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Search for nonresonant Higgs boson pair production in the four leptons plus twob jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

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

Abstract: The first search for nonresonant production of Higgs boson pairs (HH) with one H decaying into four leptons and the other into a pair of b quarks is presented, using proton-proton collisions recorded at a center-of-mass energy of $\sqrt{s} = 13$ TeV by the CMS experiment. The analyzed data correspond to an integrated luminosity of 138 fb^{-1}. A 95% confidence level upper limit of 32.4 is set on the signal strength modifier μ, defined as the ratio of the observed HH production rate in the HH $\to$ ZZ*b$\bar{\text{b}}$ $\to$ 4ℓb$\bar{\text{b}}$ decay channel to the standard model (SM) expectation. Possible modifications of the H trilinear coupling λ_{HHH} with respect to the SM value are investigated. The coupling modifier κ_λ, defined as λ_{HHH} divided by its SM prediction, is constrained to be within the observed (expected) range $-8.8\,(-9.8) < \kappa_\lambda < 13.4\,(15.0)$ at 95% confidence level.

Keywords: Hadron-Hadron Scattering , Higgs Physics

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1 Introduction

The discovery of the Higgs boson (H) by the ATLAS and CMS Collaborations [1, 2] is the first experimental proof of the predicted mechanism of electroweak symmetry breaking. Further measurements of the H properties performed by both Collaborations were found to be compatible with the standard model (SM) predictions [3–5]. A determination of the H self-coupling provides an independent test of the SM by probing the Higgs scalar field potential [6]; this parameter can be obtained by measuring the production of H pair (HH) at the LHC.

By exploiting different decay channels, studies of HH production allow different regions of the kinematic parameters describing possible extensions of the SM and of the nonresonant invariant mass spectrum to be probed. A combination of different decay channels is therefore needed to achieve the best possible sensitivity to HH production.

A wide variety of HH decay channels and their combination were studied by the ATLAS [7–10] and CMS [11–17] Collaborations: the most recent published results on the HH combination [18, 19], with a data set corresponding to an integrated luminosity of about 36 fb^{-1}, set an observed (expected) upper limit of, respectively, 7 (10) and 22 (13) at the 95% confidence level (CL) on the SM production cross section times the theoretical prediction.

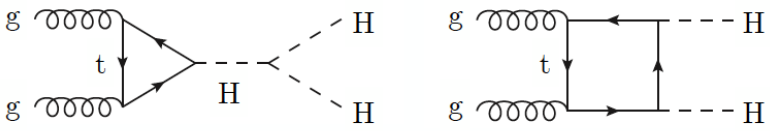

Figure 1. Feynman diagrams contributing to Higgs boson pair production via gluon-gluon fusion in the SM at LO.

The H to four-lepton ($H \to ZZ^* \to 4\ell$, $\ell = e, \mu$) decay channel is the rarest observed so far at the LHC but it has the largest signal-to-background ratio. The analysis presented in this paper focuses on gluon-gluon fusion HH production where one H decays to a Z boson pair, which in turn decays into 4ℓ, and the other to a pair of b quarks ($b\bar{b}$), hadronizing into jets. The final state forms a clear signature granted by the presence of the four leptons, while the high branching fraction of the $b\bar{b}$ decay channel partially compensates for the small branching fraction of the 4ℓ channel. The leading-order (LO) $gg \to HH$ Feynman diagrams are shown in figure 1.

The HH SM production cross section via gluon-gluon fusion has been computed at next-to-next-to-LO (NNLO) in quantum chromodynamics (QCD), including next-to-next-to-leading logarithmic (NNLL) corrections and finite top quark mass (m_{top}) effects at next-to-LO (NLO). Its value is $\sigma_{HH} = 31.05^{+2.2}_{-5.0}\%(\text{scale uncertainties}) \pm 2.1\%(\text{PDF}) \pm 2.1\%(\alpha_S)^{+4.0}_{-18.0}\%(m_{\text{top}})\,\text{fb}$ in proton-proton (pp) collisions at 13 TeV for a H mass of 125 GeV [20], where PDF stands for parton distribution function. After accounting for the branching fraction $\mathcal{B}(HH \to ZZ^*b\bar{b} \to 4\ell b\bar{b})$, the cross section is reduced to approximately 4.5 ab in the SM.

Beyond the SM physics can significantly modify the cross section and the kinematic properties of HH production, such as the HH invariant mass distribution. In order to provide constraints on these effects, an electroweak chiral Lagrangian model [21, 22], an effective field theory based approach that extends the SM with dimension-six operators, is used in an equivalent way as done in ref. [23] but at NLO in QCD. This approach results in five couplings relevant for HH production, out of which the H trilinear coupling λ_{HHH} is selected to perform scans of its allowed variations based on the results of this analysis. The variations of this coupling with respect to its SM prediction are parametrized by the coupling modifier, $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$.

2 The CMS detector

The CMS detector features a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the

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solenoid. Events of interest are selected using a two-tiered trigger system. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [24].

3 Data sets and simulations

Data from pp collisions collected by the CMS experiment in 2016–2018, at a center-of-mass energy of 13 TeV, are used for the analysis. Data-taking conditions vary year by year, and the samples used correspond to a total integrated luminosity of 138 fb^{-1}. The triggers used for this analysis require the presence of a pair of loosely isolated leptons (muons or electrons), whose exact requirements depend on the data-taking year. Triggers requiring a triplet of low transverse momentum (p_{T}) leptons, and isolated single-electron and single-muon triggers are used as well to recover efficiency. The overall trigger efficiency for events that satisfy the 4ℓ selection described below is greater than 98%. The trigger scheme used is the same as that used in the $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ analysis previously published by the CMS Collaboration [25].

