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Search for rare decays of the Z and Higgs bosons to a J/ψ or ψ(2S) meson and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

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Abstract

A search is presented for rare decays of the Z and Higgs bosons to a photon and a J/ψ or a ψ(2S) meson, with the charmonium state subsequentially decaying to a pair of muons. The data set corresponds to an integrated luminosity of 123 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV collected with the CMS detector at the LHC. No evidence for branching fractions of these rare decay channels larger than predicted in the standard model is observed. Upper limits at 95% confidence level are set: $\mathcal{B}(\mathrm{H} \to \mathrm{J}/\psi\gamma) < 2.6 \times 10^{-4}$, $\mathcal{B}(\mathrm{H} \to \psi(2\mathrm{S})\gamma) < 9.9 \times 10^{-4}$, $\mathcal{B}(\mathrm{Z} \to \mathrm{J}/\psi\gamma) < 0.6 \times 10^{-6}$, and $\mathcal{B}(\mathrm{Z} \to \psi(2\mathrm{S})\gamma) < 1.3 \times 10^{-6}$. The ratio of the Higgs boson coupling modifiers κ_c/κ_γ is constrained to be in the interval $(-157, +199)$ at 95% confidence level. Assuming $\kappa_\gamma = 1$, this interval becomes $(-166, +208)$.

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*See Appendix A for the list of collaboration members

1 Introduction

The discovery of the Higgs boson by the ATLAS and CMS Collaborations in 2012 [1–3] represented a milestone in the understanding of the electroweak sector of the standard model (SM) of elementary particles [4, 5], and it started a new era of precision measurements of the couplings of the Higgs boson to the other SM bosons and fermions [6, 7]. New particles, postulated by theories that extend the SM, may contribute to quantum loops and modify the branching fractions of rare decays of the Higgs boson. A channel which would be sensitive to such contributions is the decay of the Higgs boson to a photon (γ) and a J/ψ or $\psi(2S)$ meson, collectively referred to as $\psi(nS)$, followed by the decay of the $\psi(nS)$ meson to a pair of muons. The $H \to \psi(nS)\gamma$ decay could take place through c quark loops, as shown in Fig. 1, and thus an accurate measurement of this process would constrain the couplings of the Higgs boson to c quarks, providing complementary information to searches for Higgs boson decay to a pair of c quarks hadronizing into jets [8–10]. Although the latter has a better sensitivity to the coupling between the Higgs boson and the charm quark, the loop-mediated $H \to \psi(nS)\gamma$ is also sensitive to additional contributions that can arise in certain extensions of the SM [11, 12]. Instead, the yet outstanding observation of the $Z \to \psi(nS)\gamma$ process would represent an objective that is achievable with the integrated luminosity of the HL-LHC [13].

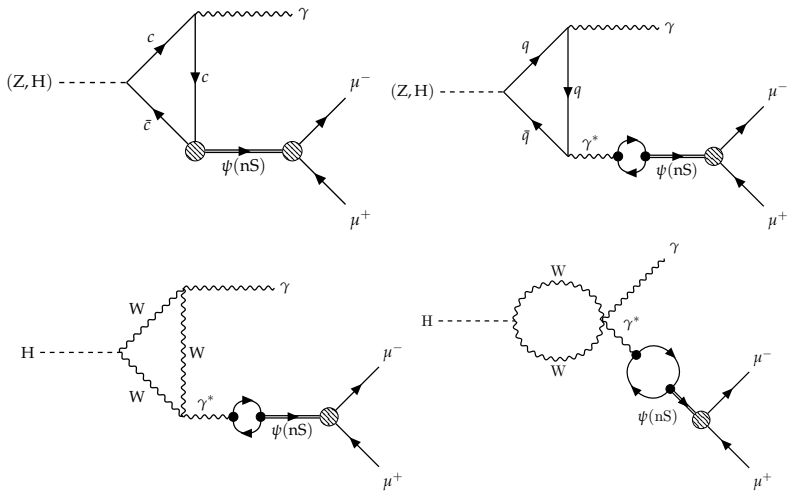


Figure 1: Leading-order Feynman diagrams of Z and Higgs boson rare decays to J/ψ or $\psi(2S)$, and a photon, through the direct (upper left) and indirect (upper right, lower left, and lower right) processes. These four diagrams are considered as the signal of this analysis.

The boson decays to $\psi(nS)$ are considered as "rare", as the branching fractions range between $\approx 10^{-6}$ and $\approx 10^{-8}$ [11, 13–22]. On the other hand, the branching fractions of the decays of the $\psi(nS)$ to a pair of muons have been measured with great precision [23]. The values considered in this analysis are reported in Table 1.

The search for the decays $Z \to \psi(nS)\gamma$ and $H \to \psi(nS)\gamma$ was previously performed by both the ATLAS and CMS Collaborations using data collected in 2016 [24, 25] and the ATLAS Collaboration recently updated its search using the complete Run 2 data set [26]. The present search is performed with data from proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 123 fb^{-1}, collected with the CMS detector during the LHC Run 2 (2016–2018).

Tabulated results are provided in the HEPData record for this analysis [27].

Table 1: The SM predictions of the branching fractions of the Higgs and Z boson decays to $\psi(\mathrm{nS})\gamma$ used in this analysis, and measured branching fractions for the $\psi(\mathrm{nS}) \to \mu\mu$ decays.

Process	$\mathcal{B}$	Ref.
$\mathrm{H} \to \mathrm{J}/\psi\gamma$	$(3.01 \pm 0.15) \times 10^{-6}$	[20]
$\mathrm{Z} \to \mathrm{J}/\psi\gamma$	$8.96^{+1.51}_{-1.38} \times 10^{-8}$	[18]
$\mathrm{H} \to \psi(2\mathrm{S})\gamma$	$(1.03 \pm 0.06) \times 10^{-6}$	[20]
$\mathrm{Z} \to \psi(2\mathrm{S})\gamma$	$4.83^{+1.02}_{-0.91} \times 10^{-8}$	[18]
$\mathrm{J}/\psi \to \mu^-\mu^+$	$(5.961 \pm 0.033) \times 10^{-2}$	[23]
$\psi(2\mathrm{S}) \to \mu^-\mu^+$	$(8.0 \pm 0.6) \times 10^{-3}$	[23]

2 The CMS detector and event reconstruction

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, is reported in Ref. [28].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the magnetic 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. The ECAL and HCAL provide pseudorapidity coverage up to $|\eta| < 3.0$, which is further extended by forward calorimeters to $|\eta| < 5.0$ [28]. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [29]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [30].

The silicon tracker used in 2016 measured charged particles within the range $|\eta| < 2.5$. For nonisolated particles of $1 < p_\mathrm{T} < 10$ GeV and $|\eta| < 1.4$, the track resolutions were typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [31]. At the start of 2017, a new pixel detector was installed [32]; the upgraded tracker measured particles up to $|\eta| = 3.0$ with typical resolutions of 1.5% in p_T and 20–75 μm in the transverse impact parameter [33] for nonisolated particles of $1 < p_\mathrm{T} < 10$ GeV.

