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Citation: Khachatryan, V., et al. "Search for a Pseudoscalar Boson Decaying into a Z Boson and the 125 GeV Higgs Boson in $#[superscript +]#[superscript -]b[\bar{over b}]$ Final States." Physics Letters B 748 (September 2015): 221–243. © 2015 CERN for the benefit of the CMS Collaboration

As Published: <http://dx.doi.org/10.1016/j.physletb.2015.07.010>

Publisher: Elsevier

Persistent URL: <http://hdl.handle.net/1721.1/98213>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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Search for a pseudoscalar boson decaying into a Z boson and the 125 GeV Higgs boson in $\ell^+\ell^-\bar{b}b$ final states



CMS Collaboration*

CERN, Switzerland

ARTICLE INFO

Article history:

Received 18 April 2015

Received in revised form 25 June 2015

Accepted 7 July 2015

Available online 9 July 2015

Editor: M. Doser

Keywords:

CMS

Higgs

2HDM

MSSM

BSM

ABSTRACT

Results are reported on a search for decays of a pseudoscalar A boson into a Z boson and a light scalar h boson, where the Z boson decays into a pair of oppositely-charged electrons or muons, and the h boson decays into $b\bar{b}$. The search is based on data from proton–proton collisions at a center-of-mass energy $\sqrt{s} = 8$ TeV collected with the CMS detector, corresponding to an integrated luminosity of 19.7 fb^{-1} . The h boson is assumed to be the standard model-like Higgs boson with a mass of 125 GeV. With no evidence for signal, upper limits are obtained on the product of the production cross section and the branching fraction of the A boson in the Zh channel. Results are also interpreted in the context of two Higgs doublet models.

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1. Introduction

The discovery of a scalar boson at the CERN LHC [1–3] with properties in agreement with those predicted by the standard model (SM) raises the question of whether the Higgs sector consists of only one physical state, as expected in the SM, or whether additional bosons are also involved.

An extension of the SM Higgs sector is provided in two Higgs doublet models (2HDM) [4], which introduce a second scalar doublet in addition to the one from the SM. Different formulations of 2HDM predict different couplings of the two doublets to quarks and to leptons. In Type-I 2HDM, all fermions couple to only one Higgs doublet, while in Type-II, up- and down-type quarks couple to different doublets. One example of a Type-II 2HDM is the minimal supersymmetric standard model [5], despite that supersymmetry is not explicitly required in 2HDM. The second Higgs doublet entails the presence of five physical states: two neutral, CP-even states, representing a light h and a heavy H boson; a neutral, CP-odd A boson; and two charged scalar H^\pm bosons. The lightest scalar h is assumed to be the boson observed at the LHC at a mass of 125 GeV [6–9]. If the masses of the heavier bosons are at or below the TeV scale, they can be accessible at the LHC. Searches for this extended sector can be performed either by measuring the values of the couplings of the discovered h boson to other SM particles [10–12], or via direct searches in final states disfavored by

the SM [13]. A way to probe this kind of new physics is therefore to search for bosons that decay into final states that contain an SM-like Higgs boson.

This paper describes a search for a heavy pseudoscalar A boson that decays into a Z and an h boson, both on-shell, with the Z boson decaying into a pair of $\ell^+\ell^-$ leptons (ℓ being e or μ), and the h boson into $b\bar{b}$. In most 2HDM formulations [4], the A boson is produced predominantly through gluon–gluon fusion and decays to on-shell Z and h bosons, provided that the mass of the A boson satisfies $m_A \gtrsim m_h + m_Z \approx 216$ GeV. This channel is expected to be viable for m_A smaller than twice the top quark mass (m_t), where the decay $A \rightarrow Zh$ is generally dominant, but, depending on model parameters, it can also be sensitive at larger values of m_A . The $h \rightarrow b\bar{b}$ decay has a large branching fraction for most of the parameter space in 2HDM [11]. A similar analysis has been recently published by ATLAS [14].

The analysis strategy is to reconstruct the Z, h, and A boson candidates from the visible decay products in the event. The signal would manifest itself as a peak in the four-body invariant mass ($m_{\ell\ell b\bar{b}}$) spectrum over an expected SM continuum. Irreducible backgrounds correspond to Z boson production with two accompanying b quark jets, and $t\bar{t}$ events in the dileptonic final state. These backgrounds are evaluated and normalized directly using appropriate control regions in data. The h boson produced in association with a Z boson provides a contribution to the background, but it differs from signal because the $m_{\ell\ell b\bar{b}}$ mass does not contain a resonant peak. Signal sensitivity is improved by exploiting the known value of the h boson mass, using it to rescale the jet

* E-mail address: cms-publication-committee-chair@cern.ch.

momenta to match the value expected for the dijet invariant mass. In addition, optimal signal efficiency and background rejection is achieved using a multivariate discriminator. Results are extracted through a two-dimensional (2D) fit to $m_{\ell\ell b\bar{b}}$ and the discriminator output; upper limits are presented on the product of the total cross section and the $A \rightarrow Zh$, $Z \rightarrow \ell\ell$, and $h \rightarrow b\bar{b}$ branching fractions for a pseudoscalar boson, and interpreted within the 2HDM.

2. CMS detector

A detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in Ref. [15]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. The field volume contains a silicon pixel and strip tracker, a homogeneous electromagnetic calorimeter (ECAL), and a sampling hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range of $|\eta| < 2.5$. For non-isolated particles with transverse momenta of $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T , and between 25–90 and 45–150 μm , respectively, in transverse and longitudinal impact parameters relative to the production vertex [16]. The ECAL consists of lead tungstate crystals that provide a coverage up to $|\eta| < 3.0$. The mass resolution for $Z \rightarrow e^+e^-$ decays when both electrons are in the ECAL barrel is 1.6%, and is 2.6% when both electrons are in the endcaps. The HCAL has alternating layers of brass as absorber and plastic scintillators, and covers the range of $|\eta| < 3.0$, which is extended to $|\eta| \lesssim 5.2$ through forward calorimetry. Muons are measured in the range of $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode-strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker provides a p_T resolution of 1.3–2.0% for muons with $20 < p_T < 100$ GeV in the barrel and better than 6% in the endcaps.

3. Data and simulation

Data used for this analysis were collected using double-muon and double-electron triggers, with p_T thresholds set to 17 and 8 GeV for the highest and next highest p_T lepton, respectively, and an isolation requirement used in the electron trigger to maintain an acceptable rate. The analyzed events correspond to an integrated luminosity of $19.7 \pm 0.5 \text{ fb}^{-1}$ of pp collisions at $\sqrt{s} = 8 \text{ TeV}$ [17].