Signal samples of the SM $\mathrm{gg} \to \mathrm{HH} \to \mathrm{ZZ}^*\mathrm{b\bar{b}} \to 4\ell\mathrm{b\bar{b}}$ process are generated at NLO in QCD using the POWHEG v2 [26–28] generator with the implementation described in [21, 22]. Using the same model, beyond SM signal samples with alternative values of κ_λ in steps of size 0.5 between -10 and $+10$ are generated. Single H production processes constitute the main SM background for this analysis. Descriptions of these processes are obtained using the POWHEG v2 generator for the six main production modes: gluon fusion (ggH), vector boson fusion (VBF) [29], and associated production (WH, ZH, $\mathrm{b\bar{b}H}$, and $\mathrm{t\bar{t}H}$ [30]). In the case of ggH, WH, and ZH, the MiNLO extension of POWHEG is used [31, 32] to increase the accuracy in the dijet phase space. The description of the decay of the H to 4ℓ is obtained using the JHUGEN generator [33] version 7.0.9. In the case of WH, ZH, $\mathrm{b\bar{b}H}$, and $\mathrm{t\bar{t}H}$, the H is allowed to decay to $\mathrm{H} \to \mathrm{ZZ}^* \to 2\ell 2\mathrm{X}$ where X could be any other particle from the Z decay so that 4ℓ events where two leptons originate from the decay of associated vector bosons or top quarks are also taken into account. The hadronic shower propagation of parton-level events, referred to as showering, is then performed by allowing QCD emissions at all energies in the shower and by vetoing them afterwards according to the POWHEG internal scale [27].

Several backgrounds include genuine nonresonant ZZ^* events. Production of ZZ^* via quark-antiquark annihilation is generated at NLO using MADGRAPH5_aMC@NLO with up to one extra parton, with appropriate settings to merge jet multiplicities [34]. As this simulation covers a large range of ZZ^* invariant masses $m(\mathrm{ZZ}^*)$, dynamical factorization and renormalization scales have been chosen. The simulated sample is rescaled by the ratio (denoted K-factor) of NNLO to NLO cross sections, and additional NLO electroweak corrections [35] are applied to the Monte Carlo (MC) sample as a function of $m(\mathrm{ZZ}^*)$.

The $\mathrm{gg} \to \mathrm{ZZ}^*$ process is simulated at LO with MCFM [36, 37] version 7.0.1. In order to match the $\mathrm{gg} \to \mathrm{H} \to \mathrm{ZZ}^*$ p_{T} spectra predicted at NLO, the showering for MCFM samples is performed allowing only emissions up to the parton-level scale. An exact calculation beyond the NLO does not exist for the $\mathrm{gg} \to \mathrm{ZZ}^*$ background, but it has been shown [38]

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that the soft collinear approximation can describe the background cross section and the interference term at NNLO. The NNLO K-factor for the gluon fusion H production is obtained as a function of $m(\mathrm{ZZ}^*)$ using the HNNLO v2 MC generator [39–41]. Triboson production with at least one Z boson with leptonic decays is generated at NLO using MadGraph5_aMC@NLO, using similar settings.

The contribution from Z+jets events is estimated from data-driven techniques as described in section 5.2. Other small backgrounds, such as $\mathrm{t\bar{t}Z}$, are estimated from simulation.

The pythia 8.2.30 [42] package is used for parton showering, hadronization, and the underlying event simulation, with parameters set according to the CUETP8M1 tune [43] for the 2016 data-taking period and the CP5 tune [44] for the 2017-2018 data-taking periods. The NNPDF set of PDFs [45] is used, NNPDF3.0 (3.1) for the 2016 (2017-2018) periods.

The detector response is simulated using a detailed description of the CMS detector implemented using the Geant4 package [46, 47]. Simulated events are reconstructed by the same algorithms used for the data. The simulated samples include additional interactions in the same and neighboring bunch crossings, referred to as pileup. Simulated events are weighted to match the pileup distribution observed in the data; this procedure is performed separately for each year.

4 Event reconstruction and selection

The final state consists of at least two pairs of opposite-charged isolated leptons and at least two jets. The 4ℓ selection is similar to that used in the CMS $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ measurement described in refs. [4, 25].

Events are reconstructed using a particle-flow algorithm [48] that aims at reconstructing and identifying each individual particle with an optimized combination of all subdetector information.

The primary interaction vertex, from which the H candidates arise, is chosen to be the one corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in ref. [49].

Electrons are identified with a multivariate classifier, which includes observables sensitive to Bremsstrahlung along the electron trajectory, the geometrical and kinematical compatibility between the electron track and the associated energy cluster in the electromagnetic calorimeter, the shape of the electromagnetic shower, and variables that discriminate against electrons originating from photon conversions [50].

In order to further suppress electrons from photon conversions and muons originating from in-flight decays of hadrons, the three-dimensional impact parameter significance is required to be smaller than four.

Muons are reconstructed by combining information from the silicon tracker and the muon system [51]. The muons are selected from the reconstructed muon track candidates by applying minimal requirements on the track in both the muon system and silicon tracker, and taking into account their compatibility with small energy deposits in the calorimeters.

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Muons are required to be isolated from other particles in the event. The relative isolation is defined as

$$R_{\text{iso}} = \left[\sum_{\substack{\text{charged} \\ \text{hadrons}}} p_{\text{T}} + \max\left(0, \sum_{\substack{\text{neutral} \\ \text{hadrons}}} p_{\text{T}} + \sum_{\text{photons}} p_{\text{T}} - \Delta\beta\right)\right] \Big/ p_{\text{T}}^{\ell}, \tag{4.1}$$

where the sums run over the charged and neutral hadrons, and photons, in a cone defined by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the lepton trajectory, where ϕ is the azimuthal angle in radians, and p_{T}^{ℓ} is the muon transverse momentum. To minimize the contribution of particles originating from pileup interactions to the isolation calculation, charged hadrons are included only if they originate from the primary vertex. The $\Delta\beta$ term is a correction factor accounting for the energy deposits originating from pileup interactions [52]. Muons with $R_{\text{iso}} < 0.35$ are considered isolated. A similar requirement is not applied to electrons, because the isolation information is included in the multivariate classifier.

