ K. Lee⁸⁵ K. S. Lee⁸⁵ J. Lim⁸⁵ J. Park⁸⁵
 S. K. Park⁸⁵ J. Yoo⁸⁵ J. Goh⁸⁶ H. S. Kim⁸⁷ Y. Kim⁸⁷ S. Lee⁸⁷ J. Almond⁸⁸ J. H. Bhyun⁸⁸ J. Choi⁸⁸ S. Jeon⁸⁸
 W. Jun⁸⁸ J. Kim⁸⁸ J. Kim⁸⁸ J. S. Kim⁸⁸ S. Ko⁸⁸ H. Kwon⁸⁸ H. Lee⁸⁸ J. Lee⁸⁸ S. Lee⁸⁸ B. H. Oh⁸⁸
 M. Oh⁸⁸ S. B. Oh⁸⁸ H. Seo⁸⁸ U. K. Yang⁸⁸ I. Yoon⁸⁸ W. Jang⁸⁹ D. Y. Kang⁸⁹ Y. Kang⁸⁹ D. Kim⁸⁹
 S. Kim⁸⁹ B. Ko⁸⁹ J. S. H. Lee⁸⁹ Y. Lee⁸⁹ J. A. Merlin⁸⁹ I. C. Park⁸⁹ Y. Roh⁸⁹ D. Song⁸⁹ I. J. Watson⁸⁹
 S. Yang⁸⁹ S. Ha⁹⁰ H. D. Yoo⁹⁰ M. Choi⁹¹ M. R. Kim⁹¹ H. Lee⁹¹ Y. Lee⁹¹ Y. Lee⁹¹ I. Yu⁹¹
 T. Beyrouthy⁹² Y. Maghrbi⁹² K. Dreimanis⁹³ A. Gaile⁹³ A. Potrebko⁹³ T. Torims⁹³ V. Veckalns⁹³
 M. Ambrozas⁹⁴ A. Carvalho Antunes De Oliveira⁹⁴ A. Juodagalvis⁹⁴ A. Rinkevicius⁹⁴ G. Tamulaitis⁹⁴
 N. Bin Norjoharuddeen⁹⁵ S. Y. Hoh^{95,aaa} I. Yusuff^{95,aaa} Z. Zolkapli⁹⁵ J. F. Benitez⁹⁶ A. Castaneda Hernandez⁹⁶
 H. A. Encinas Acosta⁹⁶ L. G. Gallegos Maríñez⁹⁶ M. León Coello⁹⁶ J. A. Murillo Quijada⁹⁶ A. Sehrawat⁹⁶
 L. Valencia Palomo⁹⁶ G. Ayala⁹⁷ H. Castilla-Valdez⁹⁷ I. Heredia-De La Cruz^{97,bbb} R. Lopez-Fernandez⁹⁷
 C. A. Mondragon Herrera⁹⁷ D. A. Perez Navarro⁹⁷ A. Sánchez Hernández⁹⁷ C. Oropeza Barrera⁹⁸
 F. Vazquez Valencia⁹⁸ I. Pedraza⁹⁹ H. A. Salazar Ibarguen⁹⁹ C. Uribe Estrada⁹⁹ I. Bujanja¹⁰⁰ J. Mijuskovic^{100,ccc}
 N. Raicevic¹⁰⁰ A. Ahmad¹⁰¹ M. I. Asghar¹⁰¹ A. Awais¹⁰¹ M. I. M. Awan¹⁰¹ M. Gul¹⁰¹ H. R. Hoorani¹⁰¹
 W. A. Khan¹⁰¹ M. Shoaib¹⁰¹ M. Waqas¹⁰¹ V. Avati¹⁰² L. Grzanka¹⁰² M. Malawski¹⁰² H. Bialkowska¹⁰³
 M. Bluj¹⁰³ B. Boimska¹⁰³ M. Górski¹⁰³ M. Kazana¹⁰³ M. Szleper¹⁰³ P. Zalewski¹⁰³ K. Bunkowski¹⁰⁴
 K. Doroba¹⁰⁴ A. Kalinowski¹⁰⁴ M. Konecki¹⁰⁴ J. Krolikowski¹⁰⁴ M. Araujo¹⁰⁵ P. Bargassa¹⁰⁵ D. Bastos¹⁰⁵
 A. Boletti¹⁰⁵ P. Faccioli¹⁰⁵ M. Gallinaro¹⁰⁵ J. Hollar¹⁰⁵ N. Leonardo¹⁰⁵ T. Niknejad¹⁰⁵ M. Pisano¹⁰⁵
 J. Seixas¹⁰⁵ O. Toldaiev¹⁰⁵ J. Varela¹⁰⁵ P. Adzic^{106,ddd} M. Dordevic¹⁰⁶ P. Milenovic¹⁰⁶ J. Milosevic¹⁰⁶
 M. Aguilar-Benitez¹⁰⁷ J. Alcaraz Maestre¹⁰⁷ A. Álvarez Fernández¹⁰⁷ M. Barrio Luna¹⁰⁷ Cristina F. Bedoya¹⁰⁷
 C. A. Carrillo Montoya¹⁰⁷ M. Cepeda¹⁰⁷ M. Cerrada¹⁰⁷ N. Colino¹⁰⁷ B. De La Cruz¹⁰⁷ A. Delgado Peris¹⁰⁷
 D. Fernández Del Val¹⁰⁷ J. P. Fernández Ramos¹⁰⁷ J. Flix¹⁰⁷ M. C. Fouz¹⁰⁷ O. Gonzalez Lopez¹⁰⁷
 S. Goy Lopez¹⁰⁷ J. M. Hernandez¹⁰⁷ M. I. Josa¹⁰⁷ J. León Holgado¹⁰⁷ D. Moran¹⁰⁷ C. Perez Dengra¹⁰⁷
 A. Pérez-Calero Yzquierdo¹⁰⁷ J. Puerta Pelayo¹⁰⁷ I. Redondo¹⁰⁷ D. D. Redondo Ferrero¹⁰⁷ L. Romero¹⁰⁷