In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The energy resolution of the remaining barrel photons is about 1.3% up to $|\eta| = 1$, changing to about 2.5% at $|\eta| = 1.4$. In the endcaps, the energy resolution is about 2.5% for unconverted or late-converting photons, and between 3 and 4% for the other ones [34]. Electrons mimicking photons are rejected by requiring the absence of charged particle tracks, with a hit in the innermost layer of the pixel detector not matched to a reconstructed conversion vertex, pointing to the photon cluster in the ECAL [34]. The photon energy in simulation is corrected with a multivariate regression to match the energy resolution observed in data [35].

The efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the endcaps [36]. The simulated muons are calibrated to match the momentum scale and resolution observed in $\mathrm{Z} \to \mu\mu$ data.

The event reconstruction is performed with a particle-flow (PF) algorithm [37], which uses an optimized combination of information from the various elements of the CMS detector to reconstruct and identify individual particles produced in each collision. The algorithm identifies each reconstructed particle either as an electron, a muon, a photon, or a charged or neutral hadron. The PF candidates are then clustered into jets using the anti-k_T algorithm [38] implemented in the FASTJET package [39, 40] with a distance parameter $R = 0.4$. The charged component of the pileup contribution is removed from jets by applying the charged-hadron subtraction (CHS) mitigation algorithm [41]. Jets that originate from b quarks are identified with the DEEPCSV b tagging algorithm [42], which uses the tracks and secondary vertices associated with the jets as inputs to a neural network. The working point considered in this search provides a b jet tagging efficiency of 70%, and a misidentification rate in a sample of quark and gluon jets of about 1% [42].

3 Data and simulated samples

The data used in this search have been collected with a trigger algorithm that selects events with at least one muon with $p_T > 17\,\text{GeV}$ and one photon with transverse energy $E_T > 30\,\text{GeV}$. This trigger collected data with an integrated luminosity of $123\,\text{fb}^{-1}$.

The $Z/H \to \psi(nS)\gamma$ signal Monte Carlo (MC) events are simulated at leading order (LO) accuracy in QCD with the MADGRAPH5_aMC@NLO v2.6.5 matrix element generator [43], directly including the spin correlations [44] using a model based on Refs. [17, 18] instead of reweighting the simulated events as in previous analyses [24–26]. Whereas the Z boson production is simulated through quark-antiquark annihilation ($q\bar{q} \to Z$), the simulation of the H boson production is performed separately for each production mode, namely through gluon-fusion (ggF), vector-boson fusion (VBF), vector boson associated production (WH and ZH), and bottom- and top-quark associated production ($b\bar{b}H$ and $t\bar{t}H$). The Higgs boson mass is set to 125 GeV. For each boson and production mode, two different samples are generated, with the Z and H bosons decaying to $J/\psi\gamma$ or $\psi(2S)\gamma$, where the $\psi(nS)$ decays to a pair of muons.

Cascade decays $\psi(2S) \to J/\psi + X \to \mu\mu + X$, even though they provide a nonnegligible number of events compared with the direct decays $\psi(2S) \to \mu\mu$, are not considered in this analysis because the momentum carried away by the additional particles (X) makes their invariant mass $m_{\mu\mu\gamma}$ nonresonant and shifts it towards smaller $m_{\mu\mu\gamma}$ values, not contributing to the peak of the expected signal.

The Z boson cross section is calculated at next-to-next-to-LO (NNLO) using FEWZ v3.1 [45]. The Higgs boson cross section is normalized to a theoretical prediction at up to next-to-NNLO [14]. The branching fractions used are listed in Table 1. The Z boson produced through VBF has a cross section that is several orders of magnitude smaller than the $q\bar{q}$ production mechanism, and is therefore considered negligible.

The SM electroweak backgrounds include resonant processes that produce a pair of muons and a photon, which consist of Z and H bosons that decay through quark loops without the intermediate resonant $c\bar{c}$ state, referred to as "Dalitz decays", and Z boson decays to a pair of muons with a final-state radiation photon. Both processes are generated at next-to-LO (NLO) in QCD with the MADGRAPH5_aMC@NLO event generator. The decay of a Higgs boson into two muons with a photon radiated from one of the muons represents another potential source of background, but its contribution is negligible.

In all simulated samples, parton showering and hadronization processes are simulated by in-

terfacing the event generators with PYTHIA 8.230 with the CP5 underlying event tune [46]. The NNPDF3.1 NNLO [47, 48] parton distribution functions (PDFs) are used to model the momentum distribution of the colliding partons inside the protons. The generated events include additional proton-proton interactions within the same or adjacent bunch crossings (pileup) with a distribution that matches that observed in the data. The response of the CMS detector to the generated particles is modeled using the GEANT4 toolkit [49]. Simulated events are reconstructed with the same algorithms used for data.

4 Event selection

Events are required to contain at least two reconstructed muons with $p_{\mathrm{T}} > 18$ and 5 GeV, respectively, fulfilling the *medium* identification requirement [36], and at least one photon with $p_{\mathrm{T}} > 32$ GeV passing a multivariate identification criteria that is 80% efficient for signal photons [35]. Both the muons and the photon are required to be isolated from other hadronic activity in the event. If more than two muons are present in the same event, the opposite-sign pair with the smallest $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ distance is chosen.

The observable used for signal extraction in this search is the invariant mass $m_{\mu\mu\gamma}$. Events are separated into three regions based on the invariant mass $m_{\mu\mu}$: (i) events with $3.0 < m_{\mu\mu} < 3.2$ GeV are considered to be J/ψ candidates and belong to a signal region (SR) called SR1; (ii) events with $3.60 < m_{\mu\mu} < 3.75$ GeV are assumed to originate from a $\psi(2S)$ state and belong to a separate signal region SR2; and (iii) events that do not belong to either SR1 or SR2, but satisfy $2 < m_{\mu\mu} < 8$ GeV, are a control region (CR) that is used to constrain the resonant $m_{\mu\mu\gamma}$ background.

Depending on the signal process, additional categories are defined to exploit distinct physical features. Three categories maximize the sensitivity to the main Higgs boson production modes: (i) the VBF category contains events with at least one pair of jets with $p_{\mathrm{T}} > 30\,(50)$ GeV in the central (forward) regions of the detector with an invariant mass larger than 350 GeV; (ii) the heavy-flavor (HF) category contains events with at least one b tagged jet with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$ and targets the Higgs boson production in association with bottom and top quarks; (iii) events that do not belong to the previous categories constitute the ggF category. The data set we used does not contain enough events for a dedicated category targeting leptonic decays of the W or Z boson.

The same categorization is not applicable to the Z boson search since the Z boson is predominantly produced through $\mathrm{q\bar{q}}$ annihilation. Instead, the Z, $\psi(\mathrm{nS})$, and γ spin correlations are used to build a multivariate likelihood discriminator (LD) to separate the $\mathrm{Z} \to \mathrm{J}/\psi\gamma$ signal from the main background. The input variables of the discriminator are: the cosine of the angle between the momentum directions of the J/ψ boson and of the beam in the rest frame of the Z boson ($\cos\theta^*$), the angle between the momentum directions of the positively charged muon and the J/ψ in the rest frame of the J/ψ ($\cos\theta_1$), which is sensitive to the transverse polarization of the J/ψ along its momentum direction, and the angle between the decay plane of the two muons and the plane of the J/ψ and the photon (ϕ_1). Since these variables are uncorrelated with each other and from $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$, a selection on the discriminator output does not alter the shape of the $m_{\mu\mu\gamma}$ distribution. The LD is used to define two categories, denoted as high-purity (Z-HP) and low-purity (Z-LP) categories, which contain events with an LD score larger or smaller than 0.5, respectively. The discriminator is applied to only the $\mathrm{Z} \to \mathrm{J}/\psi\gamma$ category to separate the signal and the background. In the $\mathrm{H} \to \mathrm{J}/\psi\gamma$ ggF region, most of the discriminating power comes from the $|\cos\theta^*|$ variable. Thus, this variable is used in place of the LD

to define high-purity (ggF-HP) and low-purity (ggF-LP) categories, containing events with a $|\cos\theta^*|$ value larger or smaller than 0.5, respectively. Because of the limited number of events in the other signal regions, the LD categorization or the angular selections are not applied.