Signal samples and SM background processes $Z + \text{jets}$, $W + \text{jets}$, and $t\bar{t} + \text{jets}$ or a vector boson ($t\bar{t}V$) are simulated using the MADGRAPH 5.1 [18] Monte Carlo (MC) generator; multijets and dibosons (VV' , with V, V' being W or Z) are generated using LO PYTHIA 6.4 [19] and the CTEQ6L [20] parton distribution functions (PDF). Single top quark production, and SM Higgs boson production in association with an electroweak vector boson (Vh) are generated using the next-to-leading-order (NLO) POWHEG 1.0 [21–23] MC generator and the MSTW2008NLO PDF [24]. Parton showering and hadronization are performed with PYTHIA using the Z2* tune [25]. The generated MC events, including additional pp interactions (pileup) occurring in the bunch crossing containing the high- p_T scatter, are processed through a full detector simulation based on GEANT4 [26] and reconstructed with the same algorithms as used for data.

The pseudoscalar A boson is assumed to be produced via the gluon–gluon fusion process and to have a narrow width. The va-

lidity of the narrow-width approximation is discussed in Section 7. The branching fraction $\mathcal{B}(A \rightarrow Zh)$ is set to 100%, and similarly only the Z boson decays into electrons or muons, and the h boson decays into a pair of $b\bar{b}$ quarks, are considered. Other decay modes have negligible efficiency for passing the selections. The mass of the light Higgs boson is set to $m_h = 125 \text{ GeV}$, while the search for the A boson is performed in the mass range from 225 to 600 GeV, above which the efficiency to reconstruct two separate jets from h decay becomes too small because of its increased momentum.

4. Event reconstruction

A global reconstruction of the event is achieved using a particle-flow (PF) technique, which reconstructs and identifies individual particles emerging from each collision using information from all CMS subdetectors [27,28].

Electron candidates are reconstructed for $|\eta| < 2.5$ by matching energy depositions in the ECAL with reconstructed tracks [29]. The identification relies on a multivariate technique that combines observables sensitive to the amount of bremsstrahlung along the electron trajectory, the compatibility of the measured position, direction and momentum of the reconstructed track in the inner tracker, and the energy deposition reconstructed in the ECAL cluster. Additional requirements are imposed to remove electrons produced by photon conversions in the detector material.

Muons are reconstructed within $|\eta| < 2.4$, combining information from both the silicon tracker and the outer muon spectrometer [30], requiring small energy depositions in the calorimeters [31]. Muon candidates have to fulfill restrictive selection criteria based on the quality and the impact parameter of the track, as well as on the number of hits observed in the tracker and muon systems.

An isolation variable is defined for each lepton through the scalar sum over the p_T of all PF candidates, excluding the lepton, within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the lepton direction, where ϕ is the azimuthal angle in radians, subtracting the pileup contribution [32], and then dividing by the lepton p_T . The lepton is rejected if the isolation exceeds 0.15 for electrons and 0.12 for muons.

Jets are formed from all particles, charged and neutral, reconstructed through the PF algorithm, and clustered with the anti- k_T algorithm [33,34] with a distance parameter of 0.5. Jet energy corrections are determined from dijet and $Z/\gamma + \text{jet}$ events, and applied to both data and simulation [35]. The imbalance in transverse momentum is calculated as the negative of the vectorial sum of transverse momenta of all the PF candidates, and its magnitude is denoted as E_T^{miss} [36].

The combined secondary vertex (CSV) b tagging algorithm [37] is used to identify jets that originate from b quarks. This algorithm combines information from track impact parameters relative to the primary and secondary (displaced) vertices into a likelihood discriminant. Two standard working points are set on the discriminant, corresponding to restrictive (tight) and less-restrictive (loose) thresholds that provide on average 50% and 80% b tagging efficiencies, with respective misidentification probabilities of about 0.1% and 10% for light-flavor jets, and about 5% and 25% for c jets. The CSV distribution is corrected in simulation to take into account a difference at the percent level in algorithm performance for data and simulation.

5. Event selection

Events are required to have at least two electrons or two muons within the geometrical acceptance regions, and to satisfy the reconstruction, identification, and isolation requirements. The

Table 1

Scale factors for the four main backgrounds obtained from a fit to the control regions. Reported uncertainties are statistical in nature.

Background	Scale factor
Z + jets	1.069 ± 0.002
Z + b	0.945 ± 0.012
Z + $b\bar{b}$	1.008 ± 0.020
$t\bar{t}$	0.984 ± 0.010

p_T threshold is set to 20 GeV for the lepton with highest p_T , and to 10 GeV for the lepton with next-highest p_T . The Z boson candidate is formed from the two highest- p_T , opposite-charge, same-flavor leptons, and must have an invariant mass larger than 50 GeV. In addition, at least two jets are required with $p_T > 20$ GeV, within $|\eta| < 2.4$, and with angular separation relative to each lepton of $\Delta R > 0.5$. The h boson candidate is formed from the two jets that have the highest values of the b tagging discriminant. Additional jets in the event are ignored.

Signal events are expected to have at least one jet b-tagged with the tight and one with the loose CSV working points; after b tagging application, the contribution from pileup jets becomes negligible. The invariant masses of the two leptons and of the two jets are required to be compatible with those of the Z boson ($75 < m_{\ell\ell} < 105$ GeV) and h boson ($90 < m_{bb} < 140$ GeV), and the value of the E_T^{miss} in the event has to be compatible with zero. After these selections, the signal efficiencies range from 10.0% for $m_A = 250$ GeV to 20.7% for $m_A = 600$ GeV.

Dedicated control regions are defined to check both the normalizations and distributions of the most important backgrounds by inverting the selections used to enhance signal. Drell–Yan backgrounds (from $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ production) are considered separately as a function of the number of b jets, distinguishing Z + jets (no b jets), Z + b (1 b jet) and Z + $b\bar{b}$ (2 b jets). The corresponding control regions are selected by requiring $80 < m_{\ell\ell} < 100$ GeV, $E_T^{\text{miss}} < 40$ GeV, vetoing of dijet masses close to the Higgs boson mass of $90 < m_{jj} < 140$ GeV, and applying different b-tagging selections. In the Z + jets control region, no cutoffs are applied on b tagging discriminators. The Z + b control region contains events with one b jet fulfilling the tight CSV working point, and no other jets passing the loose threshold. Events that enter the Z + $b\bar{b}$ control region should have at least two b-tagged jets, with one passing the tight and the other the loose working point. The $t\bar{t}$ control region is defined by inverting the $m_{\ell\ell}$ and E_T^{miss} selections, dropping the requirement of the dijet mass, and requiring at least one tight and one loose b-tagged jet.