S. Sánchez Navas¹⁰⁷, J. Sastre¹⁰⁷, L. Urda Gómez¹⁰⁷, J. Vazquez Escobar¹⁰⁷, C. Willmott¹⁰⁷, J. F. de Trocóniz¹⁰⁸, B. Alvarez Gonzalez¹⁰⁹, J. Cuevas¹⁰⁹, J. Fernandez Menendez¹⁰⁹, S. Folgueras¹⁰⁹, I. Gonzalez Caballero¹⁰⁹, J. R. González Fernández¹⁰⁹, E. Palencia Cortezon¹⁰⁹, C. Ramón Álvarez¹⁰⁹, V. Rodríguez Bouza¹⁰⁹, A. Soto Rodríguez¹⁰⁹, A. Trapote¹⁰⁹, C. Vico Villalba¹⁰⁹, J. A. Brochero Cifuentes¹¹⁰, I. J. Cabrillo¹¹⁰, A. Calderon¹¹⁰, J. Duarte Campderros¹¹⁰, M. Fernandez¹¹⁰, C. Fernandez Madrazo¹¹⁰, A. García Alonso¹¹⁰, G. Gomez¹¹⁰, C. Lasasa García¹¹⁰, C. Martinez Rivero¹¹⁰, P. Martinez Ruiz del Arbol¹¹⁰, F. Matorras¹¹⁰, P. Matorras Cuevas¹¹⁰, J. Piedra Gomez¹¹⁰, C. Prieels¹¹⁰, A. Ruiz-Jimeno¹¹⁰, L. Scodellaro¹¹⁰, I. Vila¹¹⁰, J. M. Vizan Garcia¹¹⁰, M. K. Jayananda¹¹¹, B. Kailasapathy^{111,eee}, D. U. J. Sonnadara¹¹¹, D. D. C. Wickramaratna¹¹¹, W. G. D. Dharmaratna¹¹², K. Liyanage¹¹², N. Perera¹¹², N. Wickramage¹¹², D. Abbaneo¹¹³, J. Alimena¹¹³, E. Auffray¹¹³, G. Auzinger¹¹³, J. Baechler¹¹³, P. Baillon^{113,a}, D. Barney¹¹³, J. Bendavid¹¹³, M. Bianco¹¹³, B. Bilin¹¹³, A. Bocci¹¹³, E. Brondolin¹¹³, C. Caillol¹¹³, T. Camporesi¹¹³, G. Cerminara¹¹³, N. Chernyavskaya¹¹³, S. S. Chhibra¹¹³, S. Choudhury¹¹³, M. Cipriani¹¹³, L. Cristella¹¹³, D. d'Enterria¹¹³, A. Dabrowski¹¹³, A. David¹¹³, A. De Roeck¹¹³, M. M. Defranchis¹¹³, M. Deile¹¹³, M. Dobson¹¹³, M. Dünser¹¹³, N. Dupont¹¹³, A. Elliott-Peisert¹¹³, F. Fallavollita^{113,fff}, A. Florent¹¹³, L. Forthomme¹¹³, G. Franzoni¹¹³, W. Funk¹¹³, S. Ghosh¹¹³, S. Giani¹¹³, D. Gigi¹¹³, K. Gill¹¹³, F. Glege¹¹³, L. Gouskos¹¹³, E. Govorkova¹¹³, M. Haranko¹¹³, J. Hegeman¹¹³, V. Innocente¹¹³, T. James¹¹³, P. Janot¹¹³, J. Kaspar¹¹³, J. Kieseler¹¹³, N. Kratochwil¹¹³, S. Laurila¹¹³, P. Lecoq¹¹³, E. Leutgeb¹¹³, A. Lintuluoto¹¹³, C. Lourenço¹¹³, B. Maier¹¹³, L. Malgeri¹¹³, M. Mannelli¹¹³, A. C. Marini¹¹³, F. Meijers¹¹³, S. Mersi¹¹³, E. Meschi¹¹³, F. Moortgat¹¹³, M. Mulders¹¹³, S. Orfanelli¹¹³, L. Orsini¹¹³, F. Pantaleo¹¹³, E. Perez¹¹³, M. Peruzzi¹¹³, A. Petrilli¹¹³, G. Petrucciani¹¹³, A. Pfeiffer¹¹³, M. Pierini¹¹³, D. Piparo¹¹³, M. Pitt¹¹³, H. Qu¹¹³, T. Quast¹¹³, D. Rabady¹¹³, A. Racz¹¹³, G. Reales Gutiérrez¹¹³, M. Rovere¹¹³, H. Sakulin¹¹³, J. Salfeld-Nebgen¹¹³, S. Scarfi¹¹³, M. Selvaggi¹¹³, A. Sharma¹¹³, P. Silva¹¹³, P. Sphicas^{113,ggg}, A. G. Stahl Leitner¹¹³, S. Summers¹¹³, K. Tatar¹¹³, V. R. Tavolaro¹¹³, D. Treille¹¹³, P. Tropea¹¹³, A. Tsiro¹¹³, J. Wanczyk^{113,hhh}, K. A. Wozniak¹¹³, W. D. Zeuner¹¹³, L. Caminada^{114,iii}, A. Ebrahimi¹¹⁴, W. Erdmann¹¹⁴, R. Horisberger¹¹⁴, Q. Ingram¹¹⁴, H. C. Kaestli¹¹⁴, D. Kotlinski¹¹⁴, C. Lange¹¹⁴, M. Missiroli^{114,iii}, L. Noehte^{114,iii}, T. Rohe¹¹⁴, T. K. Aarrestad¹¹⁵, K. Androsov^{115,hhh}, M. Backhaus¹¹⁵, P. Berger¹¹⁵, A. Calandri¹¹⁵, K. Datta¹¹⁵, A. De Cosa¹¹⁵, G. Dissertori¹¹⁵, M. Dittmar¹¹⁵, M. Donegà¹¹⁵, F. Eble¹¹⁵, M. Galli¹¹⁵, K. Gedia¹¹⁵, F. Glessgen¹¹⁵, T. A. Gómez Espinosa¹¹⁵, C. Grab¹¹⁵, D. Hits¹¹⁵, W. Lustermann¹¹⁵, A.-M. Lyon¹¹⁵, R. A. Manzoni¹¹⁵, L. Marchese¹¹⁵, C. Martin Perez¹¹⁵, A. Mascellani^{115,hhh}, M. T. Meinhard¹¹⁵, F. Nessi-Tedaldi¹¹⁵, J. Niedziela¹¹⁵, F. Pauss¹¹⁵, V. Perovic¹¹⁵, S. Pigazzini¹¹⁵, M. G. Ratti¹¹⁵, M. Reichmann¹¹⁵, C. Reissel¹¹⁵, T. Reitenspiess¹¹⁵, B. Ristic¹¹⁵, F. Riti¹¹⁵, D. Ruini¹¹⁵, D. A. Sanz Becerra¹¹⁵, J. Steggemann^{115,hhh}, D. Valsecchi^{115,u}, R. Wallny¹¹⁵, C. AMSler^{116,iii}, P. Bäertschi¹¹⁶, C. Botta¹¹⁶, D. Brzhechko¹¹⁶, M. F. Canelli¹¹⁶, K. Cormier¹¹⁶, A. De Wit¹¹⁶, R. Del Burgo¹¹⁶, J. K. Heikkilä¹¹⁶, M. Huwiler¹¹⁶, W. Jin¹¹⁶, A. Jofrehei¹¹⁶, B. Kilminster¹¹⁶, S. Leontsinis¹¹⁶, S. P. Liechi¹¹⁶, A. Macchiolo¹¹⁶, P. Meiring¹¹⁶, V. M. Mikuni¹¹⁶, U. Molinatti¹¹⁶, I. Neutelings¹¹⁶, A. Reimers¹¹⁶, P. Robmann¹¹⁶, S. Sanchez Cruz¹¹⁶, K. Schweiger¹¹⁶, M. Senger¹¹⁶, Y. Takahashi¹¹⁶, C. Adloff^{117,kkk}, C. M. Kuo¹¹⁷, W. Lin¹¹⁷, S. S. Yu¹¹⁷, L. Ceard¹¹⁸, Y. Chao¹¹⁸, K. F. Chen¹¹⁸, P. s. Chen¹¹⁸, H. Cheng¹¹⁸, W.-S. Hou¹¹⁸, Y. y. Li¹¹⁸, R.-S. Lu¹¹⁸, E. Paganis¹¹⁸, A. Psallidas¹¹⁸, A. Steen¹¹⁸, H. y. Wu¹¹⁸, E. Yazgan¹¹⁸, P. r. Yu¹¹⁸, C. Asawatangtrakuldee¹¹⁹, N. Srimanobhas¹¹⁹, D. Agyel¹²⁰, F. Boran¹²⁰, Z. S. Demiroglu¹²⁰, F. Dolek¹²⁰, I. Dumanoglu^{120,iii}, E. Eskut¹²⁰, Y. Guler^{120,mmm}, E. Gurpinar Guler^{120,mmm}, C. Isik¹²⁰, O. Kara¹²⁰, A. Kayis Topaksu¹²⁰, U. Kiminsu¹²⁰, G. Onengut¹²⁰, K. Ozdemir^{120,nnn}, A. Polatoz¹²⁰, A. E. Simsek¹²⁰, B. Tali^{120,ooo}, U. G. Tok¹²⁰, S. Turkcpar¹²⁰, E. Uslan¹²⁰, I. S. Zorbakir¹²⁰, G. Karapinar^{121,ppp}, K. Ocalan^{121,qqq}, M. Yalvac^{121,rrr}, B. Akgun¹²², I. O. Atakisi¹²², E. Gülmez¹²², M. Kaya^{122,sss}, O. Kaya^{122,ttt}, Ö. Özçelik¹²², S. Tekten^{122,uuu}, A. Cakir¹²³, K. Cankocak^{123,iii}, Y. Komurcu¹²³, S. Sen^{123,vvv}, O. Aydılek¹²⁴, S. Cerci^{124,ooo}, B. Hacıahinoglu¹²⁴, I. Hos^{124,www}, B. Isildak^{124,xxx}, B. Kaynak¹²⁴, S. Ozkorucuklu¹²⁴, C. Simsek¹²⁴, D. Sunar Cerci^{124,ooo}, B. Grynyov¹²⁵, L. Levchuk¹²⁶, D. Anthony¹²⁷, E. Bhal¹²⁷, J. J. Brooke¹²⁷, A. Bundock¹²⁷, E. Clement¹²⁷, D. Cussans¹²⁷, H. Flacher¹²⁷, M. Glowacki¹²⁷, J. Goldstein¹²⁷, G. P. Heath¹²⁷, H. F. Heath¹²⁷, L. Kreczko¹²⁷, B. Krikler¹²⁷, S. Paramesvaran¹²⁷, S. Seif El Nasr-Storey¹²⁷, V. J. Smith¹²⁷, N. Stylianou^{127,yyy}, K. Walkingshaw Pass¹²⁷, R. White¹²⁷, A. H. Ball¹²⁸, K. W. Bell¹²⁸, A. Belyaev^{128,zzz}, C. Brew¹²⁸, R. M. Brown¹²⁸, D. J. A. Cockerill¹²⁸, C. Cooke¹²⁸, K. V. Ellis¹²⁸, K. Harder¹²⁸, S. Harper¹²⁸, M.-L. Holmberg^{128,aaaa}, J. Linacre¹²⁸, K. Manolopoulos¹²⁸, D. M. Newbold¹²⁸