The efficiency of the lepton reconstruction and selection is measured in both data and simulated samples in bins of lepton transverse momentum, p_{T}^{ℓ}, and pseudorapidity, η^{ℓ}, by using the tag-and-probe technique applied to leptonic Z boson decays [53]. Correction factors, denoted *scale factors* (SFs), are used to rescale the simulation so that it matches the data [25]. Leptons energy scale and resolution corrections are derived using the J/ψ meson and Z boson leptonic decays in bins of p_{T}^{ℓ} and η^{ℓ}.

The lepton final-state radiation is recovered following an algorithm described in ref. [4].

Jets are reconstructed from particle-flow candidates using the anti-k_{T} clustering algorithm [54], as implemented in the FASTJET package [55], with a distance parameter of 0.4. To ensure a good reconstruction efficiency and to reduce the instrumental background as well as the contamination from pileup, loose identification criteria based on the multiplicities and energy fractions carried by charged and neutral hadrons are imposed on jets [56]. Only jets in the tracker fiducial region ($|\eta| < 2.4$) are considered.

Jet energy corrections are extracted from data and simulated events to account for the effects of pileup, non-uniformity of the detector response, and residual differences between the jet energy scale in the data and in the simulation. The jet energy scale calibration [57–59] relies on corrections parametrized in terms of the raw (uncorrected) p_{T} and η of the jet. In order to ensure that jets are well measured and to reduce the pileup contamination, all jets must have a corrected $p_{\text{T}} > 20\,\text{GeV}$.

Jets originating from the fragmentation of one b quark are identified by using the *DeepCSV* algorithm [60], which combines impact parameter significance, secondary vertex, and jet kinematical information to provide a final output discriminator whose score is computed using a deep artificial neural network. Data-to-simulation b-tagging correction factors are applied to simulated events as a function of jet p_{T}, η, and flavour.

A signal event must contain at least two Z boson candidates, each formed from pairs of isolated electrons or muons of opposite electrical charges; these leptons are selected according to the studies described in ref. [4]. Only reconstructed electrons (muons) with a $p_{\text{T}} > 7(5)\,\text{GeV}$ are considered. Among the 4ℓ, the highest-p_{T} one must have $p_{\text{T}} > 20\,\text{GeV}$, while the second-highest p_{T} one must have $p_{\text{T}} > 12\,(10)\,\text{GeV}$ if it is an electron (muon). All

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Final state	Signal	$t\bar{t}Z$	$t\bar{t}H$	$b\bar{b}H$	ZZ	ggH+VBF	ZH+WH	Others	Z+X	Total expected	Observed
4μ	0.056	0.58	0.68	0.16	3.75	12.35	1.61	0.04	3.87	23.10	29
4e	0.030	0.37	0.39	0.07	1.42	6.16	0.82	0.02	2.65	11.93	12
$2e2\mu$	0.082	0.95	0.91	0.20	4.93	15.56	2.08	0.10	7.22	32.03	33

Table 1. Expected yields in the 4ℓ SR after additionally requiring at least two jets in the event. "Others" represents contributions from $t\bar{t}W$, WWZ, WZZ, and ZZZ processes.

leptons are required to be separated by $\Delta R(\ell_1, \ell_2) > 0.02$ from each other, and electrons are required to be separated from muons by $\Delta R(e, \mu) > 0.05$.

Within each event, all permutations of leptons giving a valid pair of Z boson candidates are considered. For each ZZ candidate, the lepton pair with the invariant mass closest to the nominal Z boson mass is denoted Z_1 and required to have a mass greater than 40 GeV. The other dilepton candidate is denoted Z_2 and must satisfy $12 < m_{Z_2} < 120$ GeV where the lower cut is used to discard low mass dilepton resonances while the upper threshold corresponds to the higher limit of the Z_1 mass range, as described in ref. [4]. All pairs of oppositely charged leptons that can be built from the ZZ candidate, regardless of flavour, are required to satisfy a requirement on their invariant mass, $m_{\ell\ell'}$, to be larger than 4 GeV to suppress the QCD background with low transverse momentum leptons from hadron decays. If more than one ZZ candidate passes the selection, the one with the highest value of the scalar p_T-sum of leptons is retained.

In order to search for HH production, in addition to the ZZ selections, events are required to have at least two jets, which are required to be separated from the leptons of the ZZ candidate by $\Delta R(\text{lepton}, \text{jet}) > 0.3$ and to have $p_T > 20$ GeV. At this stage, no other requirement on the value of the invariant mass or on the score of the *DeepCSV* b-tagging algorithm for the jets is applied. The $b\bar{b}$ candidate is formed using the two jets with the highest b-tagging score.

The 4ℓ *signal region* (SR) is defined by applying the additional requirement on the four-lepton invariant mass to be $115 < m(4\ell) < 135$ GeV. Events that do not satisfy this requirement are included in the 4ℓ *control region* (CR). The expected yields in the SR after the above selection are reported in table 1. Figure 2 shows the $m(4\ell)$ and $m(b\bar{b})$ distributions in signal, estimated background components, and data.

5 Background estimation

5.1 Irreducible background

The irreducible background to the HH signal is estimated from simulation. One of the main background contributions is the production of single H decaying into ZZ^*, whose description is provided using the POWHEG v2 generator. For the gluon fusion H production mode, NNLO parton shower weights are applied. Another large contribution is the $q\bar{q} \to ZZ^*$ process, which is simulated at NLO and then reweighted with NNLO/NLO K-factors to account for the missing higher orders in the cross section used. The $gg \to ZZ^*$ contribution too is estimated from MC by reweighting it with NNLO K-factors. Other backgrounds, such as $t\bar{t}Z$ and $t\bar{t}W$, are also estimated from simulation.