The scale factors that are used to correct the normalization of Drell–Yan and $t\bar{t}$ backgrounds, reported in Table 1, are obtained from a simultaneous likelihood fit to data and simulation in the four control regions and are applied in the following steps of the analysis. Multijet contamination in control and signal regions is evaluated with data by inverting lepton isolation criteria, and its contribution is found to be negligible. The yield of the Vh, $t\bar{t}V$, and single top production through the s channel are calculated at NLO [38,39], while the other single top channels and dibosons are normalized to the measured cross sections [40–42]. A mismodeling in simulation, observed in the control regions relative to data, is corrected by reweighting with a linear function the event centrality distribution (defined as the ratio of the sums in scalar p_T and the energy of the two leptons and two jets in the rest frame of the four objects) in all Monte Carlo events, improving the overall agreement between simulation and data.

An important feature of the signal is that the two b jets originate from the decay of the h boson, whose mass is known with better precision than that provided by the $b\bar{b}$ invariant mass res-

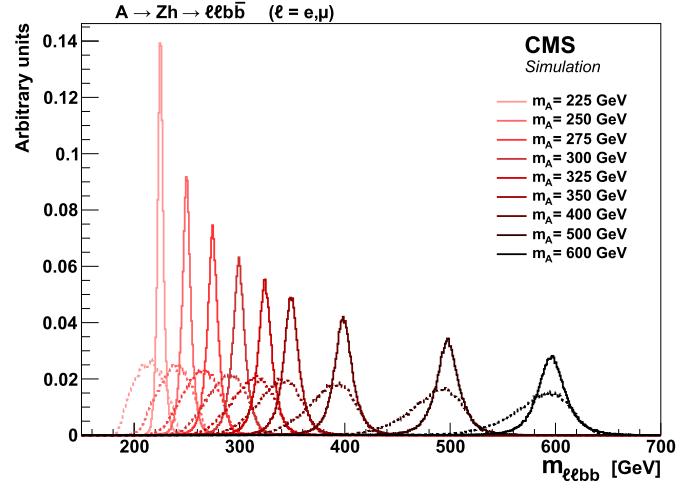


Fig. 1. Simulated distributions for $m_{\ell\ell b\bar{b}}$ before (dotted lines) and after the kinematic fits (solid lines). Histograms are normalized to unit area.

Table 2

Summary of systematic uncertainties. Normalization: sources of systematic uncertainty and their effect in percent on the normalization of signal and background distributions. Shape: sources of systematic uncertainty and the range of their effect in percent on relative changes made in the form of the background and signal distributions.

Sources	Backgrounds		Signal
	Drell–Yan, $t\bar{t}$	Others	
Normalization			
Control region fitting	<2.4%	–	–
Extrapolation	2–13%	–	–
Lepton and trigger efficiency	–	2.5%	2.5%
Jet energy scale	–	5.7%	3.8–0.2%
Jet energy resolution	–	3.2%	0.8–0.5%
b tagging	–	4.9%	3.6–3.2%
Unclassified energy	–	1.9%	1.4–1.0%
Pileup	–	0.9%	1.2%
PDF	–	4.3%	4.0–7.9%
Cross section	–	9.2–15%	–
Integrated luminosity	–	2.6%	2.6%
Shape			
Jet energy scale	<4%	<8%	<8%
Jet energy resolution	<2%	<4%	<4%
b tagging	<4%	<8%	<8%
Factorization and renormalization scales	<6%	6–10%	6–10%
Monte Carlo reweighting	<15%	–	–
Monte Carlo statistics	1–4%	–	–

olution [43]. The measured jet p_T , η , and φ values are therefore varied according to their resolution, in a kinematic fit based on Lagrange multipliers, to constrain the dijet invariant mass to $m_h = 125$ GeV. The fit χ^2 is used in subsequent steps of the analysis as a discriminant in place of m_{bb} . The kinematic fit improves the relative four-body invariant mass resolution from 6.3% to 1.2% and 4.0% to 1.9%, respectively, for the smallest and largest values of m_A , centering the peaks around their nominal values, as shown in Fig. 1. The effect of the kinematic fit is larger at low m_A , where the constraint on the Higgs invariant mass has the largest contribution. Although both the background and signal $m_{\ell\ell b\bar{b}}$ distributions are modified by the kinematic fit, the signal significance in a mass window close to the investigated A boson mass increases by a factor of two at the lowest mass and by 34% at the highest mass. The resulting jet three-momenta are used to redefine all the kinematic variables in the event.

Discrimination of signal from backgrounds is achieved through a multivariate discriminant. Simulated mass points are divided