E. Olaiya,¹²⁸ D. Petyt,¹²⁸ T. Reis,¹²⁸ G. Salvi,¹²⁸ T. Schuh,¹²⁸ C. H. Shepherd-Themistocleous,¹²⁸ I. R. Tomalin,¹²⁸ T. Williams,¹²⁸ R. Bainbridge,¹²⁹ P. Bloch,¹²⁹ S. Bonomally,¹²⁹ J. Borg,¹²⁹ S. Breeze,¹²⁹ C. E. Brown,¹²⁹ O. Buchmuller,¹²⁹ V. Cacchio,¹²⁹ V. Cepaitis,¹²⁹ G. S. Chahal,^{129,bbbb} D. Colling,¹²⁹ J. S. Dancu,¹²⁹ P. Dauncey,¹²⁹ G. Davies,¹²⁹ J. Davies,¹²⁹ M. Della Negra,¹²⁹ S. Fayer,¹²⁹ G. Fedi,¹²⁹ G. Hall,¹²⁹ M. H. Hassanshahi,¹²⁹ A. Howard,¹²⁹ G. Iles,¹²⁹ J. Langford,¹²⁹ L. Lyons,¹²⁹ A.-M. Magnan,¹²⁹ S. Malik,¹²⁹ A. Martelli,¹²⁹ M. Mieskolainen,¹²⁹ D. G. Monk,¹²⁹ J. Nash,^{129,cccc} M. Pesaresi,¹²⁹ B. C. Radburn-Smith,¹²⁹ D. M. Raymond,¹²⁹ A. Richards,¹²⁹ A. Rose,¹²⁹ E. Scott,¹²⁹ C. Seez,¹²⁹ A. Shtipliyski,¹²⁹ R. Shukla,¹²⁹ A. Tapper,¹²⁹ K. Uchida,¹²⁹ G. P. Uttley,¹²⁹ L. H. Vage,¹²⁹ T. Virdee,^{129,u} M. Vojinovic,¹²⁹ N. Wardle,¹²⁹ S. N. Webb,¹²⁹ D. Winterbottom,¹²⁹ K. Coldham,¹³⁰ J. E. Cole,¹³⁰ A. Khan,¹³⁰ P. Kyberd,¹³⁰ I. D. Reid,¹³⁰ S. Abdullin,¹³¹ A. Brinkerhoff,¹³¹ B. Caraway,¹³¹ J. Dittmann,¹³¹ K. Hatakeyama,¹³¹ A. R. Kanuganti,¹³¹ B. McMaster,¹³¹ M. Saunders,¹³¹ S. Sawant,¹³¹ C. Sutantawibul,¹³¹ J. Wilson,¹³¹ R. Bartek,¹³² A. Dominguez,¹³² R. Uniyal,¹³² A. M. Vargas Hernandez,¹³² A. Buccilli,¹³³ S. I. Cooper,¹³³ D. Di Croce,¹³³ S. V. Gleyzer,¹³³ C. Henderson,¹³³ C. U. Perez,¹³³ P. Rumerio,^{133,dddd} C. West,¹³³ A. Akpinar,¹³⁴ A. Albert,¹³⁴ D. Arcaro,¹³⁴ C. Cosby,¹³⁴ Z. Demiragli,¹³⁴ C. Erice,¹³⁴ E. Fontanesi,¹³⁴ D. Gastler,¹³⁴ S. May,¹³⁴ J. Rohlf,¹³⁴ K. Salyer,¹³⁴ D. Sperka,¹³⁴ D. Spitzbart,¹³⁴ I. Suarez,¹³⁴ A. Tsatsos,¹³⁴ S. Yuan,¹³⁴ G. Benelli,¹³⁵ B. Burkle,¹³⁵ X. Coubez,^{135,w} D. Cutts,¹³⁵ M. Hadley,¹³⁵ U. Heintz,¹³⁵ J. M. Hogan,^{135,eeee} T. Kwon,¹³⁵ G. Landsberg,¹³⁵ K. T. Lau,¹³⁵ D. Li,¹³⁵ J. Luo,¹³⁵ M. Narain,¹³⁵ N. Pervan,¹³⁵ S. Sagir,^{135,ffff} F. Simpson,¹³⁵ E. Usai,¹³⁵ W. Y. Wong,¹³⁵ X. Yan,¹³⁵ D. Yu,¹³⁵ W. Zhang,¹³⁵ J. Bonilla,¹³⁶ C. Brainerd,¹³⁶ R. Breedon,¹³⁶ M. Calderon De La Barca Sanchez,¹³⁶ M. Chertok,¹³⁶ J. Conway,¹³⁶ P. T. Cox,¹³⁶ R. Erbacher,¹³⁶ G. Haza,¹³⁶ F. Jensen,¹³⁶ O. Kukral,¹³⁶ G. Mocellin,¹³⁶ M. Mulhearn,¹³⁶ D. Pellett,¹³⁶ B. Regnery,¹³⁶ D. Taylor,¹³⁶ Y. Yao,¹³⁶ F. Zhang,¹³⁶ M. Bachtis,¹³⁷ R. Cousins,¹³⁷ A. Datta,¹³⁷ D. Hamilton,¹³⁷ J. Hauser,¹³⁷ M. Ignatenko,¹³⁷ M. A. Iqbal,¹³⁷ T. Lam,¹³⁷ W. A. Nash,¹³⁷ S. Regnard,¹³⁷ D. Saltzberg,¹³⁷ B. Stone,¹³⁷ V. Valuev,¹³⁷ Y. Chen,¹³⁸ R. Clare,¹³⁸ J. W. Gary,¹³⁸ M. Gordon,¹³⁸ G. Hanson,¹³⁸ G. Karapostoli,¹³⁸ O. R. Long,¹³⁸ N. Manganelli,¹³⁸ W. Si,¹³⁸ S. Wimpenny,¹³⁸ J. G. Branson,¹³⁹ P. Chang,¹³⁹ S. Cittolin,¹³⁹ S. Cooperstein,¹³⁹ D. Diaz,¹³⁹ J. Duarte,¹³⁹ R. Gerosa,¹³⁹ L. Giannini,¹³⁹ J. Guiang,¹³⁹ R. Kansal,¹³⁹ V. Krutelyov,¹³⁹ R. Lee,¹³⁹ J. Letts,¹³⁹ M. Masciovecchio,¹³⁹ F. Mokhtar,¹³⁹ M. Pieri,¹³⁹ B. V. Sathia Narayanan,¹³⁹ V. Sharma,¹³⁹ M. Tadel,¹³⁹ F. Würthwein,¹³⁹ Y. Xiang,¹³⁹ A. Yagil,¹³⁹ N. Amin,¹⁴⁰ C. Campagnari,¹⁴⁰ M. Citron,¹⁴⁰ G. Collura,¹⁴⁰ A. Dorsett,¹⁴⁰ V. Dutta,¹⁴⁰ J. Incandela,¹⁴⁰ M. Kilpatrick,¹⁴⁰ J. Kim,¹⁴⁰ A. J. Li,¹⁴⁰ B. Marsh,¹⁴⁰ P. Masterson,¹⁴⁰ H. Mei,¹⁴⁰ M. Oshiro,¹⁴⁰ M. Quinnan,¹⁴⁰ J. Richman,¹⁴⁰ U. Sarica,¹⁴⁰ R. Schmitz,¹⁴⁰ F. Setti,¹⁴⁰ J. Sheplock,¹⁴⁰ P. Siddireddy,¹⁴⁰ D. Stuart,¹⁴⁰ S. Wang,¹⁴⁰ A. Bornheim,¹⁴¹ O. Cerri,¹⁴¹ I. Dutta,¹⁴¹ J. M. Lawhorn,¹⁴¹ N. Lu,¹⁴¹ J. Mao,¹⁴¹ H. B. Newman,¹⁴¹ T. Q. Nguyen,¹⁴¹ M. Spiropulu,¹⁴¹ J. R. Vlimant,¹⁴¹ C. Wang,¹⁴¹ S. Xie,¹⁴¹ R. Y. Zhu,¹⁴¹ J. Alison,¹⁴² S. An,¹⁴² M. B. Andrews,¹⁴² P. Bryant,¹⁴² T. Ferguson,¹⁴² A. Harilal,¹⁴² C. Liu,¹⁴² T. Mudholkar,¹⁴² S. Murthy,¹⁴² M. Paulini,¹⁴² A. Roberts,¹⁴² A. Sanchez,¹⁴² W. Terrill,¹⁴² J. P. Cumalat,¹⁴³ W. T. Ford,¹⁴³ A. Hassani,¹⁴³ G. Karathanasis,¹⁴³ E. MacDonal,¹⁴³ F. Marini,¹⁴³ R. Patel,¹⁴³ A. Perloff,¹⁴³ C. Savard,¹⁴³ N. Schonbeck,¹⁴³ K. Stenson,¹⁴³ K. A. Ulmer,¹⁴³ S. R. Wagner,¹⁴³ N. Zipper,¹⁴³ J. Alexander,¹⁴⁴ S. Bright-Thonney,¹⁴⁴ X. Chen,¹⁴⁴ D. J. Cranshaw,¹⁴⁴ J. Fan,¹⁴⁴ X. Fan,¹⁴⁴ D. Gadkari,¹⁴⁴ S. Hogan,¹⁴⁴ J. Monroy,¹⁴⁴ J. R. Patterson,¹⁴⁴ D. Quach,¹⁴⁴ J. Reichert,¹⁴⁴ M. Reid,¹⁴⁴ A. Ryd,¹⁴⁴ J. Thom,¹⁴⁴ P. Wittich,¹⁴⁴ R. Zou,¹⁴⁴ M. Albrow,¹⁴⁵ M. Alyari,¹⁴⁵ G. Apollinari,¹⁴⁵ A. Apresyan,¹⁴⁵ L. A. T. Bauerdick,¹⁴⁵ D. Berry,¹⁴⁵ J. Berryhill,¹⁴⁵ P. C. Bhat,¹⁴⁵ K. Burkett,¹⁴⁵ J. N. Butler,¹⁴⁵ A. Canepa,¹⁴⁵ G. B. Cerati,¹⁴⁵ H. W. K. Cheung,¹⁴⁵ F. Chlebana,¹⁴⁵ K. F. Di Petrillo,¹⁴⁵ J. Dickinson,¹⁴⁵ V. D. Elvira,¹⁴⁵ Y. Feng,¹⁴⁵ J. Freeman,¹⁴⁵ A. Gandrakota,¹⁴⁵ Z. Gecse,¹⁴⁵ L. Gray,¹⁴⁵ D. Green,¹⁴⁵ S. Grünendahl,¹⁴⁵ O. Gutsche,¹⁴⁵ R. M. Harris,¹⁴⁵ R. Heller,¹⁴⁵ T. C. Herwig,¹⁴⁵ J. Hirschauer,¹⁴⁵ L. Horyn,¹⁴⁵ B. Jayatilaka,¹⁴⁵ S. Jindariani,¹⁴⁵ M. Johnson,¹⁴⁵ U. Joshi,¹⁴⁵ T. Klijnsma,¹⁴⁵ B. Klima,¹⁴⁵ K. H. M. Kwok,¹⁴⁵ S. Lammel,¹⁴⁵ D. Lincoln,¹⁴⁵ R. Lipton,¹⁴⁵ T. Liu,¹⁴⁵ C. Madrid,¹⁴⁵ K. Maeshima,¹⁴⁵ C. Mantilla,¹⁴⁵ D. Mason,¹⁴⁵ P. McBride,¹⁴⁵ P. Merkel,¹⁴⁵ S. Mrenna,¹⁴⁵ S. Nahn,¹⁴⁵ J. Ngadiuba,¹⁴⁵ D. Noonan,¹⁴⁵ V. Papadimitriou,¹⁴⁵ N. Pastika,¹⁴⁵ K. Pedro,¹⁴⁵ C. Pena,^{145,gggg} F. Ravera,¹⁴⁵ A. Reinsvold Hall,^{145,hhhh} L. Ristori,¹⁴⁵ E. Sexton-Kennedy,¹⁴⁵ N. Smith,¹⁴⁵ A. Soha,¹⁴⁵ L. Spiegel,¹⁴⁵ J. Strait,¹⁴⁵ L. Taylor,¹⁴⁵ S. Tkaczyk,¹⁴⁵ N. V. Tran,¹⁴⁵ L. Uplegger,¹⁴⁵ E. W. Vaandering,¹⁴⁵ H. A. Weber,¹⁴⁵ I. Zoi,¹⁴⁵ P. Avery,¹⁴⁶ D. Bourilkov,¹⁴⁶ L. Cadamuro,¹⁴⁶ V. Cherepanov,¹⁴⁶ R. D. Field,¹⁴⁶ D. Guerrero,¹⁴⁶ M. Kim,¹⁴⁶ E. Koenig,¹⁴⁶ J. Konigsberg,¹⁴⁶ A. Korytov,¹⁴⁶