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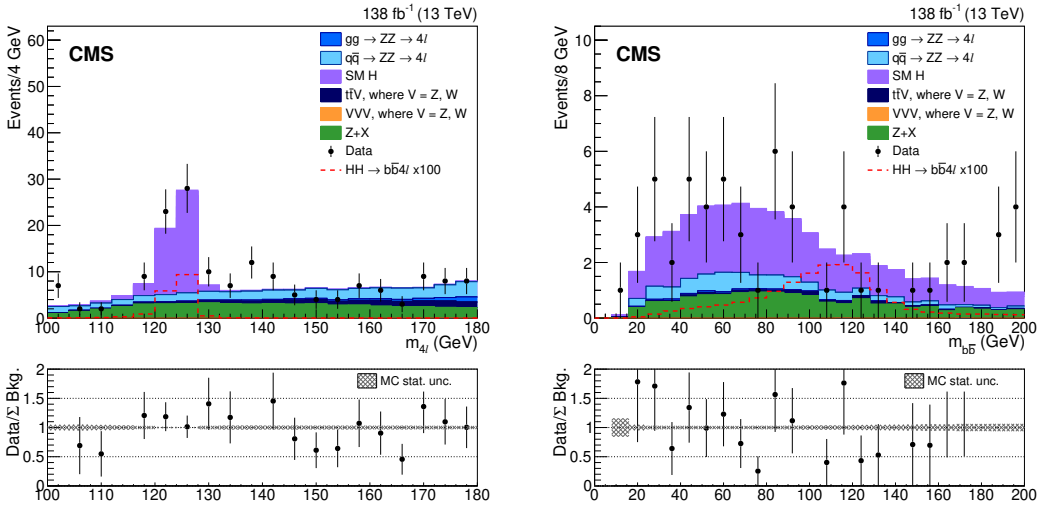

Figure 2. The $m(4\ell)$ (left) and $m(\mathrm{b\bar{b}})$ (right) distributions. The $m(\mathrm{b\bar{b}})$ plot is drawn after the selection: $115 < m(4\ell) < 135\,\mathrm{GeV}$. In the ratio plot, the grey dashed shades represent the relative statistical uncertainty on the total estimated background.

5.2 Reducible background

The reducible background (Z+X) originates from processes that contain one or more non-prompt leptons (leptons not originating from the hard-interaction primary vertex). The main sources of non-prompt leptons are non-isolated electrons and muons coming from decays of heavy-flavour hadrons, misreconstructed jets (usually originating mostly from light-flavour quarks), and electrons from photon conversions.

The number of expected events for these background processes is estimated by measuring the probabilities f_e and f_μ for misidentified electrons and muons that do pass looser selection criteria to also pass the final selection criteria in selected samples of $\mathrm{Z}(\ell\ell)+\mathrm{e}+2$ jets and $\mathrm{Z}(\ell\ell)+\mu+2$ jets events, where the additional lepton (e or μ) satisfies a loose selection. The misidentification probabilities are evaluated using the requirement $|m_\mathrm{inv}(\ell_1\ell_2) - M_\mathrm{Z}| < 7\,\mathrm{GeV}$, to reduce the contribution from asymmetric conversions of photons, which is dominant at low dilepton masses. The misidentification rates are measured in bins of the p_T of the loosely-identified lepton and separately for the barrel and the endcap regions.

To estimate the Z+X yield in the SR, we define two control samples as subsets of $\mathrm{Z}+2$ jets events that pass the Z candidate selection, requiring an additional pair of loose leptons of same flavour and opposite charge passing the impact parameter selection. The first control sample is obtained by requiring that the two loose leptons, which do not form the Z_1 candidate, do not pass the final identification and isolation criteria (2P2F region). The second control sample is obtained by requiring that one of the 4ℓ does not pass the final identification and isolation criteria, and the other three leptons do (3P1F region).

The expected number of events from reducible backgrounds in the SR can be written as described in ref. [4]:

$$N_\mathrm{SR}^\mathrm{Z+X} = \Sigma \frac{f_i}{(1-f_i)}(N_\mathrm{3P1F} - N_\mathrm{3P1F}^\mathrm{bkg} - N_\mathrm{3P1F}^\mathrm{ZZ}) + \Sigma \frac{f_i}{(1-f_i)}\frac{f_j}{(1-f_j)} N_\mathrm{2P2F}, \tag{5.1}$$

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where N_{2P2F} is the observed number of events in the first control sample, N_{3P1F} is the observed number of events in the second control sample, N_{3P1F}^{bkg} is the contamination of 2P2F in the 3P1F CR, N_{3P1F}^{ZZ} is the number of background events which have 4 real leptons and 2 jets estimated from MC simulation, and f_i and f_j are the estimated misidentification probabilities of the two loose leptons.

The dominant systematic uncertainty in the reducible background estimation arises mainly from the limitated number of events both in the CR and in the region where the misidentification rates are computed. Uncertainties that arise from the difference in the composition of the sample from which the misidentification rate is computed are also taken into account.

6 Multivariate analysis

A boosted decision tree (BDT) is used to further discriminate signal from backgrounds. The BDT is implemented in the TMVA tool of the ROOT analysis package [61], and trained using simulated events in the 4ℓ SR; training is done using the gluon-gluon HH process as signal and all the other processes as background.