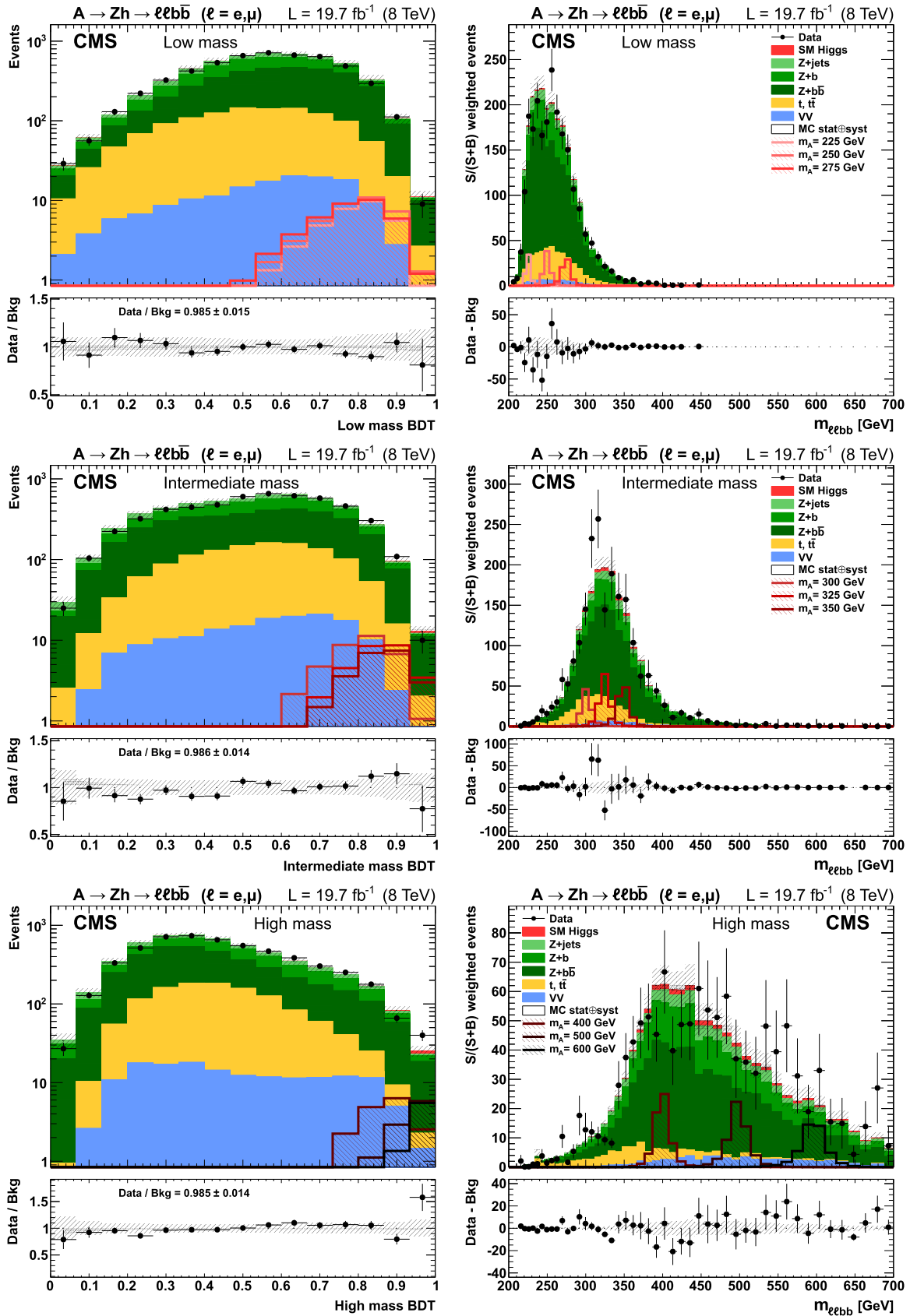


Fig. 2. BDT outputs and invariant mass distributions in the low, intermediate, and high mass regions. The $m_{\ell\ell b\bar{b}}$ plots are for BDT > 0.6 , weighted by $S/(S+B)$ in each BDT bin. Histograms for signal are normalized to the expected exclusion limit at 95% confidence level. Statistical and systematic uncertainties in simulated samples are shown as well. Either the ratio (left) or the difference (right) between data and SM background is given at the bottom of each panel.

into three mass regions: low ($m_A = 225, 250,$ and 275 GeV), intermediate ($m_A = 300, 325,$ and 350 GeV), and high mass ($m_A = 400, 500,$ and 600 GeV). Three boosted decision trees (BDT) [44] are trained separately, one for each region. The inputs of each BDT consist of 16 discriminating variables, selected from a list of more than 40 variables: the p_T of the Z and h boson candidates, the χ^2 of the kinematic fit, the significance of E_T^{miss} [36], the dilepton invariant mass, the ΔR separation and the “twist” angle (defined as $\tan^{-1} \Delta\varphi/\Delta\eta$) between the two b jets [45], their CSV discriminator values, the flight directions of the Z boson and of the beam in the rest frame of the A boson ($\cos\theta^*$), the decay angle of the Z boson relative to its flight direction in the rest frame of the Z boson ($\cos\theta_1$), which is sensitive to the transverse polarization of the Z boson along its flight direction, the angle of the pull vector [46, 47] of the highest- p_T jet, which exploits the color connection between the two b quarks originating from the h boson, the scalar sum of E_T^{miss} and the p_T of jets and leptons in the event (S_T), the number of jets with $p_T > 20$ GeV, the event centrality, and aplanarity [45]. The distribution in BDT outputs for data, for simulated signal (S), and for the expected SM background (B) events are shown in Fig. 2, weighting each entry in the $m_{\ell\ell b\bar{b}}$ distribution by the expected $S/(S+B)$ ratio of the BDT bin in the signal-sensitive region with $\text{BDT} > 0.6$.

6. Systematic uncertainties

The sensitivity of the analysis is currently limited by the available data, and not by systematic uncertainties.

The uncertainties in the normalizations of the four main backgrounds (Z + jets, Z + b, Z + $b\bar{b}$, and $t\bar{t}$) originate both from the fits in the control regions and from the extrapolation to the signal region. The former are reported in Table 1, and the latter is evaluated through a simultaneous likelihood fit to data and to simulated yields in several statistically independent regions, obtained by altering the selections used to define the four control regions. A 13% normalization uncertainty due to this extrapolation is assigned to Z + jets, 12% to Z + b, 2.1% to Z + $b\bar{b}$, and 6.2% to $t\bar{t}$ events. Normalization uncertainties for other SM backgrounds correspond to the ones on their measured or theoretical cross sections.

The uncertainties in lepton reconstruction, identification, isolation, and trigger efficiencies are evaluated through specific studies of events with masses in the region of the Z peak. Uncertainties in background or signal normalization and distribution due to uncertainties in jet energy scale and resolution [35] and b tagging scale factors [37] are estimated by changing the corresponding values by ± 1 standard deviation (σ). Additional systematic uncertainties affecting the normalization of backgrounds and signal from the choice of PDF [48,49], contributions from pileup, E_T^{miss} fluctuations because of the presence of unclustered energy in the event, and integrated luminosity [17] are also considered in the analysis and are reported in Table 2 (Normalization).

Results are extracted from an analysis based on a binned likelihood fit to the two-dimensional (2D) distribution of $m_{\ell\ell b\bar{b}}$ versus BDT. Dependence on jet energy scale and resolution, b tagging, as well as factorization and renormalization scales are propagated to the 2D-templates, taking into account the correlations between the two variables. The impact of reweighting the Monte Carlo distributions is considered as an additional source of background in modeling the uncertainty. Finally, the uncertainty from the limited number of simulated events is treated as in Ref. [50]. The sources of systematic uncertainty affecting the forms of the distributions are summarized in the first column of Table 2 (Shape). The second and third columns indicate the respective ranges in the relative impact in percent, obtained by the changes implemented in the background and signal contributions.