K. H. Lo,¹⁴⁶ K. Matchev¹⁴⁶, N. Menendez¹⁴⁶, G. Mitselmakher¹⁴⁶, A. Muthirakalayil Madhu¹⁴⁶, N. Rawal¹⁴⁶,
 D. Rosenzweig¹⁴⁶, S. Rosenzweig¹⁴⁶, K. Shi¹⁴⁶, J. Wang¹⁴⁶, Z. Wu¹⁴⁶, T. Adams¹⁴⁷, A. Askew¹⁴⁷,
 R. Habibullah¹⁴⁷, V. Hagopian¹⁴⁷, R. Khurana¹⁴⁷, T. Kolberg¹⁴⁷, G. Martinez¹⁴⁷, H. Prosper¹⁴⁷, C. Schiber¹⁴⁷,
 O. Viazlo¹⁴⁷, R. Yohay¹⁴⁷, J. Zhang¹⁴⁷, M. M. Baarmand¹⁴⁸, S. Butalla¹⁴⁸, T. Elkafrawy^{148,yy}, M. Hohlmann¹⁴⁸,
 R. Kumar Verma¹⁴⁸, M. Rahmani¹⁴⁸, F. Yumiceva¹⁴⁸, M. R. Adams¹⁴⁹, H. Becerril Gonzalez¹⁴⁹, R. Cavanaugh¹⁴⁹,
 S. Dittmer¹⁴⁹, O. Evdokimov¹⁴⁹, C. E. Gerber¹⁴⁹, D. J. Hofman¹⁴⁹, D. S. Lemos¹⁴⁹, A. H. Merrit¹⁴⁹, C. Mills¹⁴⁹,
 G. Oh¹⁴⁹, T. Roy¹⁴⁹, S. Rudrabhatla¹⁴⁹, M. B. Tonjes¹⁴⁹, N. Varelas¹⁴⁹, X. Wang¹⁴⁹, Z. Ye¹⁴⁹, J. Yoo¹⁴⁹,
 M. Alhusseini¹⁵⁰, K. Dilsiz^{150,iiii}, L. Emediato¹⁵⁰, R. P. Gandrajula¹⁵⁰, G. Karaman¹⁵⁰, O. K. Köseyan¹⁵⁰,
 J.-P. Merlo¹⁵⁰, A. Mestvirishvili^{150,jjjj}, J. Nachtman¹⁵⁰, O. Neogi¹⁵⁰, H. Ogul^{150,kkkk}, Y. Onel¹⁵⁰, A. Penzo¹⁵⁰,
 C. Snyder¹⁵⁰, E. Tiras^{150,llll}, O. Amram¹⁵¹, B. Blumenfeld¹⁵¹, L. Corcodilos¹⁵¹, J. Davis¹⁵¹, A. V. Gritsan¹⁵¹,
 L. Kang¹⁵¹, S. Kyriacou¹⁵¹, P. Maksimovic¹⁵¹, J. Roskes¹⁵¹, S. Sekhar¹⁵¹, M. Swartz¹⁵¹, T. Á. Vámi¹⁵¹,
 A. Abreu¹⁵², L. F. Alcerro Alcerro¹⁵², J. Anguiano¹⁵², P. Baringer¹⁵², A. Bean¹⁵², Z. Flowers¹⁵², T. Isidori¹⁵²,
 S. Khalil¹⁵², J. King¹⁵², G. Krintiras¹⁵², M. Lazarovits¹⁵², C. Le Mahieu¹⁵², C. Lindsey¹⁵², J. Marquez¹⁵²,
 N. Minafra¹⁵², M. Murray¹⁵², M. Nickel¹⁵², C. Rogan¹⁵², C. Royon¹⁵², R. Salvatico¹⁵², S. Sanders¹⁵²,
 E. Schmitz¹⁵², C. Smith¹⁵², Q. Wang¹⁵², J. Williams¹⁵², G. Wilson¹⁵², B. Allmond¹⁵³, S. Duric¹⁵³,
 R. Gujju Gurunadha¹⁵³, A. Ivanov¹⁵³, K. Kaadze¹⁵³, D. Kim¹⁵³, Y. Maravin¹⁵³, T. Mitchell¹⁵³, A. Modak¹⁵³,
 K. Nam¹⁵³, J. Natoli¹⁵³, D. Roy¹⁵³, F. Rebassoo¹⁵⁴, D. Wright¹⁵⁴, E. Adams¹⁵⁵, A. Baden¹⁵⁵, O. Baron¹⁵⁵,
 A. Belloni¹⁵⁵, A. Bethani¹⁵⁵, S. C. Eno¹⁵⁵, N. J. Hadley¹⁵⁵, S. Jabeen¹⁵⁵, R. G. Kellogg¹⁵⁵, T. Koeth¹⁵⁵,
 Y. Lai¹⁵⁵, S. Lascio¹⁵⁵, A. C. Mignerey¹⁵⁵, S. Nabili¹⁵⁵, C. Palmer¹⁵⁵, C. Papageorgakis¹⁵⁵, M. Seidel¹⁵⁵,
 L. Wang¹⁵⁵, K. Wong¹⁵⁵, D. Abercrombie¹⁵⁶, R. Bi¹⁵⁶, W. Busza¹⁵⁶, I. A. Cali¹⁵⁶, Y. Chen¹⁵⁶, M. D'Alfonso¹⁵⁶,
 J. Eysermans¹⁵⁶, C. Freer¹⁵⁶, G. Gomez-Ceballos¹⁵⁶, M. Goncharov¹⁵⁶, P. Harris¹⁵⁶, M. Hu¹⁵⁶, D. Kovalskiy¹⁵⁶,
 J. Krupa¹⁵⁶, Y.-J. Lee¹⁵⁶, K. Long¹⁵⁶, C. Mironov¹⁵⁶, C. Paus¹⁵⁶, D. Rankin¹⁵⁶, C. Roland¹⁵⁶, G. Roland¹⁵⁶,
 Z. Shi¹⁵⁶, G. S. F. Stephans¹⁵⁶, J. Wang¹⁵⁶, Z. Wang¹⁵⁶, B. Wyslouch¹⁵⁶, R. M. Chatterjee¹⁵⁷, B. Crossman¹⁵⁷,
 A. Evans¹⁵⁷, J. Hiltbrand¹⁵⁷, Sh. Jain¹⁵⁷, B. M. Joshi¹⁵⁷, C. Kapsiak¹⁵⁷, M. Krohn¹⁵⁷, Y. Kubota¹⁵⁷, J. Mans¹⁵⁷,