The selections used to divide events into the eight signal regions and the control region are summarized in Table 2.

Table 2: Summary of the selections of the seven signal regions (SRs) and the control region (CR). The SR1 category requires an $m_{\mu\mu}$ value compatible with the J/ψ mass hypothesis, and is further divided depending on the value of the LD variable (Z-HP, Z-LP), the Higgs boson production mode (ggF, VBF, HF), and the value of the $\cos\theta^*$ variable (ggF-HP, ggF-LP). The SR2 category requires a $m_{\mu\mu}$ value compatible with the $\psi(2S)$ mass hypothesis and is not further categorized. The CR category is made orthogonal to the SRs by vetoing $m_{\mu\mu}$ values compatible with the $\psi(nS)$ mass hypotheses.

	SR1						SR2	CR
	Z-HP	Z-LP	ggF-HP	ggF-LP	VBF	HF		
$p_T(\mu_1)$	>18 GeV							
$p_T(\mu_2)$	>5 GeV							
$p_T(\gamma)$	>32 GeV							
$\lvert\eta(\mu_{1,2})\rvert$	<2.4							
$\lvert\eta^\gamma\rvert$	<2.5, excluding ECAL transition region							
$m_{\mu\mu}$ (GeV)	[3.0, 3.2]						[3.6, 3.75]	[2.0, 3.0], [3.2, 3.6], [3.75, 8.0]
$\lvert\cos\theta^*\rvert$	—	—	>0.5	<0.5	—	—	—	—
LD	>0.5	<0.5	—	—	—	—	—	—
b jets	—	—	0	0	0	≥ 1	—	—
VBF candidates ($m_{jj} > 350$ GeV)	—	—	0	0	≥ 1	0	—	—

5 Signal and background modeling

Backgrounds are separated into two classes. The electroweak-induced backgrounds are composed of Dalitz decays of the Higgs boson and $Z \to \mu\mu$ events with final-state radiation, and are modeled with MC simulation. The QCD multijet production, which does not exhibit a resonant shape in $m_{\mu\mu\gamma}$, is estimated from data with parametric functions.

The resonant backgrounds and the signals appear as resonances in the $m_{\mu\mu\gamma}$ distribution and are modeled with double-sided Crystal Ball (DSCB) functions [50], which consist of a Gaussian core and two power-law functions that describe the lower and upper tails, below and above a certain threshold. An alternative Voigt distribution, which consists of a convolution of a Gaussian with a Cauchy-Lorentzian, is also evaluated. Both functions are able to describe the resonant shape, but the DSCB is chosen because of its better modeling of the lower tails. The Gaussian core of the DSCB fitted to the H boson signal is dominated by the measurement resolution and has a relative width of 1%. The Z boson signal width, instead, is dominated by the natural width of the Z resonance.

The nonresonant background is modeled separately for each category directly from data using parametric functions to describe the $m_{\mu\mu\gamma}$ distribution. Several choices of function families are

considered in the statistical analysis and, for each family, models with different numbers of parameters are included. These functions are: power-law and exponential with a number of parameters between 1 and 4; Bernstein polynomials with a number of parameters between 3 and 5. For each function family, a procedure based on the Fisher F-test [51] starts from the simplest functional form and checks iteratively, using a confidence level of 95%, if additional parameters are needed to model the background distributions.

The measured $m_{\mu\mu\gamma}$ distributions are well modeled by the background parametric functions, as shown in Figs. 2–4. The width of the mass bins is chosen according to the experimental mass resolution.