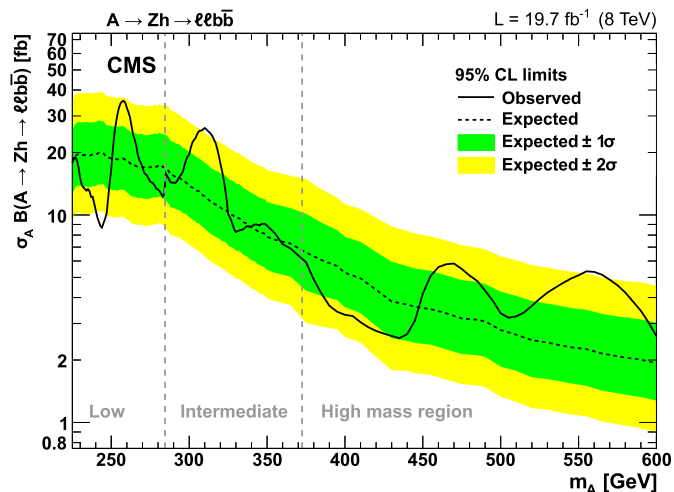


Fig. 3. Observed and expected 95% CL upper limit on $\sigma_A \mathcal{B}(A \rightarrow Zh \rightarrow \ell\ell b\bar{b})$ as a function of m_A in the narrow-width approximation, including all statistical and systematic uncertainties. The green and yellow bands are the ± 1 and $\pm 2\sigma$ uncertainty bands on the expected limit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The systematic uncertainty with the largest impact on the expected limit is from the reweighting of the background (accounting for a $\lesssim 6\%$ difference on the expected limit, depending on m_A), which is followed by the limitations in the number of simulated events ($\lesssim 4\%$), and the factorization and renormalization scales ($\lesssim 2\%$). The effect of the other sources is small ($\lesssim 1\%$).

7. Results and their interpretation

Results are obtained from the combined signal and background fit to the binned two-dimensional distribution of the four-body invariant mass $m_{\ell\ell b\bar{b}}$ and the BDT output in the signal-sensitive ($\text{BDT} > 0.6$) region. With no evidence of significant deviation from background expectations, the asymptotic modified frequentist method is used to determine the limit at the 95% confidence level (CL) on the contribution from signal, treating systematic uncertainties as nuisance parameters that are integrated over in the fit [51–54].

The observed limit, as well as the expected limit and its relative ± 1 and $\pm 2\sigma$ bands of uncertainty, are reported as a function of the A boson mass in Fig. 3 for $\sigma_A \mathcal{B}(A \rightarrow Zh \rightarrow \ell\ell b\bar{b})$, i.e. the product of the cross section and the $A \rightarrow Zh$, $h \rightarrow b\bar{b}$, and $Z \rightarrow \ell\ell$ branching fractions, with $\ell = e$ or μ . The limits are obtained by considering the A boson produced via the gluon-gluon fusion process in the narrow-width approximation. Interpolated mass points are obtained as in Ref. [55], and numerical values are reported in Table 3. A signal upper limit at 95% CL is set on $\sigma_A \mathcal{B}(A \rightarrow Zh \rightarrow \ell\ell b\bar{b})$, excluding from 10 to 30 fb for m_A near the kinematic threshold, ≈ 8 fb for $m_A \approx 2m_t$, and up to ≈ 3 fb at the high end (600 GeV) of the considered mass range. Comparable limits have been recently obtained for the same channel by the ATLAS Collaboration [14]. The most significant excess at $m_{\ell\ell b\bar{b}} = 560$ GeV has a local significance of 2.6σ , which becomes a global 1.1σ significance taking into account the *look-elsewhere* effect [56].

For $m_A > 2m_t$, the width of the A boson depends strongly on the model parameters. Different limits are provided by taking into account the natural width of the A boson (Γ_A) in the reconstructed $m_{\ell\ell b\bar{b}}$, leaving the BDT unchanged. Fig. 4 shows the exclusion limit above $2m_t$ for an average width of 30 GeV, and the dependence of the observed limit on Γ_A for $m_A = 500$ GeV. The local and global

Table 3
Observed and expected 95% CL upper limits on $\sigma_A \mathcal{B}(A \rightarrow Z h \rightarrow \ell \ell b \bar{b})$ as a function of m_A in the narrow-width approximation, including statistical and systematic uncertainties.

m_A [GeV]	225	250	275	300	325	350	400	500	600
Observed [fb]	17.9	16.8	14.8	19.5	10.1	8.84	3.29	3.35	2.61
Expected [fb]	17.9	18.1	16.4	13.6	10.0	7.84	5.27	2.79	1.93

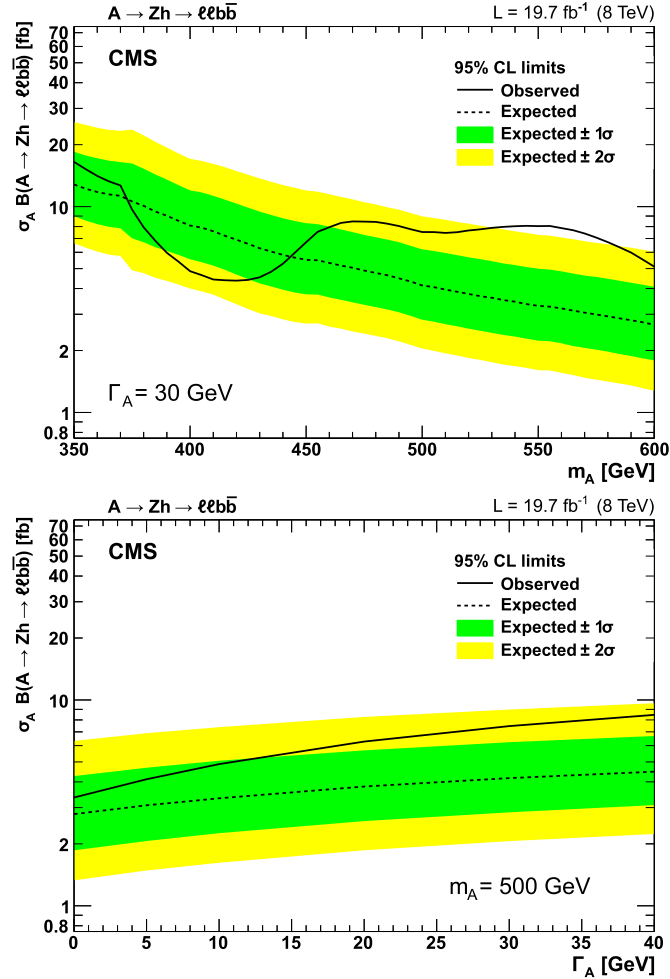


Fig. 4. Observed and expected 95% CL upper limit on $\sigma_A \mathcal{B}(A \rightarrow Z h \rightarrow \ell \ell b \bar{b})$ for $\Gamma_A = 30$ GeV as a function of m_A (top), and for $m_A = 500$ GeV as a function of the width of the A boson (bottom).

significance at $m_{\ell \ell b \bar{b}} = 560$ GeV become, respectively, 2.9σ and 1.5σ , assuming $\Gamma_A = 30$ GeV.