 M. Revering¹⁵⁷, R. Rusack¹⁵⁷, R. Saradhy¹⁵⁷, N. Schroeder¹⁵⁷, N. Strobbe¹⁵⁷, M. A. Wadud¹⁵⁷,
 L. M. Cremaldi¹⁵⁸, K. Bloom¹⁵⁹, M. Bryson¹⁵⁹, D. R. Claes¹⁵⁹, C. Fangmeier¹⁵⁹, L. Finco¹⁵⁹, F. Golf¹⁵⁹,
 C. Joo¹⁵⁹, I. Kravchenko¹⁵⁹, I. Reed¹⁵⁹, J. E. Siado¹⁵⁹, G. R. Snow^{159,a}, W. Tabb¹⁵⁹, A. Wightman¹⁵⁹, F. Yan¹⁵⁹,
 A. G. Zecchinelli¹⁵⁹, G. Agarwal¹⁶⁰, H. Bandyopadhyay¹⁶⁰, L. Hay¹⁶⁰, I. Iashvili¹⁶⁰, A. Kharchilava¹⁶⁰,
 C. McLean¹⁶⁰, M. Morris¹⁶⁰, D. Nguyen¹⁶⁰, J. Pekkanen¹⁶⁰, S. Rappoccio¹⁶⁰, A. Williams¹⁶⁰, G. Alverson¹⁶¹,
 E. Barberis¹⁶¹, Y. Haddad¹⁶¹, Y. Han¹⁶¹, A. Krishna¹⁶¹, J. Li¹⁶¹, J. Lidrych¹⁶¹, G. Madigan¹⁶¹,
 B. Marzocchi¹⁶¹, D. M. Morse¹⁶¹, V. Nguyen¹⁶¹, T. Orimoto¹⁶¹, A. Parker¹⁶¹, L. Skinnari¹⁶¹,
 A. Tishelman-Charny¹⁶¹, T. Wamorkar¹⁶¹, B. Wang¹⁶¹, A. Wisecarver¹⁶¹, D. Wood¹⁶¹, S. Bhattacharya¹⁶²,
 J. Bueghly¹⁶², Z. Chen¹⁶², A. Gilbert¹⁶², T. Gunter¹⁶², K. A. Hahn¹⁶², Y. Liu¹⁶², N. Odell¹⁶², M. H. Schmitt¹⁶²,
 M. Velasco¹⁶², R. Band¹⁶³, R. Bucci¹⁶³, S. Castells¹⁶³, M. Cremonesi¹⁶³, A. Das¹⁶³, R. Goldouzian¹⁶³,
 M. Hildreth¹⁶³, K. Hurtado Anampa¹⁶³, C. Jessop¹⁶³, K. Lannon¹⁶³, J. Lawrence¹⁶³, N. Loukas¹⁶³, L. Lutton¹⁶³,
 J. Mariano¹⁶³, N. Marinelli¹⁶³, I. Mcalister¹⁶³, T. McCauley¹⁶³, C. Mcgrady¹⁶³, K. Mohrman¹⁶³, C. Moore¹⁶³,
 Y. Musienko^{163,n}, H. Nelson¹⁶³, R. Ruchti¹⁶³, A. Townsend¹⁶³, M. Wayne¹⁶³, H. Yockey¹⁶³, M. Zarucki¹⁶³,
 L. Zygala¹⁶³, B. Bylsma¹⁶⁴, M. Carrigan¹⁶⁴, L. S. Durkin¹⁶⁴, B. Francis¹⁶⁴, C. Hill¹⁶⁴, A. Lesauvage¹⁶⁴,
 M. Nunez Ornelas¹⁶⁴, K. Wei¹⁶⁴, B. L. Winer¹⁶⁴, B. R. Yates¹⁶⁴, F. M. Addesa¹⁶⁵, B. Bonham¹⁶⁵, P. Das¹⁶⁵,
 G. Dezoort¹⁶⁵, P. Elmer¹⁶⁵, A. Frankenthal¹⁶⁵, B. Greenberg¹⁶⁵, N. Haubrich¹⁶⁵, S. Higginbotham¹⁶⁵,
 A. Kalogeropoulos¹⁶⁵, G. Kopp¹⁶⁵, S. Kwan¹⁶⁵, D. Lange¹⁶⁵, D. Marlow¹⁶⁵, K. Mei¹⁶⁵, I. Ojalvo¹⁶⁵,
 J. Olsen¹⁶⁵, D. Stickland¹⁶⁵, C. Tully¹⁶⁵, S. Malik¹⁶⁶, S. Norberg¹⁶⁶, A. S. Bakshi¹⁶⁷, V. E. Barnes¹⁶⁷,
 R. Chawla¹⁶⁷, S. Das¹⁶⁷, L. Gutay¹⁶⁷, M. Jones¹⁶⁷, A. W. Jung¹⁶⁷, D. Kondratyev¹⁶⁷, A. M. Koshy¹⁶⁷, M. Liu¹⁶⁷,
 G. Negro¹⁶⁷, N. Neumeister¹⁶⁷, G. Paspalaki¹⁶⁷, S. Piperov¹⁶⁷, A. Purohit¹⁶⁷, J. F. Schulte¹⁶⁷, M. Stojanovic¹⁶⁷,
 J. Thieman¹⁶⁷, F. Wang¹⁶⁷, R. Xiao¹⁶⁷, W. Xie¹⁶⁷, J. Dolen¹⁶⁸, N. Parashar¹⁶⁸, D. Acosta¹⁶⁹, A. Baty¹⁶⁹,
 T. Carnahan¹⁶⁹, M. Decaro¹⁶⁹, S. Dildick¹⁶⁹, K. M. Ecklund¹⁶⁹, P. J. Fernández Manteca¹⁶⁹, S. Freed¹⁶⁹,
 P. Gardner¹⁶⁹, F. J. M. Geurts¹⁶⁹, A. Kumar¹⁶⁹, W. Li¹⁶⁹, B. P. Padley¹⁶⁹, R. Redjimi¹⁶⁹, J. Rotter¹⁶⁹, W. Shi¹⁶⁹,
 S. Yang¹⁶⁹, E. Yigitbasi¹⁶⁹, L. Zhang^{169,mmmm}, Y. Zhang¹⁶⁹, X. Zuo¹⁶⁹, A. Bodek¹⁷⁰, P. de Barbaro¹⁷⁰,
 R. Demina¹⁷⁰, J. L. Dulemba¹⁷⁰, C. Fallon¹⁷⁰, T. Ferbel¹⁷⁰, M. Galanti¹⁷⁰, A. Garcia-Bellido¹⁷⁰, O. Hindrichs¹⁷⁰