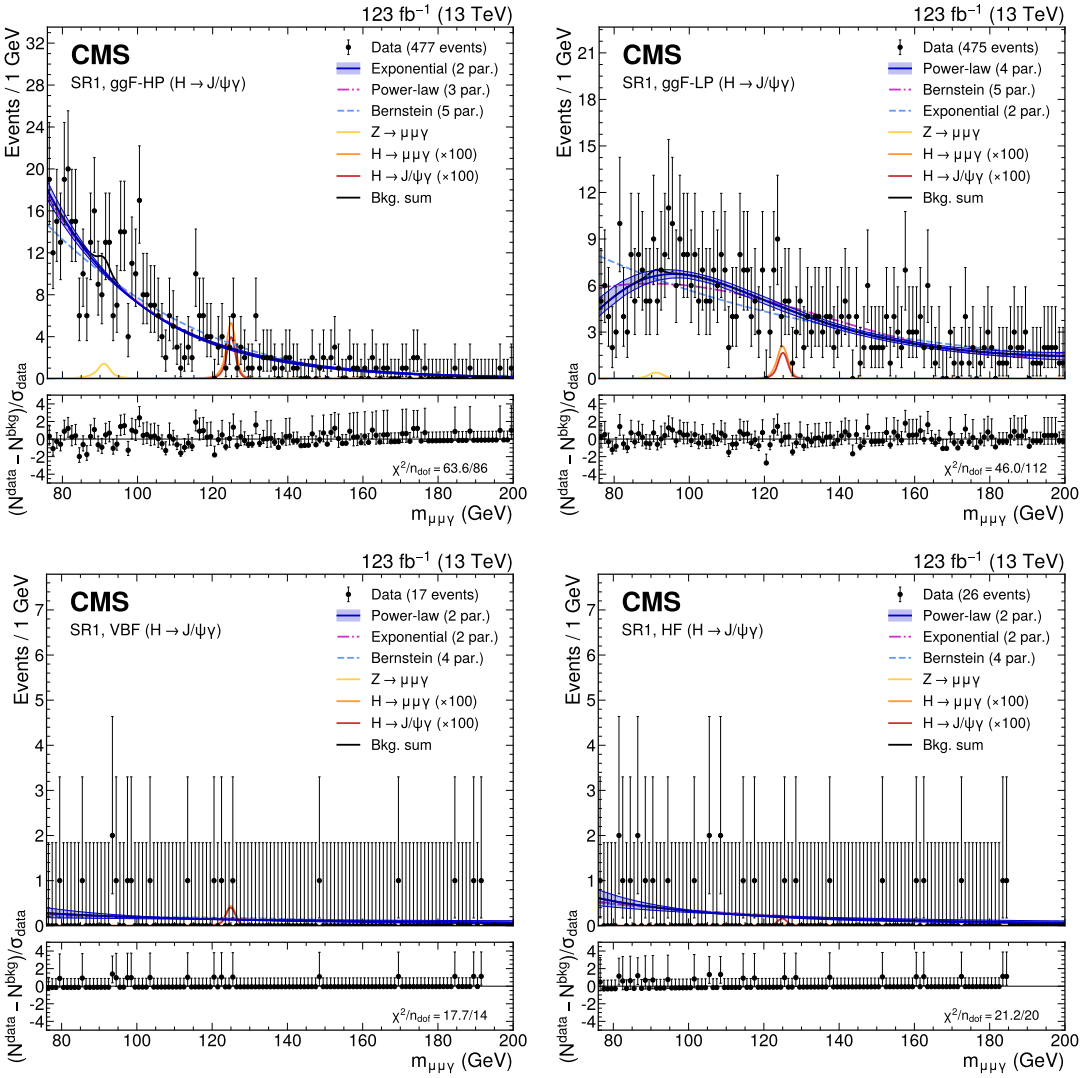


Figure 2: The upper panels show the background-only fit using the power-law, exponential, and Bernstein polynomial functions with the optimal number of parameters determined with the F-test, and ranked according to the fit χ^2. The resonant background contributions are added with the normalization fixed to the SM expectation. The vertical error bars on the data points show the statistical uncertainty. The bottom panels show the pulls for the fit result for the model with lowest χ^2. Upper left: H $\to$ J/$\psi\gamma$ ggF-HP category. Upper right: H $\to$ J/$\psi\gamma$ ggF-LP category. Lower left: H $\to$ J/$\psi\gamma$ VBF category. Lower right: H $\to$ J/$\psi\gamma$ HF category.

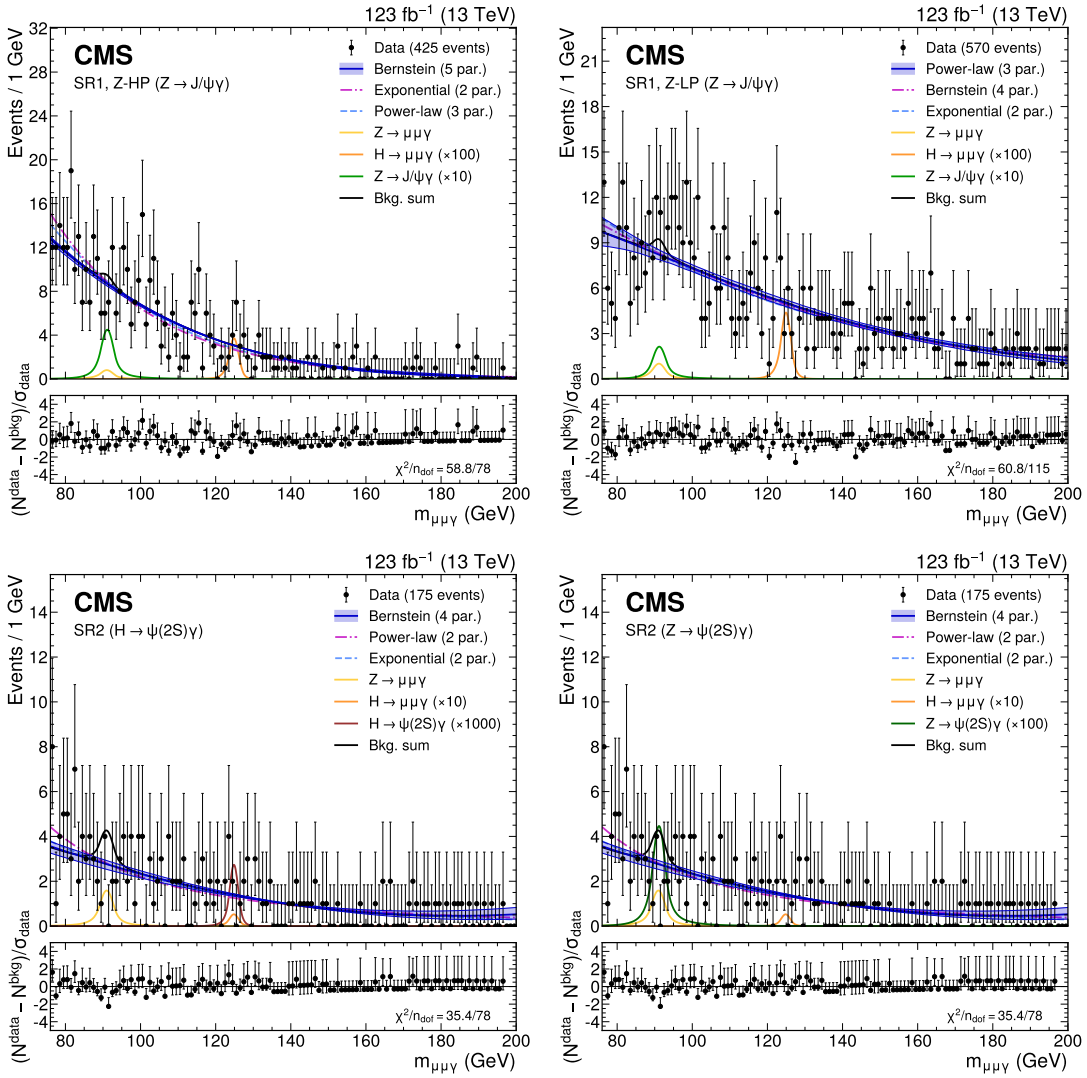


Figure 3: The upper panels show the background-only fit using the power-law, exponential, and Bernstein polynomial functions with the optimal number of parameters determined with the F-test, and ranked according to the fit χ^2. The resonant background contributions are added with the normalization fixed to the SM expectation. The vertical error bars on the data points show the statistical uncertainty. The bottom panels show the pulls for the fit result for the model with lowest χ^2. Upper left: $Z \to J/\psi\gamma$ HP category. Upper right: $Z \to J/\psi\gamma$ LP category. Lower left: $H \to \psi(2S)\gamma$ category. Lower right: $Z \to \psi(2S)\gamma$ category.

6 Systematic uncertainties

Systematic uncertainties include the modeling of the backgrounds, the detector simulation, the integrated luminosity, and the theoretical prediction of the signal production mechanism.

The uncertainty related to the choice of function used to model the QCD multijet background is addressed by introducing the *discrete profiling* method [52]. This method considers all function families listed in Section 5, with the number of free parameters determined with an F-test, and fitted to the appropriate $m_{\mu\mu\gamma}$ distribution in each category by minimizing the negative logarithm of the likelihood multiplied by two (2NLL). The functions with resulting fit p-values smaller than 0.05 (and that, hence, do not fit the data sufficiently well) are discarded. A unitary penalty term is added to the 2NLL to account for the number of floating parameters in each