As an independent cross-check of the 2D fit, the signal is extracted by applying two complementary strategies, based on one-dimensional fits. The first one consists of fitting the $m_{\ell \ell b \bar{b}}$ distribution, after selecting events in a signal-enriched region by applying a $\text{BDT} > 0.8$ selection. The second relies on fits to the BDT distributions, after selecting events within the resolution of the signal $m_{\ell \ell b \bar{b}}$ peak. The two methods give upper limits compatible with those from the 2D fit, but 10 to 20% less stringent.

The results are interpreted in terms of Type-I and Type-II 2HDM formulations [4]. The $\mathcal{B}(A \rightarrow Z h)$ and $\mathcal{B}(h \rightarrow b \bar{b})$ branching fractions and the signal cross sections are computed at next-to-next-to-leading-order (NNLO) with SuSHI 1.2.0 [57] and 2HDMC 1.6.4 [58], respectively, using the MSTW2008LO , NLO , and NNLO sets of PDF. The $\mathcal{B}(Z \rightarrow \ell \ell)$ branching fraction, with $\ell = e$ or μ , is taken from the measured value [59]. Both gluon-gluon fusion and associated production with b quarks have been consid-

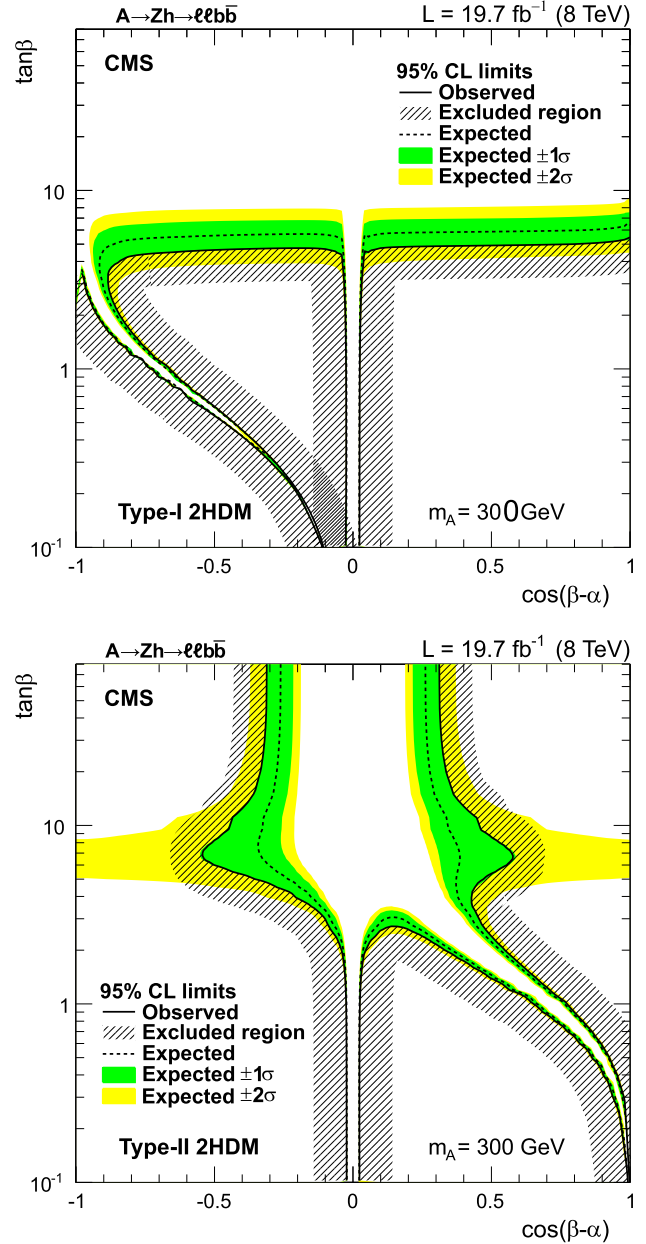


Fig. 5. Observed and expected (together with $\pm 1, 2\sigma$ uncertainty bands) exclusion limit for Type-I (top) and Type-II (bottom) models, as a function of $\tan\beta$ and $\cos(\beta - \alpha)$. Contours are derived from the projection on the 2HDM parameter space for the $m_A = 300$ GeV signal hypothesis; the observed limit is close to 1σ above the expected limit, as shown in Fig. 3.

ered. The latter is rescaled to the fusion process, taking account of the difference in acceptance for signal, as well as the efficiency for selecting dijet pairs in the presence of combinatorial contributions from additional b quarks in the event. The parameters used for the models are: $m_h = 125$ GeV, $m_H = m_{H^\pm} = m_A$, $m_{12}^2 = m_A^2 [\tan\beta] / [1 + \tan^2\beta]$, $\lambda_{6,7} = 0$ [60], while $m_A = 225\text{--}600$ GeV,

$0.1 \leq \tan \beta \leq 100$, and $-1 \leq \cos(\beta - \alpha) \leq 1$, using the convention $0 < \beta - \alpha < \pi$, where $\tan \beta$ and α are, respectively, the ratio of the vacuum expectation values, and the mixing angle of the two Higgs doublets [4].

The observed limit, together with the expected limit and its relative ± 1 and $\pm 2\sigma$ uncertainty bands, are shown in Fig. 5, interpreted in Type-I and Type-II 2HDM for $m_A = 300$ GeV. A sizeable fraction of the 2HDM phase space is excluded at a 95% CL with respect to the previous CMS searches [13].