A. Khukhunaishvili¹⁷⁰ E. Ranken¹⁷⁰ R. Taus¹⁷⁰ G. P. Van Onsem¹⁷⁰ K. Goulianos¹⁷¹ B. Chiarito,¹⁷²
 J. P. Chou¹⁷² Y. Gershtein¹⁷² E. Halkiadakis¹⁷² A. Hart¹⁷² M. Heindl¹⁷² D. Jaroslawski¹⁷²
 O. Karacheban^{172,y} I. Laflotte¹⁷² A. Lath¹⁷² R. Montalvo,¹⁷² K. Nash,¹⁷² M. Osherson¹⁷² S. Salur¹⁷²
 S. Schnetzer,¹⁷² S. Somalwar¹⁷² R. Stone¹⁷² S. A. Thayil¹⁷² S. Thomas,¹⁷² H. Wang¹⁷² H. Acharya,¹⁷³
 A. G. Delannoy¹⁷³ S. Fiorendi¹⁷³ T. Holmes¹⁷³ E. Nibigira¹⁷³ S. Spanier¹⁷³ O. Bouhali^{174,nnnn}
 M. Dalchenko¹⁷⁴ A. Delgado¹⁷⁴ R. Eusebi¹⁷⁴ J. Gilmore¹⁷⁴ T. Huang¹⁷⁴ T. Kamon^{174,oooo} H. Kim¹⁷⁴
 S. Luo¹⁷⁴ S. Malhotra,¹⁷⁴ R. Mueller¹⁷⁴ D. Overton¹⁷⁴ D. Rathjens¹⁷⁴ A. Safonov¹⁷⁴ N. Akchurin¹⁷⁵
 J. Damgov¹⁷⁵ V. Hegde¹⁷⁵ K. Lamichhane¹⁷⁵ S. W. Lee¹⁷⁵ T. Mengke,¹⁷⁵ S. Muthumuni¹⁷⁵ T. Peltola¹⁷⁵
 I. Volobouev¹⁷⁵ Z. Wang¹⁷⁵ A. Whitbeck¹⁷⁵ E. Appelt¹⁷⁶ S. Greene,¹⁷⁶ A. Gurrola¹⁷⁶ W. Johns¹⁷⁶
 A. Melo¹⁷⁶ F. Romeo¹⁷⁶ P. Sheldon¹⁷⁶ S. Tuo¹⁷⁶ J. Velkovska¹⁷⁶ J. Viinikainen¹⁷⁶ B. Cardwell¹⁷⁷
 B. Cox¹⁷⁷ G. Cummings¹⁷⁷ J. Hakala¹⁷⁷ R. Hirosky¹⁷⁷ M. Joyce¹⁷⁷ A. Ledovskoy¹⁷⁷ A. Li¹⁷⁷ C. Neu¹⁷⁷
 C. E. Perez Lara¹⁷⁷ B. Tannenwald¹⁷⁷ P. E. Karchin¹⁷⁸ N. Poudyal¹⁷⁸ S. Banerjee¹⁷⁹ K. Black¹⁷⁹ T. Bose¹⁷⁹
 S. Dasu¹⁷⁹ I. De Bruyn¹⁷⁹ P. Everaerts¹⁷⁹ C. Galloni,¹⁷⁹ H. He¹⁷⁹ M. Herndon¹⁷⁹ A. Herve¹⁷⁹
 C. K. Koraka¹⁷⁹ A. Lanaro,¹⁷⁹ A. Loeliger¹⁷⁹ R. Loveless¹⁷⁹ J. Madhusudanan Sreekala¹⁷⁹ A. Mallampalli¹⁷⁹
 A. Mohammadi¹⁷⁹ S. Mondal¹⁷⁹ G. Parida¹⁷⁹ D. Pinna,¹⁷⁹ A. Savin,¹⁷⁹ V. Shang¹⁷⁹ V. Sharma¹⁷⁹
 W. H. Smith¹⁷⁹ D. Teague,¹⁷⁹ H. F. Tsoi¹⁷⁹ W. Vetens¹⁷⁹ S. Afanasiev,¹⁸⁰ V. Andreev¹⁸⁰ Yu. Andreev¹⁸⁰
 T. Aushev¹⁸⁰ M. Azarkin¹⁸⁰ A. Babaev¹⁸⁰ A. Belyaev¹⁸⁰ V. Blinov,^{180,pppp} E. Boos¹⁸⁰ V. Borshch¹⁸⁰
 D. Budkouski¹⁸⁰ V. Bunichev¹⁸⁰ V. Chekhovsky,¹⁸⁰ R. Chistov^{180,pppp} M. Danilov^{180,pppp} A. Dermenev¹⁸⁰
 T. Dimova^{180,pppp} I. Dremin¹⁸⁰ M. Dubinin^{180,gggg} L. Dudko¹⁸⁰ V. Epshteyn¹⁸⁰ A. Ershov¹⁸⁰ G. Gavrilo¹⁸⁰
 V. Gavrilo¹⁸⁰ S. Gninenko¹⁸⁰ V. Golovtsov¹⁸⁰ N. Golubev¹⁸⁰ I. Golutvin,¹⁸⁰ I. Gorbunov¹⁸⁰ V. Ivanchenko¹⁸⁰
 Y. Ivanov¹⁸⁰ V. Kachanov¹⁸⁰ L. Kardapoltsev^{180,pppp} V. Karjavine¹⁸⁰ A. Karneyeu¹⁸⁰ V. Kim^{180,pppp}
 M. Kirakosyan,¹⁸⁰ D. Kirpichnikov¹⁸⁰ M. Kirsanov¹⁸⁰ V. Klyukhin¹⁸⁰ O. Kodolova^{180,qqqq} D. Konstantinov¹⁸⁰
 V. Korenkov¹⁸⁰ A. Kozyrev^{180,pppp} N. Krasnikov¹⁸⁰ E. Kuznetsova,^{180,rrrr} A. Lanev¹⁸⁰ P. Levchenko¹⁸⁰
 A. Litomin,¹⁸⁰ O. Lukina¹⁸⁰ N. Lychkovskaya¹⁸⁰ V. Makarenko¹⁸⁰ A. Malakhov¹⁸⁰ V. Matveev^{180,pppp}
 V. Murzin¹⁸⁰ A. Nikitenko^{180,ssss} S. Obraztsov¹⁸⁰ V. Okhotnikov¹⁸⁰ A. Oskin,¹⁸⁰ I. Ovtin^{180,pppp} V. Palichik¹⁸⁰
 P. Parygin¹⁸⁰ V. Perelygin¹⁸⁰ G. Pivovarov¹⁸⁰ S. Polikarpov^{180,pppp} V. Popov,¹⁸⁰ O. Radchenko^{180,pppp}
 M. Savina¹⁸⁰ V. Savrin¹⁸⁰ D. Selivanova¹⁸⁰ V. Shalae¹⁸⁰ S. Shmatov¹⁸⁰ S. Shulha¹⁸⁰ Y. Skovpen^{180,pppp}
 S. Slabospitskii¹⁸⁰ V. Smirnov¹⁸⁰ A. Snigirev¹⁸⁰ D. Sosnov¹⁸⁰ A. Stepenov¹⁸⁰ V. Sulimov¹⁸⁰
 E. Tcherniaev¹⁸⁰ A. Terkulov¹⁸⁰ O. Teryaev¹⁸⁰ I. Tlisova¹⁸⁰ M. Toms¹⁸⁰ A. Toropin¹⁸⁰ L. Uvarov¹⁸⁰
 A. Uzunian¹⁸⁰ E. Vlasov¹⁸⁰ A. Vorobyev,¹⁸⁰ N. Voytishin¹⁸⁰ B. S. Yuldashev,^{180,tttt} A. Zarubin¹⁸⁰
 I. Zhizhin¹⁸⁰ and A. Zhokin¹⁸⁰