An optimal set of input variables was chosen maximizing the area under the receiver operating characteristic curve for each resulting discriminator. The optimized set contains ten variables, namely: the p_T of each of the 4ℓ, the ΔR between the reconstructed $H \to ZZ^* \to 4\ell$ and $H \to b\bar{b}$ systems, the two b-tagging scores, the p_T of each of the two jets with the highest value of b-tagging score and their invariant mass. The most important variables for the BDT training are the b-tagging scores of the two selected jets, the invariant mass of the dijet system, and the ΔR between the reconstructed $H \to ZZ^* \to 4\ell$ and $H \to b\bar{b}$ systems.

To take into account the possible differences due to data-taking conditions and final states, the BDT is trained separately for each data-taking year and for each of the leptonic final states (4μ, 4e, and $2e2\mu$), for a total of nine independent discriminators. Detailed studies were performed on the discrimination ranking, variable correlations, and possible discriminator overtraining. Figure 3 shows the inclusive BDT discriminator distribution for simulated signal, estimated background components, and data: different data-taking years and leptonic final states are combined together (4μ, 4e, and $2e2\mu$). Signal and backgrounds normalisation results from the fit procedure described in section 8. The binning of the BDT output distribution is chosen in order to have (almost) the same statistical uncertainties in the last 4–5 bins, which is around 10% and which ensures stable results under statistical fluctuations of the most sensitive bins.

The output of the BDT is used in a statistical analysis as the input variable of a maximum likelihood fit to set constraints on both the signal strength and the κ_λ coupling modifier.

7 Systematic uncertainties

Systematic uncertainties are modelled in a maximum likelihood fit as nuisance parameters. Two types of nuisance parameters are considered: *normalization* uncertainties, describ-

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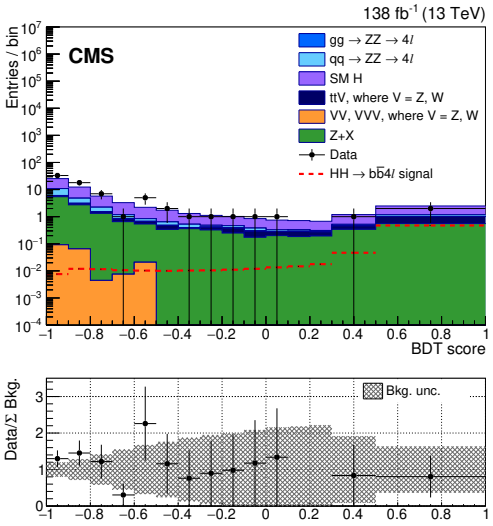

Figure 3. Inclusive BDT distributions for simulated signal, estimated background components, and data for the combination of the three different final states (4μ, 4e, and 2e2μ) and data-taking years. In the ratio plot, the grey dashed shades represent the total uncertainties on the estimated background.

ing possible modification to the event yields, and *shape* uncertainties, accounting also for variations of the shape of distributions. The former are assigned a log-normal probability density function, while the latter are included as template shape variations and taken into account via continuous template morphing [62].

The experimental uncertainties considered for the measurement arise from different sources. The uncertainty in the integrated luminosity is 1.2% for 2016 [63], 2.3% for 2017 [64], and 2.5% for 2018 [65]. The uncertainty in the lepton identification and reconstruction efficiency ranges $1.0 - -15.5\%$ on the overall event yield for the different final states. Muon uncertainties are always below 3%, while electron uncertainties surpass 10% for electrons with $p_{\mathrm{T}} < 20\,\mathrm{GeV}$ and $|\eta| > 1.5$. The uncertainties in the jet energy scale (JES) and jet energy resolution (JER) are accounted for by changing the jet p_{T} by one standard deviation for each of the several uncorrelated sources considered [57]. The effects on the signal acceptance are also accounted for. Uncertainties in the scale factors are computed and applied as a function of the jet p_{T}, η, and hadron flavour. The above uncertainties apply equally to all simulated signal and background samples. The JES, JER, and b-tagging scale factor systematics are considered shape uncertainties. The JES, together with the statistical uncertainties in the yield of the last bin of the BDT, are the systematic effects with the largest impact on the final result. All the other sources are considered normalization uncertainties. The experimental uncertainties originating from the reducible background estimation, described in section 5.2, are also considered. The main contribution comes from the mismatch in the composition of backgrounds between the samples where the misidentification probability is derived and those where it is applied. The summary of the experimental systematic uncertainties is reported in table 2.

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Experimental uncertainties			
Source	2016	2017	2018
Integrated luminosity	1.2%	2.3%	2.5%
Lepton reco./ident. eff.	1.6–15.5%	1.1–12.1%	1.0–11.0%
b-tagging SF	shape	shape	shape
JES	shape	shape	shape
JER	shape	shape	shape
Z+X bkg. uncertainties	30–41%	30–38%	30–37%

Table 2. Summary of experimental systematic uncertainties. The effect of b-tagging SF, JER, and JES is propagated to the shape of the BDT distribution.

Theoretical uncertainties arise from the choice of the PDF set, the uncertainty in α_S, and the renormalization and factorization scales [66]: they affect both signal and background processes. For the HH signal, in addition to the uncertainty sources just described, an uncertainty caused by missing finite m_{top} effects [20] contributes, too. No additional uncertainties on H production without real b jets are applied since they are negligible compared to all the other uncertainties involved. An additional uncertainty of 10% for the $gg \to ZZ^*$ prediction and of 0.1% for the $qq \to ZZ^*$ prediction is considered to account for the uncertainty in the applied K-factors, described in section 3.

The uncertainty in the luminosity is treated as partially correlated across data-taking periods. All the other experimental uncertainties are considered uncorrelated: they are estimated for each year independently and therefore their dominating statistical uncertainty is uncorrelated. All theoretical uncertainties are considered correlated among the three data-taking years. A summary of the theory systematic uncertainties is reported in table 3.

This analysis is still dominated by statistical uncertainties, thus the impact of the systematic uncertainties is overall negligible.