8. Summary

A search is presented for new physics in the extended Higgs sector, in signatures expected from decays of a pseudoscalar boson A into a Z boson and an SM-like h boson, with the Z boson decaying into $\ell^+\ell^-$ (ℓ being either e or μ) and the h boson into $b\bar{b}$. Different techniques are employed to increase the sensitivity to signal, exploiting the presence of the three resonances A , Z , and h to discriminate against standard model backgrounds. Upper limits at a 95% CL are set on the product of a narrow pseudoscalar boson cross section and branching fraction $\sigma_A \mathcal{B}(A \rightarrow Zh \rightarrow \ell\ell b\bar{b})$, which exclude 30 to 3 fb at the low and high ends of the 250–600 GeV mass range. Results are also presented as a function of the width of the A boson. Interpretations are given in the context of Type-I and Type-II 2HDM formulations, thereby reducing the parameter space for extensions of the standard model.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, co-financed from European Union, Regional Development Fund; the

Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

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CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, V. Knünz, A. König, M. Krammer¹, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, J. Schieck¹, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè, A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

Université Libre de Bruxelles, Bruxelles, Belgium

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi³, O. Bondu, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Belyi, T. Caebergs, G.H. Hammad

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Hensel, C. Mora Herrera, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

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

S. Ahuja, C.A. Bernardes^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, C.S. Moon^{a,7}, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad, J.C. Ruiz Vargas

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, V. Genchev², R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁸, F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang⁹, W. Zou

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, D. Polic, I. Puljak

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, K. Kadija, J. Luetic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Bodlak, M. Finger, M. Finger Jr.¹⁰

Charles University, Prague, Czech Republic

A. Ali^{11,12}, R. Aly¹³, S. Aly¹³, Y. Assran¹⁴, A. Ellithi Kamel¹⁵, A. Lotfy¹⁶, M.A. Mahmoud¹⁶, R. Masod¹¹, A. Radi^{12,11}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, J. Pekkanen, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

J.-L. Agram¹⁷, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁷, J.-C. Fontaine¹⁷, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin², K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet⁸, G. Boudoul², E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

Z. Tsamalaidze¹⁰

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov⁵

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, L. Sonnenschein, D. Teysier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann², A. Nehr Korn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borrás, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo, J. Garay Garcia, A. Geiser, A. Gikhko, P. Gunnellini, J. Hauk, M. Hempel¹⁸, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁸, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁸, R. Mankel, I. Marfin¹⁸, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, D. Nowatschin, J. Ott, F. Pantaleo², T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann², U. Husemann, F. Kassel², I. Katkov⁵, A. Kornmayer², P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, A. Psallidas, I. Topsis-Giotis

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath¹⁹, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, J. Molnar, J. Palinkas, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók²², A. Makovec, P. Raics, Z.L. Trocsanyi

University of Debrecen, Debrecen, Hungary

P. Mal, K. Mandal, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, N. Nishu, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, Arun Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, Sh. Jain, R. Khurana, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²³, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²⁴, G. Kole, S. Kumar, B. Mahakud, M. Maity²³, G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar²³, K. Sudhakar, N. Sur, B. Sutar, N. Wickramage²⁵

Tata Institute of Fundamental Research, Mumbai, India

S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²⁶, A. Fahim²⁷, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁸, M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b,2}, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,2}, R. Venditti^{a,b}, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,2}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

^c CSFNSM, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Gonzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}, L. Viliani^{a,b}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^{a,2}, R. Gerosa^{a,b}, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M.T. Lucchini^{a,b,2}, S. Malvezzi^a, R.A. Manzoni^{a,b}, B. Marzocchi^{a,b,2}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}, C. Sciacca^{a,b}, F. Thyssen

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi ^{a,2}, N. Bacchetta ^a, D. Bisello ^{a,b}, A. Branca ^{a,b}, R. Carlin ^{a,b}, A. Carvalho Antunes De Oliveira ^{a,b}, P. Checchia ^a, M. Dall’Osso ^{a,b}, T. Dorigo ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, A. Gozzelino ^a, K. Kanishchev ^{a,c}, S. Lacaprara ^a, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, J. Pazzini ^{a,b}, N. Pozzobon ^{a,b}, P. Ronchese ^{a,b}, F. Simonetto ^{a,b}, E. Torassa ^a, M. Tosi ^{a,b}, S. Vanini ^{a,b}, M. Zanetti, P. Zotto ^{a,b}, A. Zucchetta ^{a,b}, G. Zumerle ^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri ^a, M. Gabusi ^{a,b}, A. Magnani ^a, S.P. Ratti ^{a,b}, V. Re ^a, C. Riccardi ^{a,b}, P. Salvini ^a, I. Vai ^a, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

L. Alunni Solestizi ^{a,b}, M. Biasini ^{a,b}, G.M. Bilei ^a, D. Ciangottini ^{a,b,2}, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, G. Mantovani ^{a,b}, M. Menichelli ^a, A. Saha ^a, A. Santocchia ^{a,b}, A. Spiezia ^{a,b,2}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsof ^{a,29}, P. Azzurri ^a, G. Bagliesi ^a, J. Bernardini ^a, T. Boccali ^a, G. Broccolo ^{a,c}, R. Castaldi ^a, M.A. Ciocci ^{a,29}, R. Dell’Orso ^a, S. Donato ^{a,c,2}, G. Fedi, L. Foà ^{a,c,f}, A. Giassi ^a, M.T. Grippo ^{a,29}, F. Ligabue ^{a,c}, T. Lomtadze ^a, L. Martini ^{a,b}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, A. Savoy-Navarro ^{a,30}, A.T. Serban ^a, P. Spagnolo ^a, P. Squillacioti ^{a,29}, R. Tenchini ^a, G. Tonelli ^{a,b}, A. Venturi ^a, P.G. Verdini ^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone ^{a,b}, F. Cavallari ^a, G. D’imperio ^{a,b}, D. Del Re ^{a,b}, M. Diemoz ^a, S. Gelli ^{a,b}, C. Jorda ^a, E. Longo ^{a,b}, F. Margaroli ^{a,b}, P. Meridiani ^a, F. Micheli ^{a,b}, G. Organtini ^{a,b}, R. Paramatti ^a, F. Preiato ^{a,b}, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}, L. Soffi ^{a,b}, P. Traczyk ^{a,b,2}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, R. Bellan ^{a,b}, C. Biino ^a, N. Cartiglia ^a, S. Casasso ^{a,b}, M. Costa ^{a,b}, R. Covarelli ^{a,b}, A. Degano ^{a,b}, N. Demaria ^a, L. Finco ^{a,b,2}, B. Kiani ^{a,b}, C. Mariotti ^a, S. Maselli ^a, E. Migliore ^{a,b}, V. Monaco ^{a,b}, M. Musich ^a, M.M. Obertino ^{a,c}, L. Pacher ^{a,b}, N. Pastrone ^a, M. Pelliccioni ^a, G.L. Pinna Angioni ^{a,b}, A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Sacchi ^{a,b}, A. Solano ^{a,b}, A. Staiano ^a, U. Tamponi ^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte ^a, V. Candelise ^{a,b,2}, M. Casarsa ^a, F. Cossutti ^a, G. Della Ricca ^{a,b}, B. Gobbo ^a, C. La Licata ^{a,b}, M. Marone ^{a,b}, A. Schizzi ^{a,b}, T. Umer ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S. Chang, A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