(CMS Collaboration)

¹Yerevan Physics Institute, Yerevan, Armenia

²Institut für Hochenergiephysik, Vienna, Austria

³Universiteit Antwerpen, Antwerpen, Belgium

⁴Vrije Universiteit Brussel, Brussel, Belgium

⁵Université Libre de Bruxelles, Bruxelles, Belgium

⁶Ghent University, Ghent, Belgium

⁷Université Catholique de Louvain, Louvain-la-Neuve, Belgium

⁸Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

⁹Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

¹⁰Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

¹¹Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

¹²University of Sofia, Sofia, Bulgaria

¹³Beihang University, Beijing, China

¹⁴Department of Physics, Tsinghua University, Beijing, China

¹⁵Institute of High Energy Physics, Beijing, China

¹⁶State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

¹⁷Sun Yat-Sen University, Guangzhou, China

- ¹⁸*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China*
- ¹⁹*Zhejiang University, Hangzhou, Zhejiang, China*
- ²⁰*Universidad de Los Andes, Bogota, Colombia*
- ²¹*Universidad de Antioquia, Medellin, Colombia*
- ²²*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
- ²³*University of Split, Faculty of Science, Split, Croatia*
- ²⁴*Institute Rudjer Boskovic, Zagreb, Croatia*
- ²⁵*University of Cyprus, Nicosia, Cyprus*
- ²⁶*Charles University, Prague, Czech Republic*
- ²⁷*Escuela Politecnica Nacional, Quito, Ecuador*
- ²⁸*Universidad San Francisco de Quito, Quito, Ecuador*
- ²⁹*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
- ³⁰*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
- ³¹*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
- ³²*Department of Physics, University of Helsinki, Helsinki, Finland*
- ³³*Helsinki Institute of Physics, Helsinki, Finland*
- ³⁴*Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
- ³⁵*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ³⁶*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
- ³⁷*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
- ³⁸*Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
- ³⁹*Georgian Technical University, Tbilisi, Georgia*
- ⁴⁰*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ⁴¹*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ⁴²*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
- ⁴³*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ⁴⁴*University of Hamburg, Hamburg, Germany*
- ⁴⁵*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
- ⁴⁶*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
- ⁴⁷*National and Kapodistrian University of Athens, Athens, Greece*
- ⁴⁸*National Technical University of Athens, Athens, Greece*
- ⁴⁹*University of Ioánnina, Ioánnina, Greece*
- ⁵⁰*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
- ⁵¹*Wigner Research Centre for Physics, Budapest, Hungary*
- ⁵²*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁵³*Institute of Physics, University of Debrecen, Debrecen, Hungary*
- ⁵⁴*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
- ⁵⁵*Panjab University, Chandigarh, India*
- ⁵⁶*University of Delhi, Delhi, India*
- ⁵⁷*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
- ⁵⁸*Indian Institute of Technology Madras, Madras, India*
- ⁵⁹*Bhabha Atomic Research Centre, Mumbai, India*
- ⁶⁰*Tata Institute of Fundamental Research-A, Mumbai, India*
- ⁶¹*Tata Institute of Fundamental Research-B, Mumbai, India*
- ⁶²*National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
- ⁶³*Indian Institute of Science Education and Research (IISER), Pune, India*
- ⁶⁴*Isfahan University of Technology, Isfahan, Iran*
- ⁶⁵*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁶⁶*University College Dublin, Dublin, Ireland*
- ^{67a}*INFN Sezione di Bari, Bari, Italy*
- ^{67b}*Università di Bari, Bari, Italy*
- ^{67c}*Politecnico di Bari, Bari, Italy*
- ^{68a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{68b}*Università di Bologna, Bologna, Italy*
- ^{69a}*INFN Sezione di Catania, Catania, Italy*
- ^{69b}*Università di Catania, Catania, Italy*
- ^{70a}*INFN Sezione di Firenze, Firenze, Italy*
- ^{70b}*Università di Firenze, Firenze, Italy*

- ⁷¹*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
^{72a}*INFN Sezione di Genova, Genova, Italy*
^{72b}*Università di Genova, Genova, Italy*
^{73a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
^{73b}*Università di Milano-Bicocca, Milano, Italy*
^{74a}*INFN Sezione di Napoli, Napoli, Italy*
^{74b}*Università di Napoli "Federico II", Napoli, Italy*
^{74c}*Università della Basilicata, Potenza, Italy*
^{74d}*Università G. Marconi, Roma, Italy*
^{75a}*INFN Sezione di Padova, Padova, Italy*
^{75b}*Università di Padova, Padova, Italy*
^{75c}*Università di Trento, Trento, Italy*
^{76a}*INFN Sezione di Pavia, Pavia, Italy*
^{76b}*Università di Pavia, Pavia, Italy*
^{77a}*INFN Sezione di Perugia, Perugia, Italy*
^{77b}*Università di Perugia, Perugia, Italy*
^{78a}*INFN Sezione di Pisa, Pisa, Italy*
^{78b}*Università di Pisa, Pisa, Italy*
^{78c}*Scuola Normale Superiore di Pisa, Pisa, Italy*
^{78d}*Università di Siena, Siena, Italy*
^{79a}*INFN Sezione di Roma, Roma, Italy*
^{79b}*Sapienza Università di Roma, Roma, Italy*
^{80a}*INFN Sezione di Torino, Torino, Italy*
^{80b}*Università di Torino, Torino, Italy*
^{80c}*Università del Piemonte Orientale, Novara, Italy*
^{81a}*INFN Sezione di Trieste, Trieste, Italy*
^{81b}*Università di Trieste, Trieste, Italy*
⁸²*Kyungpook National University, Daegu, Korea*
⁸³*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
⁸⁴*Hanyang University, Seoul, Korea*
⁸⁵*Korea University, Seoul, Korea*
⁸⁶*Kyung Hee University, Department of Physics, Seoul, Korea*
⁸⁷*Sejong University, Seoul, Korea*
⁸⁸*Seoul National University, Seoul, Korea*
⁸⁹*University of Seoul, Seoul, Korea*
⁹⁰*Yonsei University, Department of Physics, Seoul, Korea*
⁹¹*Sungkyunkwan University, Suwon, Korea*
⁹²*College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait*
⁹³*Riga Technical University, Riga, Latvia*
⁹⁴*Vilnius University, Vilnius, Lithuania*
⁹⁵*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
⁹⁶*Universidad de Sonora (UNISON), Hermosillo, Mexico*
⁹⁷*Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico*
⁹⁸*Universidad Iberoamericana, Mexico City, Mexico*
⁹⁹*Benemerita Universidad Autónoma de Puebla, Puebla, Mexico*
¹⁰⁰*University of Montenegro, Podgorica, Montenegro*
¹⁰¹*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
¹⁰²*AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*
¹⁰³*National Centre for Nuclear Research, Swierk, Poland*
¹⁰⁴*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
¹⁰⁵*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
¹⁰⁶*VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
¹⁰⁷*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
¹⁰⁸*Universidad Autónoma de Madrid, Madrid, Spain*
¹⁰⁹*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
¹¹⁰*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
¹¹¹*University of Colombo, Colombo, Sri Lanka*
¹¹²*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
¹¹³*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
¹¹⁴*Paul Scherrer Institut, Villigen, Switzerland*