8 Results

No significant excess of events is observed over the expected backgrounds. Upper limits are set on the production cross section of HH times the branching fraction $\mathcal{B}(\mathrm{HH} \to 4\ell\mathrm{b}\overline{\mathrm{b}})$, using the modified frequentist approach ($\mathrm{CL_s}$), taking the profile likelihood as a test statistic [67–70] in the asymptotic approximation. The limits are compared to the theoretical predictions assuming SM branching fractions for the H decays.

The results are extracted with a binned maximum likelihood fit to the nine BDT distributions in data. Shape templates for the BDT score for signal are obtained from simulated samples and for backgrounds from both simulated samples and data, as described in section 6. Systematic uncertainties are treated as described in section 7.

The observed (expected) upper limit on the signal strength modifier μ, defined as the ratio of the HH fraction in the $4\ell\mathrm{b}\overline{\mathrm{b}}$ final state to the SM expectation, is 32.4 (39.6) at 95% CL, as illustrated in figure 4 (left).

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Theory uncertainties	
Branching fractions	
$\mathcal{B}(\mathrm{H} \to \mathrm{b\bar{b}})$	1.2%
$\mathcal{B}(\mathrm{H} \to \mathrm{ZZ})$	1.5%
PDF set and α_S	
HH	3.0%
HH (m_top effects)	$^{+4.0}_{-18.0}$%
ggH (PDF set)	1.9%
ggH (α_S)	2.59–2.62%
VBFH	2.1%
ZH	1.6%
WH	1.3%
$\mathrm{b\bar{b}H}$	3.2%
$\mathrm{t\bar{t}H}$	3.0%
qqZZ	3.1–3.4%
$\mathrm{t\bar{t}Z}$	7–14%
VVV	2–17%
ggZZ	3.2%
Scale uncertainties	
HH	2.2–5%
ggH	4.27–6.49%
VBFH	0.3–0.4%
ZH	2.7–3.5%
$\mathrm{t\bar{t}H}$	6.0–9.2%
qqZZ	3.2–4.2%
$\mathrm{t\bar{t}Z}$	2–3%
VVV	3%
ggZZ	4.6–6.7%
K-factors	
qqZZ	0.1%
ggZZ	10.0%

Table 3. Summary of the theory systematic uncertainties considered in this analysis.

Upper limits are also set for different hypotheses of anomalous values of the H self-coupling κ_λ, assuming all the other couplings [71] are equal to their SM values. The result is shown in figure 4 (right), where the exclusion is compared to the theoretical prediction for the HH cross section (red line). The analysis constrains κ_λ to be within the observed (expected) range $-8.8\,(-9.8) < \kappa_\lambda < 13.4\,(15.0)$ at 95% CL.

The limits set by this analysis are obtained with a data set which is independent from those used for the other channels [11, 11, 12, 12].

The results presented in this section are provided in a tabulated form in the HEPDATA record [72] for this analysis.

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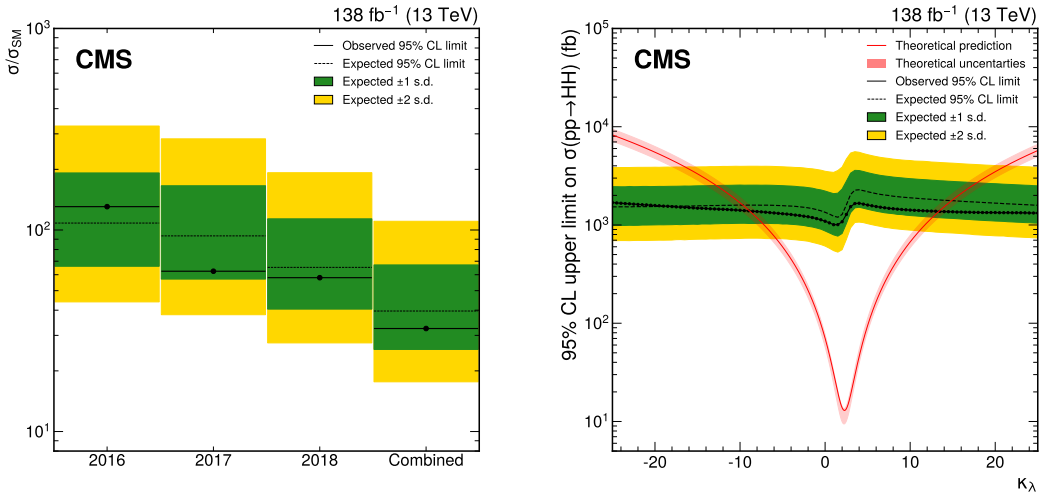

Figure 4. Left: upper limit on the signal strength at 95% CL for each year and for their combination. Right: expected and observed 95% CL upper limits on the SM-like HH production cross section obtained for different values of κ_λ. The green and yellow bands represent, respectively, the one and two standard deviation (s.d.) quantiles around the expected limit. The red curve is the HH theoretical prediction cross section as a function of κ_λ.