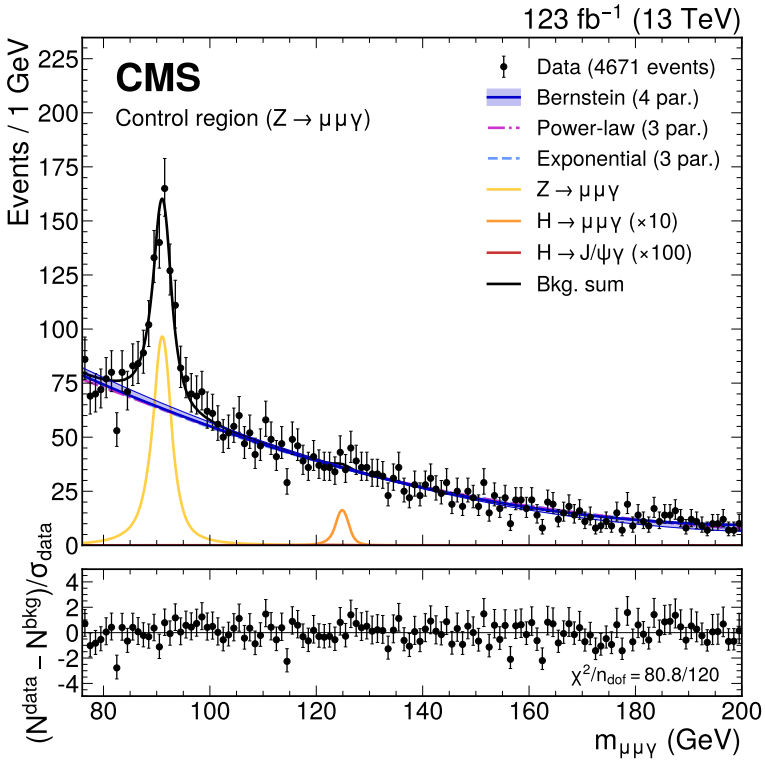


Figure 4: The upper panel shows the results of the main background fit in the CR, using the power-law, exponential, and Bernstein polynomial functions with the optimal number of parameters determined with the F-test, and ranked according to the fit χ^2. The vertical error bars on the data points show the statistical uncertainty. The bottom panel shows the pulls for the fit result for the model with lowest χ^2.

candidate function. The envelope of the 2NLL profiles for each function considered, as a function of the signal strength, is then used to determine the best-fit value and the corresponding uncertainty in the parameter of interest. The outcome of this procedure is that the selection of the background function is treated as a discrete nuisance parameter in the fit to account for the uncertainty associated with the arbitrariness of this choice.

An additional uncertainty is introduced to cover potential biases in the choice of the function used to model the signal and the resonant backgrounds. An alternate Voigtian function is used and the difference in the fitted signal strength, which is always smaller than 1%, is considered as an uncertainty.

The experimental systematic uncertainties affecting the signal normalization include the reconstruction and selection efficiency of the muons and the photon, amounting to 2.0 and 1.5%, respectively. The muon momentum scale and resolution calibration uncertainties are propagated to the $m_{\mu\mu\gamma}$ distribution, and have an effect of 0.05 and 0.80% on the Gaussian mean and width used to model the simulated samples, respectively. Similarly, the photon energy scale and photon energy resolution result in a 3.4 and 1.8% uncertainty in the Gaussian width, respectively. The jet energy scale and resolution uncertainties affect the Higgs boson normalization in the VBF category by 2.9 and 1.0%, respectively, while the jet b tagging efficiency uncertainty is 5.4% in the HF category. The effect of these uncertainties is negligible elsewhere. The uncertainty in the efficiency of the trigger is less than 3.2%. During the 2016 and 2017 data-taking periods, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the $|\eta| > 2.0$ region

caused a specific trigger inefficiency. For events containing a photon (a jet) with p_T larger than $\approx$50 GeV ($\approx$100 GeV) in the $2.5 < |\eta| < 3.0$ region, the efficiency loss is $\approx$10–20%, depending on p_T, η, and time. Correction factors were computed from data and applied to the acceptance evaluated with simulation. Other uncertainties, such as the pileup contributions (0.1%), and the measurement of the integrated luminosity (1.2% in 2016 [53], 2.3% in 2017 [54], and 2.5% in 2018 [55]) affect only the normalization of the simulated samples and have negligible effects on their $m_{\mu\mu\gamma}$ distributions.

Systematic uncertainties in the theoretical prediction arise from the choice of PDFs [56, 57], leading to a 2–3% effect on the signal cross section for the Z and H boson signals. The factorization and renormalization scale uncertainties are estimated by varying the scales up and down by a factor of 2, both simultaneously and independently, using the maximum obtained value. The resulting effect is a variation of 3–6% of the signal cross section.

A summary of the systematic uncertainties is provided in Table 3.

Table 3: Sources and types of systematic uncertainties described in Section 6. Normalization (norm.) uncertainties yield a variation in the number of events equal to the reported value. Other uncertainties also vary the shape of the mean and the width of the resonant background and signal $m_{\mu\mu\gamma}$ distributions by the indicated amount. Uncertainties in the same line are treated as correlated.

Source	Type	Backgrounds		Signals		
		QCD	$Z \to \mu\mu\gamma$	$H \to \mu\mu\gamma$	$Z \to \psi(nS)\gamma$	$H \to \psi(nS)\gamma$
Integrated luminosity	norm.	—	—	1.6%	1.6%	1.6%
Fact. and renorm. scales	norm.	—	—	3.6%	3.5%	5.6%
PDF	norm.	—	—	1.8%	1.7%	3.2%
$H \to \mu\mu\gamma$ branching ratio	norm.	—	—	5.3%	—	—
Pileup modeling	norm.	—	—	0.7%	0.9%	0.8%
Trigger efficiency	norm.	—	—	3.5%	3.5%	3.5%
Trigger timing shift	norm.	—	—	0.0%	0.6%	2.7%
Muon identification/isolation	norm.	—	—	1.6%	2.0%	1.4%
Photon identification	norm.	—	—	1.6%	1.5%	1.5%
Electron veto	norm.	—	—	1.0%	1.0%	1.0%
Jet energy scale (VBF category)	norm.	—	—	2.9%	—	2.9%
Jet energy resolution (VBF category)	norm.	—	—	1.0%	—	1.0%
Jet b tagging (HF category)	norm.	—	—	5.4%	—	5.4%
QCD background model	shape	discrete	—	—	—	—
Resonant bkg. model	norm.	—	1%	—	—	—
Signal model	norm.	—	—	1%	1%	1%
Size of MC samples	$m_{\mu\mu\gamma}$ mean	—	0.06%	0.17%	0.06%	0.06%
Size of MC samples	$m_{\mu\mu\gamma}$ width	—	0.1%	1.3%	0.1%	0.1%
μ calibration	$m_{\mu\mu\gamma}$ mean	—	0.05%	0.05%	0.05%	0.05%
μ calibration	$m_{\mu\mu\gamma}$ width	—	0.8%	0.8%	0.8%	0.8%
γ energy	$m_{\mu\mu\gamma}$ mean	—	0.04%	0.04%	0.04%	0.04%
γ energy	$m_{\mu\mu\gamma}$ width	—	3.4%	3.4%	3.4%	3.4%
γ resolution	$m_{\mu\mu\gamma}$ width	—	1.8%	1.8%	1.8%	1.8%

7 Results and interpretation

In the absence of a significant observed signal, exclusion limits are obtained by performing a background-only fit and a combined signal-plus-background fit to the $m_{\mu\mu\gamma}$ mass distributions, independently for the Z and Higgs boson signals, and the J/ψ and $\psi(2S)$ hypotheses.

The Higgs and Z boson signals are fitted to the H and Z SRs, respectively. Each fit also includes the CR, which constrains the normalization of the Z boson Dalitz backgrounds. The H

boson Dalitz backgrounds are fixed to the SM background expectation, because the number of selected events is not sufficient to constrain this process.