- ¹¹⁵*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
¹¹⁶*Universität Zürich, Zurich, Switzerland*
¹¹⁷*National Central University, Chung-Li, Taiwan*
¹¹⁸*National Taiwan University (NTU), Taipei, Taiwan*
¹¹⁹*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
¹²⁰*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
¹²¹*Middle East Technical University, Physics Department, Ankara, Turkey*
¹²²*Bogazici University, Istanbul, Turkey*
¹²³*Istanbul Technical University, Istanbul, Turkey*
¹²⁴*Istanbul University, Istanbul, Turkey*
¹²⁵*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
¹²⁶*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
¹²⁷*University of Bristol, Bristol, United Kingdom*
¹²⁸*Rutherford Appleton Laboratory, Didcot, United Kingdom*
¹²⁹*Imperial College, London, United Kingdom*
¹³⁰*Brunel University, Uxbridge, United Kingdom*
¹³¹*Baylor University, Waco, Texas, USA*
¹³²*Catholic University of America, Washington, DC, USA*
¹³³*The University of Alabama, Tuscaloosa, Alabama, USA*
¹³⁴*Boston University, Boston, Massachusetts, USA*
¹³⁵*Brown University, Providence, Rhode Island, USA*
¹³⁶*University of California, Davis, Davis, California, USA*
¹³⁷*University of California, Los Angeles, California, USA*
¹³⁸*University of California, Riverside, Riverside, California, USA*
¹³⁹*University of California, San Diego, La Jolla, California, USA*
¹⁴⁰*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
¹⁴¹*California Institute of Technology, Pasadena, California, USA*
¹⁴²*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
¹⁴³*University of Colorado Boulder, Boulder, Colorado, USA*
¹⁴⁴*Cornell University, Ithaca, New York, USA*
¹⁴⁵*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
¹⁴⁶*University of Florida, Gainesville, Florida, USA*
¹⁴⁷*Florida State University, Tallahassee, Florida, USA*
¹⁴⁸*Florida Institute of Technology, Melbourne, Florida, USA*
¹⁴⁹*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
¹⁵⁰*The University of Iowa, Iowa City, Iowa, USA*
¹⁵¹*Johns Hopkins University, Baltimore, Maryland, USA*
¹⁵²*The University of Kansas, Lawrence, Kansas, USA*
¹⁵³*Kansas State University, Manhattan, Kansas, USA*
¹⁵⁴*Lawrence Livermore National Laboratory, Livermore, California, USA*
¹⁵⁵*University of Maryland, College Park, Maryland, USA*
¹⁵⁶*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
¹⁵⁷*University of Minnesota, Minneapolis, Minnesota, USA*
¹⁵⁸*University of Mississippi, Oxford, Mississippi, USA*
¹⁵⁹*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
¹⁶⁰*State University of New York at Buffalo, Buffalo, New York, USA*
¹⁶¹*Northeastern University, Boston, Massachusetts, USA*
¹⁶²*Northwestern University, Evanston, Illinois, USA*
¹⁶³*University of Notre Dame, Notre Dame, Indiana, USA*
¹⁶⁴*The Ohio State University, Columbus, Ohio, USA*
¹⁶⁵*Princeton University, Princeton, New Jersey, USA*
¹⁶⁶*University of Puerto Rico, Mayaguez, Puerto Rico*
¹⁶⁷*Purdue University, West Lafayette, Indiana, USA*
¹⁶⁸*Purdue University Northwest, Hammond, Indiana, USA*
¹⁶⁹*Rice University, Houston, Texas, USA*
¹⁷⁰*University of Rochester, Rochester, New York, USA*
¹⁷¹*The Rockefeller University, New York, New York, USA*
¹⁷²*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
¹⁷³*University of Tennessee, Knoxville, Tennessee, USA*
¹⁷⁴*Texas A&M University, College Station, Texas, USA*

¹⁷⁵Texas Tech University, Lubbock, Texas, USA

¹⁷⁶Vanderbilt University, Nashville, Tennessee, USA

¹⁷⁷University of Virginia, Charlottesville, Virginia, USA

¹⁷⁸Wayne State University, Detroit, Michigan, USA

¹⁷⁹University of Wisconsin - Madison, Madison, Wisconsin, USA

¹⁸⁰An institute or international laboratory covered by a cooperation agreement with CERN

^aDeceased.

^bAlso at Yerevan State University, Yerevan, Armenia.

^cAlso at TU Wien, Vienna, Austria.

^dAlso at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

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

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

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

^hAlso at UFMS, Nova Andradina, Brazil.

ⁱAlso at The University of the State of Amazonas, Manaus, Brazil.

^jAlso at University of Chinese Academy of Sciences, Beijing, China.

^kAlso at Nanjing Normal University Department of Physics, Nanjing, China.

^lPresent address: The University of Iowa, Iowa City, Iowa, USA.

^mAlso at University of Chinese Academy of Sciences, Beijing, China.

ⁿAlso at Another institute or international laboratory covered by a cooperation agreement with CERN.

^oPresent address: British University in Egypt, Cairo, Egypt.

^pAlso at Suez University, Suez, Egypt.

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

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

^sAlso at Department of Physics, Tsinghua University, Beijing, China.

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

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

^vAlso at University of Hamburg, Hamburg, Germany.

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

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

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

^zAlso at Forschungszentrum Jülich, Jülich, Germany.

^{aa}Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.

^{bb}Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.

^{cc}Also at Wigner Research Centre for Physics, Budapest, Hungary.

^{dd}Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

^{ee}Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

^{ff}Present address: Universitatea Babeş-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.

^{gg}Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.

^{hh}Also at Punjab Agricultural University, Ludhiana, India.

ⁱⁱAlso at UPES—University of Petroleum and Energy Studies, Dehradun, India.

^{jj}Also at University of Visva-Bharati, Santiniketan, India.

^{kk}Also at University of Hyderabad, Hyderabad, India.

^{ll}Also at Indian Institute of Science (IISc), Bangalore, India.

^{mmm}Also at Indian Institute of Technology (IIT), Mumbai, India.

ⁿⁿAlso at IIT Bhubaneswar, Bhubaneswar, India.

^{oo}Also at Institute of Physics, Bhubaneswar, India.

^{pp}Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

^{qq}Also at Sharif University of Technology, Tehran, Iran.

^{rr}Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.

^{ss}Also at Helwan University, Cairo, Egypt.

^{tt}Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

^{uu}Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

^{vv}Also at Scuola Superiore Meridionale, Università di Napoli “Federico II”, Napoli, Italy.

^{ww}Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.

^{xx}Also at Università di Napoli “Federico II”, Napoli, Italy.

^{yy}Also at Ain Shams University, Cairo, Egypt.

^{zz}Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.

- aaa Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
- bbb Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ccc Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
- ddd Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- eee Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- fff Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ggg Also at National and Kapodistrian University of Athens, Athens, Greece.
- hhh Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- iii Also at Universität Zürich, Zurich, Switzerland.
- jjj Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- kkk Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- lll Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- mmm Also at Konya Technical University, Konya, Turkey.
- nnn Also at Izmir Bakircay University, Izmir, Turkey.
- ooo Also at Adiyaman University, Adiyaman, Turkey.
- ppp Also at Istanbul Gedik University, Istanbul, Turkey.
- qqq Also at Necmettin Erbakan University, Konya, Turkey.
- rrr Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- sss Also at Marmara University, Istanbul, Turkey.
- ttt Also at Milli Savunma University, Istanbul, Turkey.
- uuu Also at Kafkas University, Kars, Turkey.
- vvv Also at Hacettepe University, Ankara, Turkey.
- www Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- xxx Also at Yildiz Technical University, Istanbul, Turkey.
- yyy Also at Vrije Universiteit Brussel, Brussel, Belgium.
- zzz Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- aaaa Also at University of Bristol, Bristol, United Kingdom.
- bbbb Also at IPPP Durham University, Durham, United Kingdom.
- cccc Also at Monash University, Faculty of Science, Clayton, Australia.
- dddd Also at Università di Torino, Torino, Italy.
- eeee Also at Bethel University, St. Paul, Minnesota, USA.
- fff Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- gggg Also at California Institute of Technology, Pasadena, California, USA.
- hhhh Also at United States Naval Academy, Annapolis, Maryland, USA.
- iiii Also at Bingol University, Bingol, Turkey.
- jjjj Also at Georgian Technical University, Tbilisi, Georgia.
- kkkk Also at Sinop University, Sinop, Turkey.
- llll Also at Erciyes University, Kayseri, Turkey.
- mmmm Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China.
- nnnn Also at Texas A&M University at Qatar, Doha, Qatar.
- oooo Also at Kyungpook National University, Daegu, Korea.
- pppp Also at another institute or international laboratory covered by a cooperation agreement with CERN.
- qqqq Also at Yerevan Physics Institute, Yerevan, Armenia.
- rrrr Also at University of Florida, Gainesville, Florida, USA.
- ssss Also at Imperial College, London, United Kingdom.
- tttt Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.