9 Summary

The first search for nonresonant Higgs boson (H) pair production in the four lepton $\mathrm{b\bar{b}}$ final state is presented. This search uses a data sample collected in proton-proton collisions at $\sqrt{s} = 13$ TeV by the CMS detector during the years 2016–2018 corresponding to an integrated luminosity of 138 fb^{-1}. The results are found to be compatible with the standard model (SM) expectations. An observed (expected) upper limit on the HH production cross section is set at 32.4 (39.6) times the SM expected rate at the 95% confidence level. Possible modifications of the H trilinear coupling λ_{HHH} with respect to the standard model (SM) value are investigated. The coupling modifier κ_λ, defined as λ_{HHH} divided by its SM prediction, is constrained to be within the observed (expected) range $-8.8\,(-9.8) < \kappa_\lambda < 13.4\,(15.0)$ at 95% confidence level.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[2], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish[3], T. Janssen, T. Kello[4], H. Rejeb Sfar, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, K. Lee, M. Mahdavikhorrami, I. Makarenko, A. Malara, S. Paredes, L. Pétré, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium

D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

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

A. Benecke, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

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

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[8], A. Vilela Pereira

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

C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, 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. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

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

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S.Thakur

Beihang University, Beijing, China

T. Cheng, T. Javaid[9], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, G. Bauer[10], Z. Hu, S. Lezki, K. Yi[10,11]

Institute of High Energy Physics, Beijing, China

G.M. Chen[9], H.S. Chen[9], M. Chen[9], F. Iemmi, C.H. Jiang, A. Kapoor, H. Liao, Z.-A. Liu[12], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

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

A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China

M. Lu, Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao[4], D. Leggat, H. Okawa, Y. Zhang

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

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Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

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

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, B.K. Chitroda, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov[13], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

Charles University, Prague, Czech Republic
M. Finger[13], M. Finger Jr.[13], 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
Y. Assran[14,15], S. Elgammal[15]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, 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
P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[16], P. Simkina, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[17], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, C. Bernet, B. Blancon, G. Boudoul, A. Carle, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[18], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, L. Torterotot, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia
D. Chokheli, I. Lomidze, Z. Tsamalaidze[13]

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

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey, D. Fasanella, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[19], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

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Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman[20], K. Borras[21], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[20], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari[22], N.Z. Jomhari, B. Kaech, A. Kasem[21], M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka, W. Lohmann[23], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[24,21], V. Scheurer, S. Schnake[21], P. Schütze, C. Schwanenberger[20], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon[†], M. Van De Klundert, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[21], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, M. Hajheidari, J. Haller, A. Hinzmann, H.R. Jabusch, G. Kasieczka, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, J. Lange, A. Lobanov, C. Matthies, A. Mehta, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, M. Rieger, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel, S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann[25], M. Horzela, U. Husemann, P. Keicher, M. Klute, R. Koppenhöfer, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch, X. Zuo

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

G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis, I. Zisopoulos

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

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

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[26], S. Lökös[27], P. Major, K. Mandal, G. Pásztor, A.J. Rádl[28], O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[29], G. Bencze, C. Hajdu, D. Horvath[30,31], F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[29], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[32]

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[28], F. Nemes[28], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[33], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh[34], A. Singla, A. K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, M. Gola, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, S. Saumya, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[35], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[36], M. Maity[35], P. Palit, G. Saha, B. Sahu, S. Sarkar

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri[37], D. Kumar[37], A. Muhammad, L. Panwar[37], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari[37], S. Verma

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[38]

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Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[39], C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[40], A. Nayak[40], P. Saha, S.K. Swain, D. Vats[40]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[41], E. Khazaie, M. Zeinali[42]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[43], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,c,44], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], M. Ince[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], 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], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[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], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,45], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[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,46], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,46], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

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INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[25], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Bozzo[a,b], P. Chatagnon[a], F. Ferro[a], R. Mulargia[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], F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Università G. Marconi[d], Roma, Italy
S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,47], P. Paolucci[a,25], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
P. Azzi[a], N. Bacchetta[a,48], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], F. Gonella[a], G. Govi[a], G. Grosso[a], L. Layer[a,49], E. Lusiani[a], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], 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
S. Abu Zeid[a,50], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
P. Asenov[a,51], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,51], A. Piccinelli[a,b], M. Presilla[a,b], 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
P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a,b], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M.R. Di Domenico[a,d], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], G. Mandorli[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], S. Parolia[a,b], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c],

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S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy

P. Barria[a], M. Campana[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], 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], R. Tramontano[a,b]

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], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], E. Migliore[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], M. Tornago[a,b], D. Trocino[a], G. Umoret[a,b], A. Vagnerini[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], A. Da Rold[a,b], G. Della Ricca[a,b], G. Sorrentino[a,b]

Kyungpook National University, Daegu, Korea

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmen, Y.C. Yang

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

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

E. Asilar, T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh

Sejong University, Seoul, Korea

H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

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

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, Y. Lee, I. Yu

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

Riga Technical University, Riga, Latvia
K. Dreimanis, M. Seidel, T. Torims, V. Veckalns

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, S.Y. Hoh[52], I. Yusuff[52], 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, I. Heredia-De La Cruz[53], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, F. Vazquez Valencia

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

University of Montenegro, Podgorica, Montenegro
I. Bubanja, J. Mijuskovic[54], N. Raicevic

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

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AGH University of Science and Technology 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, B. Boimska, 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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic[55], M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, 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, J. León Holgado, D. Moran, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, J. Sastre, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

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, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, A. García Alonso, G. Gomez, C. Lasaosa García,

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C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda, B. Kailasapathy[56], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[57], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, A. Lintuluoto, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[58], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[59], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada[60], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[60], L. Noehte[60], T. Rohe

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

T.K. Aarrestad, K. Androsov[59], M. Backhaus, P. Berger, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani[59], M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, J. Steggemann[59], D. Valsecchi[25], R. Wallny

Universität Zürich, Zurich, Switzerland

C. Amsler[61], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei,

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B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan

C. Adloff[62], C.M. Kuo, W. Lin, P.K. Rout, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, H. Cheng, W.-S. Hou, R. Khurana, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

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

C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[63], E. Eskut, Y. Guler[64], E. Gurpinar Guler[64], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[65], A. Polatoz, A.E. Simsek, B. Tali[66], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar[67], K. Ocalan[68], M. Yalvac[69]

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[70], O. Kaya[71], Ö. Özçelik, S. Tekten[72]