In the fit, based on a profile likelihood, the parameters and the normalization of the background in each category are left free to float. The systematic uncertainties in the signal are treated as nuisance parameters profiled in the statistical interpretation [58], using log-normal constraints for the normalization uncertainties and Gaussian constraints for the muon and photon energy scale and resolution. The Z boson Dalitz background signal strength, $\mu_{Z\to\mu\mu\gamma}$, is extracted from a standalone fit to the $m_{\mu\mu\gamma}$ distribution measured for the CR events (shown in Fig. 4). The result is statistically compatible with the SM expectation: $\mu_{Z\to\mu\mu\gamma} = 1.18 \pm 0.12$.

Upper limits at 95% confidence level (CL) are set using the CL_s criterion [59, 60] in the asymptotic approximation [61] and cross-checked with those obtained using the generation of pseudo-data [58]. The limits derived with the two methods are in agreement within 5%.

The results are summarized in Fig. 5 and Table 4, where the branching fraction and signal strength values for each channel are reported. The uncertainties that affect the signal normalization (factorization and renormalization scales, and PDF) are treated differently depending on how the exclusion is presented. When deriving upper limits on $\mathcal{B}$ or $\sigma\mathcal{B}$ these uncertainties are not varied in the fit. When placing limits on the signal strength μ, these nuisance parameters are fixed at their best-fit values, in the same manner as the other systematic uncertainties. No statistically significant excess is observed. A deficit in the data consistent with a downward fluctuation with a significance of 2.2 standard deviations is seen in the $Z \to \psi(2S)\gamma$ search channel. The previous results from the CMS and ATLAS Collaborations are also included for comparison in Table 4 [24, 26].

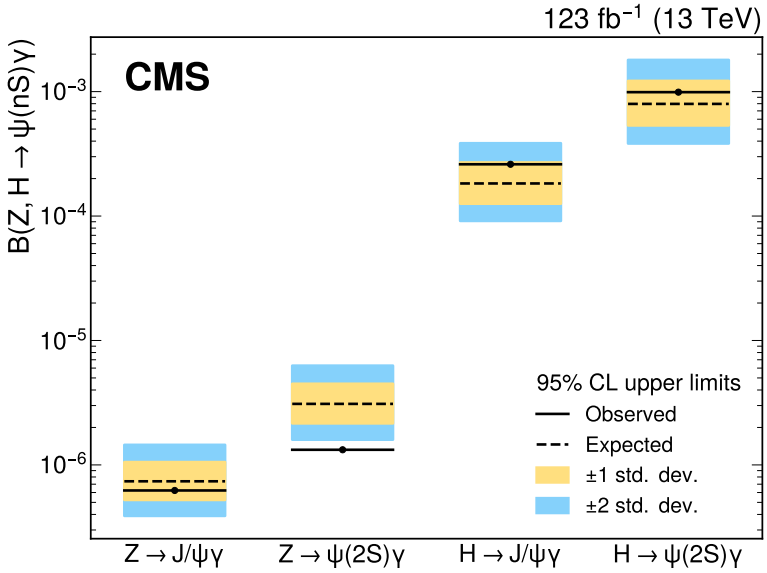


Figure 5: Observed and expected (with ±1, ±2 standard deviation bands) exclusion limits on the branching fraction of the $(H, Z) \to \psi(nS)\gamma$ decays.

The upper limits on the $H \to J/\psi\gamma$ signal strength are interpreted within the κ-framework [62] to constrain the c quark Yukawa coupling. The ratios of the signal strengths for the $H \to J/\psi\gamma$ and $H \to \gamma\gamma$ decays and their SM expectations are approximated as the ratio of their respective partial decay widths, normalized to their SM expectations Γ^{SM}. Writing the partial $H \to J/\psi\gamma$ decay width in terms of both direct and indirect amplitudes $\mathcal{A}_{dir}$ and $\mathcal{A}_{ind}$ from the diagrams reported in Fig. 1, the ratio κ_c/κ_γ between the coupling modifiers for the c quark Yukawa

Table 4: Observed (expected) upper limits at 95% CL on the normalized values with respect to the SM expectation, denoted as the signal strength parameter μ, of the product of the cross section σ and the branching fraction $\mathcal{B}$ of the $(\mathrm{H}, \mathrm{Z}) \to \psi(\mathrm{nS})\gamma$ decays, and the branching fraction, assuming a SM Z and H boson cross section. The results are compared with previous ones [24, 26].

Process	This work ($123\,\mathrm{fb}^{-1}$)			CMS ($36\,\mathrm{fb}^{-1}$) [24]	ATLAS ($139\,\mathrm{fb}^{-1}$) [26]
	$\mu_{\mathrm{obs}}(\mu_{\mathrm{exp}})$	$\sigma\mathcal{B}_{\mathrm{obs}}(\sigma\mathcal{B}_{\mathrm{exp}})$ [pb]	$\mathcal{B}_{\mathrm{obs}}(\mathcal{B}_{\mathrm{exp}})$	$\mathcal{B}_{\mathrm{obs}}(\mathcal{B}_{\mathrm{exp}})$	$\mathcal{B}_{\mathrm{obs}}(\mathcal{B}_{\mathrm{exp}})$
$\mathrm{Z} \to \mathrm{J}/\psi\gamma$	$7.2\,(8.6^{+4.1}_{-2.7})$	$3.8\,(4.4^{+1.9}_{-1.3}) \times 10^{-2}$	$0.6\,(0.7^{+0.3}_{-0.2}) \times 10^{-6}$	$1.5\,(1.7^{+0.7}_{-0.5}) \times 10^{-6}$	$1.2\,(0.7^{+0.3}_{-0.2}) \times 10^{-6}$
$\mathrm{Z} \to \psi(2\mathrm{S})\gamma$	$29\,(68^{+36}_{-22})$	$8\,(19^{+8}_{-6}) \times 10^{-2}$	$1.3\,(3.1^{+1.4}_{-0.9}) \times 10^{-6}$	—	$2.4\,(3.0^{+1.3}_{-0.8}) \times 10^{-6}$
$\mathrm{H} \to \mathrm{J}/\psi\gamma$	$88\,(62^{+30}_{-19})$	$1.4\,(1.0^{+0.5}_{-0.3}) \times 10^{-2}$	$2.6\,(1.8^{+0.9}_{-0.6}) \times 10^{-4}$	$7.6\,(5.2^{+2.4}_{-1.6}) \times 10^{-4}$	$2.0\,(1.8^{+0.8}_{-0.5}) \times 10^{-4}$
$\mathrm{H} \to \psi(2\mathrm{S})\gamma$	$970\,(780^{+420}_{-260})$	$5.5\,(4.4^{+2.3}_{-1.5}) \times 10^{-2}$	$9.9\,(8.0^{+4.2}_{-2.6}) \times 10^{-4}$	—	$10.5\,(8.1^{+3.6}_{-2.3}) \times 10^{-4}$

coupling and the effective coupling of the Higgs boson to photons can be expressed as

$$\frac{\mu(\mathrm{H} \to \mathrm{J}/\psi\gamma)}{\mu(\mathrm{H} \to \gamma\gamma)} \approx \frac{\Gamma(\mathrm{H} \to \mathrm{J}/\psi\gamma)/\Gamma^{\mathrm{SM}}(\mathrm{H} \to \mathrm{J}/\psi\gamma)}{\Gamma(\mathrm{H} \to \gamma\gamma)/\Gamma^{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)} = \\ = \frac{|\mathcal{A}_{\mathrm{ind}}\kappa_\gamma + \mathcal{A}_{\mathrm{dir}}\kappa_{\mathrm{c}}|^2}{\kappa_\gamma^2} \frac{1}{\Gamma^{\mathrm{SM}}(\mathrm{H} \to \mathrm{J}/\psi\gamma)} = \frac{|\mathcal{A}_{\mathrm{ind}} + \mathcal{A}_{\mathrm{dir}}\kappa_{\mathrm{c}}/\kappa_\gamma|^2}{\Gamma^{\mathrm{SM}}(\mathrm{H} \to \mathrm{J}/\psi\gamma)}.$$