H. Kim, T.J. Kim, M.S. Ryu

Chonbuk National University, Jeonju, Republic of Korea

S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

M. Choi, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³¹, F. Mohamad Idris, W.A.T. Wan Abdullah

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

**E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz³²,
A. Hernandez-Almada, R. Lopez-Fernandez, G. Ramirez Sanchez, A. Sanchez-Hernandez**

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler, S. Reucroft

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

**H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki,
K. Romanowska-Rybinska, M. Szleper, P. Zalewski**

National Centre for Nuclear Research, Swierk, Poland

**G. Brona, K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski,
M. Walczak**

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev³³, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, T. Toriashvili³⁴, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁵, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vasilov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilo, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Andreev, M. Azarkin³⁶, I. Dremin³⁶, M. Kirakosyan, A. Leonidov³⁶, G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³⁷, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic³⁸, M. Ekmedzic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizán Garcia

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi³⁹, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi⁴⁰, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴¹, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres²⁰, N. Wardle, H.K. Wöhri, A. Zagozdinska⁴², W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov⁴³, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny, H.A. Weber

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. AMSler⁴⁴, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

Universität Zürich, Zurich, Switzerland

M. Cardaci, K.H. Chen, T.H. Doan, C. Ferro, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng, R. Wilken

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Adiguzel, S. Cerci⁴⁵, C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁴⁶, A. Kayis Topaksu, G. Onengut⁴⁷, K. Ozdemir⁴⁸, S. Ozturk⁴⁹, B. Tali⁴⁵, H. Topakli⁴⁹, M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak⁵⁰, G. Karapinar⁵¹, U.E. Surat, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E.A. Albayrak⁵², E. Gülmez, M. Kaya⁵³, O. Kaya⁵⁴, T. Yetkin⁵⁵

Bogazici University, Istanbul, Turkey

K. Cankocak, Y.O. Günaydin⁵⁶, F.I. Vardarli

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk, P. Sorokin

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁵⁷, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁵⁸, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁵⁷, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko⁴³, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, P. Sharp[†], A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

A. Borzou, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Boston University, Boston, USA

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith

Brown University, Providence, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, H. Wei, S. Wimpenny

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D’Agnolo, A. Holzner, R. Kelley, D. Klein, D. Kovalskyi, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵⁹, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O’Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, A. Whitbeck, F. Yang, H. Yin

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic⁶⁰, G. Mitselmakher, L. Muniz, D. Rank, L. Shchutska, M. Snowball, D. Sperka, S.J. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida State University, Tallahassee, USA

V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

University of Illinois at Chicago (UIC), Chicago, USA

B. Bilki⁶¹, W. Clarida, K. Dilsiz, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶², A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁵², A. Penzo, S. Sen, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, R. Stringer, Q. Wang, J.S. Wood

The University of Kansas, Lawrence, USA

I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, K. Pedro, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. McGinn, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

B. Dahmes, A. Finkel, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northeastern University, Boston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco, S. Won

Northwestern University, Evanston, USA

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³³, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Princeton University, Princeton, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti, D. Vishnevskiy

University of Rochester, Rochester, USA

L. Demortier

The Rockefeller University, New York, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

M. Foerster, K. Rose, S. Spanier, A. York

University of Tennessee, Knoxville, USA

O. Bouhali⁶³, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁶⁴, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duder, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Texas Tech University, Lubbock, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin, Madison, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

³ Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

⁴ Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

⁵ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

⁶ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁷ Also at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.

⁸ Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.

⁹ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

¹⁰ Also at Joint Institute for Nuclear Research, Dubna, Russia.

¹¹ Also at Ain Shams University, Cairo, Egypt.

¹² Now at British University in Egypt, Cairo, Egypt.

¹³ Now at Helwan University, Cairo, Egypt.

¹⁴ Also at Suez University, Suez, Egypt.

¹⁵ Also at Cairo University, Cairo, Egypt.

¹⁶ Now at Fayoum University, El-Fayoum, Egypt.

¹⁷ Also at Université de Haute Alsace, Mulhouse, France.

¹⁸ Also at Brandenburg University of Technology, Cottbus, Germany.

¹⁹ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

²⁰ Also at Eötvös Loránd University, Budapest, Hungary.

²¹ Also at University of Debrecen, Debrecen, Hungary.

²² Also at Wigner Research Centre for Physics, Budapest, Hungary.

²³ Also at University of Visva-Bharati, Santiniketan, India.

²⁴ Now at King Abdulaziz University, Jeddah, Saudi Arabia.

²⁵ Also at University of Ruhuna, Matara, Sri Lanka.

²⁶ Also at Isfahan University of Technology, Isfahan, Iran.

²⁷ Also at University of Tehran, Department of Engineering Science, Tehran, Iran.

²⁸ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

²⁹ Also at Università degli Studi di Siena, Siena, Italy.

- ³⁰ Also at Purdue University, West Lafayette, USA.
- ³¹ Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ³² Also at Consejo Nacional de Ciencia y Tecnologia, Mexico, Mexico.
- ³³ Also at Institute for Nuclear Research, Moscow, Russia.
- ³⁴ Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia.
- ³⁵ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ³⁶ Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ³⁷ Also at California Institute of Technology, Pasadena, USA.
- ³⁸ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ³⁹ Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- ⁴⁰ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ⁴¹ Also at University of Athens, Athens, Greece.
- ⁴² Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ⁴³ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ⁴⁴ Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ⁴⁵ Also at Adiyaman University, Adiyaman, Turkey.
- ⁴⁶ Also at Mersin University, Mersin, Turkey.
- ⁴⁷ Also at Cag University, Mersin, Turkey.
- ⁴⁸ Also at Piri Reis University, Istanbul, Turkey.
- ⁴⁹ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁵⁰ Also at Ozyegin University, Istanbul, Turkey.
- ⁵¹ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁵² Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁵³ Also at Marmara University, Istanbul, Turkey.
- ⁵⁴ Also at Kafkas University, Kars, Turkey.
- ⁵⁵ Also at Yildiz Technical University, Istanbul, Turkey.
- ⁵⁶ Also at Kahramanmaras Sütçü Imam University, Kahramanmaras, Turkey.
- ⁵⁷ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁵⁸ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁵⁹ Also at Utah Valley University, Orem, USA.
- ⁶⁰ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ⁶¹ Also at Argonne National Laboratory, Argonne, USA.
- ⁶² Also at Erzincan University, Erzincan, Turkey.
- ⁶³ Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁶⁴ Also at Kyungpook National University, Daegu, Republic of Korea.