In this interpretation, the signal strength for $\mathrm{H} \to \gamma\gamma$ comes from Ref. [63], whereas the values for the direct and indirect amplitudes for $\mathrm{H} \to \mathrm{J}/\psi\gamma$ are extracted from Ref. [20]. This interpretation follows the methodology used by the ATLAS Collaboration [26], which is based on Refs. [20, 64]. The observed constraint on the $\kappa_{\mathrm{c}}/\kappa_\gamma$ ratio at 95% CL corresponds to the interval $(-157, +199)$, whereas the expected interval from pseudo-experiments is $(-121, +161)$. These results are similar to those reported by ATLAS [26].

An alternative interpretation is considered. Under the pure SM assumption, $\kappa_\gamma = 1$ and consequently $\mu(\mathrm{H} \to \gamma\gamma) = 1$. Thus, the previous equation simplifies to

$$\mu(\mathrm{H} \to \mathrm{J}/\psi\gamma) \approx \frac{|\mathcal{A}_{\mathrm{ind}} + \mathcal{A}_{\mathrm{dir}}\kappa_{\mathrm{c}}|^2}{\Gamma^{\mathrm{SM}}(\mathrm{H} \to \mathrm{J}/\psi\gamma)}.$$

In this interpretation, the constraint is applied to κ_{c} directly. The observed and expected intervals at 95% CL are $(-166, +208)$ and $(-128, +169)$, respectively.

With respect to the previous CMS search [24], the sensitivity of this analysis shows an improvement that exceeds the expectations from a simple increase in the integrated luminosity because of the optimization of the event selection, including the angular variables of the decays, the categorization of the Higgs boson depending on the production mode, and the adoption of a more advanced statistical treatment represented by the discrete profiling method, described in Section 6. When compared with the 2016 CMS search updated with the larger data set, the selections optimized to leverage the unique features of each signal process and the statistical treatment provide an improvement by a factor of 2 in the expected limit in the case of the $\mathrm{H} \to \mathrm{J}/\psi\gamma$ decay, and of 30% in the case of the $\mathrm{Z} \to \mathrm{J}/\psi\gamma$ decay.

8 Summary

A search for rare decays of the Z and H bosons to a photon and a $\psi(\mathrm{nS})$ meson decaying to a pair of muons is presented. The data were collected by the CMS experiment in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ during 2016–2018 and correspond to an integrated luminosity of

$123\,\text{fb}^{-1}$. No statistically significant excess has been observed over the standard model expectations. Upper limits at 95% confidence level are set on the branching fractions: 0.6×10^{-6} and 1.3×10^{-6} for the $Z \to J/\psi\gamma$ and $Z \to \psi(2S)\gamma$ decays, respectively, and 2.6×10^{-4} and 9.9×10^{-4} for the $H \to J/\psi\gamma$ and $H \to \psi(2S)\gamma$ decays, respectively. The limit for $H \to J/\psi\gamma$ translates to an interval constraint on the κ_c/κ_γ ratio of the Higgs boson coupling modifiers of $(-157, +199)$. If the standard model value of $\kappa_\gamma = 1$ is assumed, the observed interval becomes $(-166, +208)$.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[4], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, K. Mota Amarilo, A. Samalan, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Alves Gallo Pereira, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira[5]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[8], C. Mora Herrera, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, S. Thakur

Beihang University, Beijing, China
T. Cheng, T. Javaid, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, K. Yi[9,10]

Institute of High Energy Physics, Beijing, China
G.M. Chen[11], H.S. Chen[11], M. Chen[11], F. Iemmi, C.H. Jiang, A. Kapoor[12], H. Liao, Z.-A. Liu[13], R. Sharma[14], J.N. Song[13], J. Tao, C. Wang[11], J. Wang, Z. Wang[11], H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, L. Zhang, Y. Zhao, C. Zhou

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
K. Jaffel, N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[15], B. Li, J. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[16]

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
F. Ramirez, C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, S. Mishra, A. Starodumov[17], T. Susa

University of Cyprus, Nicosia, Cyprus

A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[18,19], S. Elgammal[20], A. Ellithi Kamel[21]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M. Abdullah Al-Mashad, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[22], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[23], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
A. Di Florio

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[24], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia[25], I. Lomidze, Z. Tsamalaidze[17]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[26], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, S. Bhattacharya, F. Blekman[27], K. Borras[28], A. Campbell, A. Cardini, C. Cheng, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[27], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[29], W. Lohmann[30], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, Y. Otarid, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, A. Saggio, M. Scham[31,28], S. Schnake[28], P. Schütze, C. Schwanenberger[27], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[28], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Fal-

termann, M. Giffels, A. Gottmann, F. Hartmann[32], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, B. Maier, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[32], A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
P. Kontaxakis, G. Melachroinos, Z. Painesis, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[33,34], K. Márton, A.J. Rádl[35], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[36], M.M.A. Gadallah[37], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[36], F. Nemes[36], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[38], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, M.K. Saini, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[39], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[40], D. Kumar[40], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Tata Institute of Fundamental Research-A, Mumbai, India
S. Dugad, G.B. Mohanty, B. Parida, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[41], C. Kar, D. Maity[42], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[42], K. Naskar[42], A. Nayak[42], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[42], D. Vats[42]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[43], A. Alpana, S. Dube, B. Gomber[43], P. Hazarika, B. Kansal, A. Laha, B. Sahu[43], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[44], A. Jafari[45], M. Zeinali[46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[47], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie[48], M. Mohammadi Najafabadi, S. Tizchang[49]

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,18], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], A. Castro[†a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,50], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,51], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,51], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
P. Assiouras[a], G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[52], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a,b], F. Brivio[a], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,53], P. Paolucci[a,32], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,54], M. Biasotto[a,55], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A. Bragagnolo[a,b], A.C.M. Bulla[a], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], R. Gröber[a,b], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
C. Aimè[a], A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,56], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
C. Baldenegro Barrera[a,b], P. Barria[a], C. Basile[a,b], M. Campana[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b],

R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, C. Huh, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea
S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, S. Yang

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, S. Ko, H. Kwon, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Gharbia

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[57], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[58], R. Lopez-Fernandez, C.A. Mondragon Herrera, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT),

Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, P. Leguina, E. Palencia Cortezon, J. Prado Pico, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[59], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[60], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[30], S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, M. Rovere, H. Sakulin, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[61], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[62], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[63], L. Caminada[63], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[63], L. Noehte[63], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T.K. Aarrestad, K. Androsov[62], M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[62], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[62], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, R. Seidita, J. Steggemann[62], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[64], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, U. Molinatti, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[65], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[40], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K.F. Chen, P.s. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[66], E. Eskut, Y. Guler[67], E. Gurpinar Guler[67], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[68], A. Polatoz, B. Tali[69], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Sokmen, M. Yalvac[70]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[71], O. Kaya[72], S. Tekten[73]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[66,74], G.G. Dincer[66], Y. Komurcu, S. Sen[75]

Istanbul University, Istanbul, Turkey
O. Aydilek[76], B. Hacisahinoglu, I. Hos[77], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci[69], B. Isildak[78], D. Sunar Cerci, T. Yetkin

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[79], K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[80], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom
I. Andreou, R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[81], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, M. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, S. Mallios, M. Mieskolainen, J. Nash[82], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[32], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, E. Collins, J. Dittmann, K. Hatakeyama, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[83], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
A. Akpinar, C. Cosby, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, J.M. Hogan[84], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, M. Narain[†], N. Pervan, T. Russell, S. Sagir[85], F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan

University of California, Davis, Davis, California, USA
S. Abbott, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, Y. Yao, S. Yoo, F. Zhang

University of California, Los Angeles, California, USA

M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, M. Quinnan, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, S. Wang, D. Zhang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, G. Karathanasis, N. Manganelli, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, M. Oshiro, J.R. Patterson, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[86], F. Ravera, A. Reinsvold Hall[87], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, E. Koenig,

M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Habibullah, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[88], M. Hohlmann, M. Rahmani, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D. S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[89], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[90], O. Neogi, H. Ogul[91], Y. Onel, A. Penzo, C. Snyder, E. Tiras[92]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, M. Pitt, S. Popescu[93], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, L. Wang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
J. Bendavid, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Bonilla, J. Dervan, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, D. Wood

Northwestern University, Evanston, Illinois, USA
J. Bueghly, S. Dittmer, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[17], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, A. Shevelev, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A. K. Virdi, F. Wang, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, USA
D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[94], E. Popova[94], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, O. Bouhali[95], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[96], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, N. Gogate, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

Wayne State University, Detroit, Michigan, USA
S. Bhattacharya, P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[97], P. Levchenko[98], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†]

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin[†], I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[97], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[99], A. Zarubin, I. Zhizhin, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[100,101], V. Popov, A. Zhokin, M. Chadeeva[97], R. Chistov[97], S. Polikarpov[97], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[86], L. Dudko, V. Klyukhin, O. Kodolova[101], O. Lukina, S. Obraztsov, M. Perfilov, V. Savrin, A. Snigirev, G. Vorotnikov, V. Blinov[97], T. Dimova[97], A. Kozyrev[97], O. Radchenko[97], Y. Skovpen[97], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin[102], V. Chekhovsky, V. Makarenko

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[4]Also at Ghent University, Ghent, Belgium
[5]Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[6]Also at Universidade Estadual de Campinas, Campinas, Brazil
[7]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[8]Also at UFMS, Nova Andradina, Brazil
[9]Also at Nanjing Normal University, Nanjing, China
[10]Now at The University of Iowa, Iowa City, Iowa, USA
[11]Also at University of Chinese Academy of Sciences, Beijing, China
[12]Also at China Center of Advanced Science and Technology, Beijing, China
[13]Also at University of Chinese Academy of Sciences, Beijing, China
[14]Also at China Spallation Neutron Source, Guangdong, China
[15]Now at Henan Normal University, Xinxiang, China
[16]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[17]Also at an institute formerly covered by a cooperation agreement with CERN
[18]Also at Helwan University, Cairo, Egypt
[19]Now at Zewail City of Science and Technology, Zewail, Egypt
[20]Now at British University in Egypt, Cairo, Egypt
[21]Now at Cairo University, Cairo, Egypt
[22]Also at Purdue University, West Lafayette, Indiana, USA
[23]Also at Université de Haute Alsace, Mulhouse, France
[24]Also at Istinye University, Istanbul, Turkey
[25]Also at Ilia State University, Tbilisi, Georgia
[26]Also at The University of the State of Amazonas, Manaus, Brazil
[27]Also at University of Hamburg, Hamburg, Germany
[28]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[29]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[30]Also at Brandenburg University of Technology, Cottbus, Germany
[31]Also at Forschungszentrum Jülich, Juelich, Germany
[32]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[33]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[34]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[35]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[36]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[37]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[38]Also at Punjab Agricultural University, Ludhiana, India
[39]Also at University of Visva-Bharati, Santiniketan, India
[40]Also at Indian Institute of Science (IISc), Bangalore, India
[41]Also at IIT Bhubaneswar, Bhubaneswar, India
[42]Also at Institute of Physics, Bhubaneswar, India
[43]Also at University of Hyderabad, Hyderabad, India
[44]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[45]Also at Isfahan University of Technology, Isfahan, Iran
[46]Also at Sharif University of Technology, Tehran, Iran

[47]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[48]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[49]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[50]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[51]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[52]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[53]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[54]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[55]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
[56]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[57]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[58]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[59]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[60]Also at Saegis Campus, Nugegoda, Sri Lanka
[61]Also at National and Kapodistrian University of Athens, Athens, Greece
[62]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[63]Also at Universität Zürich, Zurich, Switzerland
[64]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[65]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[66]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[67]Also at Konya Technical University, Konya, Turkey
[68]Also at Izmir Bakircay University, Izmir, Turkey
[69]Also at Adiyaman University, Adiyaman, Turkey
[70]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[71]Also at Marmara University, Istanbul, Turkey
[72]Also at Milli Savunma University, Istanbul, Turkey
[73]Also at Kafkas University, Kars, Turkey
[74]Now at Istanbul Okan University, Istanbul, Turkey
[75]Also at Hacettepe University, Ankara, Turkey
[76]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[77]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[78]Also at Yildiz Technical University, Istanbul, Turkey
[79]Also at Vrije Universiteit Brussel, Brussel, Belgium
[80]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[81]Also at IPPP Durham University, Durham, United Kingdom
[82]Also at Monash University, Faculty of Science, Clayton, Australia
[83]Also at Università di Torino, Torino, Italy
[84]Also at Bethel University, St. Paul, Minnesota, USA
[85]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[86]Also at California Institute of Technology, Pasadena, California, USA
[87]Also at United States Naval Academy, Annapolis, Maryland, USA
[88]Also at Ain Shams University, Cairo, Egypt
[89]Also at Bingol University, Bingol, Turkey

[90]Also at Georgian Technical University, Tbilisi, Georgia
[91]Also at Sinop University, Sinop, Turkey
[92]Also at Erciyes University, Kayseri, Turkey
[93]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[94]Now at another institute formerly covered by a cooperation agreement with CERN
[95]Also at Texas A&M University at Qatar, Doha, Qatar
[96]Also at Kyungpook National University, Daegu, Korea
[97]Also at another institute formerly covered by a cooperation agreement with CERN
[98]Also at Northeastern University, Boston, Massachusetts, USA
[99]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
[100]Also at Imperial College, London, United Kingdom
[101]Now at Yerevan Physics Institute, Yerevan, Armenia
[102]Also at Universiteit Antwerpen, Antwerpen, Belgium