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak[63], Y. Komurcu, S. Sen[73]

Istanbul University, Istanbul, Turkey

O. Aydilek, S. Cerci[66], B. Hacisahinoglu, I. Hos[74], B. Isildak[75], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci[66]

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

B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko,

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B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[76], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev[77], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[78], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal[79], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash[80], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[25], M. Vojinovic, N. Wardle, S.N. Webb, 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, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA

A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[81], C. West

Boston University, Boston, Massachusetts, USA

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Brown University, Providence, Rhode Island, USA

G. Benelli, B. Burkle, X. Coubez[21], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir[83], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA

J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

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University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny

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

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
N. Amin, C. Campagnari, M. Citron, G. Collura, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, F. Marini, R. Patel, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

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

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, 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, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl,

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O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, 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, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera, A. Reinsvold Hall[85], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, I. Zoi

University of Florida, Gainesville, Florida, USA

P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, D. Guerrero, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

Florida State University, Tallahassee, Florida, USA

T. Adams, A. Askew, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, O. Viazlo, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy[50], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

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

M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D. S. Lemos, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini, K. Dilsiz[86], L. Emediato, R.P. Gandrajula, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[87], J. Nachtman, O. Neogi, H. Ogul[88], Y. Onel, A. Penzo, C. Snyder, E. Tiras[89]

Johns Hopkins University, Baltimore, Maryland, USA

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, J. Williams, G. Wilson

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Kansas State University, Manhattan, Kansas, USA

B. Allmond, S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, D. Roy

Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA

E. Adams, A. Baden, O. Baron, A. Belloni, A. Bethani, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

D. Abercrombie, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, M. Hu, D. Kovalskyi, J. Krupa, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, A. Evans, J. Hiltbrand, Sh. Jain, B.M. Joshi, C. Kapsiak, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, R. Kamalieddin, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow†, W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, Massachusetts, USA

G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, J. Lidrych, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, Illinois, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt, M. Velasco

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University of Notre Dame, Notre Dame, Indiana, USA
R. Band, R. Bucci, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[13], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

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

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

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

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic, J. Thieman, F. Wang, R. Xiao, W. Xie

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

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, E. Yigitbasi, L. Zhang[90], Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus, G.P. Van Onsem

The Rockefeller University, New York, New York, USA
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[23], I. Laflotte, A. Lath, R. Montalvo, K. Nash,

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M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA

O. Bouhali[91], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[92], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA

N. Akchurin, J. Damgov, V. Hegde, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA

B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald

Wayne State University, Detroit, Michigan, USA

P.E. Karchin, N. Poudyal

University of Wisconsin - Madison, Madison, Wisconsin, USA

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, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[93], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, O. Bychkova, M. Chadeeva[93], V. Chekhovsky, A. Dermenev, T. Dimova[93], I. Dremin, M. Dubinin[84], L. Dudko, V. Epshteyn, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, V. Ivanchenko, Y. Ivanov, V. Kachanov, L. Kardapoltsev[93], V. Karjavine, A. Karneyeu, V. Kim[93], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova[94], D. Konstantinov, V. Korenkov, A. Kozyrev[93], N. Krasnikov, E. Kuznetsova[95], A. Lanev, P. Levchenko, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[93], V. Murzin, A. Nikitenko[96], S. Obraztsov, A. Oskin, I. Ovtin[93],

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V. Palichik, P. Parygin, V. Perelygin, M. Perfilov, S. Petrushanko, G. Pivovarov, V. Popov, E. Popova, O. Radchenko[93], V. Rusinov, M. Savina, V. Savrin, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[93], S. Slabospitskii, V. Smirnov, D. Sosnov, A. Stepennov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, M. Toms, A. Toropin, L. Uvarov, A. Uzunian, E. Vlasov, A. Vorobyev, N. Voytishin, B.S. Yuldashev[97], A. Zarubin, I. Zhizhin, A. Zhokin

[†] *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 Université Libre de Bruxelles, Bruxelles, Belgium*
[5] *Also at Universidade Estadual de Campinas, Campinas, Brazil*
[6] *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*
[7] *Also at UFMS, Nova Andradina, Brazil*
[8] *Also at The University of the State of Amazonas, Manaus, Brazil*
[9] *Also at University of Chinese Academy of Sciences, Beijing, China*
[10] *Also at Nanjing Normal University Department of Physics, Nanjing, China*
[11] *Now at The University of Iowa, Iowa City, Iowa, USA*
[12] *Also at University of Chinese Academy of Sciences, Beijing, China*
[13] *Also at an institute or an international laboratory covered by a cooperation agreement with CERN*
[14] *Also at Suez University, Suez, Egypt*
[15] *Now at British University in Egypt, Cairo, Egypt*
[16] *Also at Purdue University, West Lafayette, Indiana, USA*
[17] *Also at Université de Haute Alsace, Mulhouse, France*
[18] *Also at Department of Physics, Tsinghua University, Beijing, China*
[19] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*
[20] *Also at University of Hamburg, Hamburg, Germany*
[21] *Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[22] *Also at Isfahan University of Technology, Isfahan, Iran*
[23] *Also at Brandenburg University of Technology, Cottbus, Germany*
[24] *Also at Forschungszentrum Jülich, Juelich, Germany*
[25] *Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[26] *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
[27] *Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
[28] *Also at Wigner Research Centre for Physics, Budapest, Hungary*
[29] *Also at Institute of Physics, University of Debrecen, Debrecen, Hungary*
[30] *Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
[31] *Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania*
[32] *Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary*
[33] *Also at Punjab Agricultural University, Ludhiana, India*
[34] *Also at UPES - University of Petroleum and Energy Studies, Dehradun, India*
[35] *Also at University of Visva-Bharati, Santiniketan, India*
[36] *Also at University of Hyderabad, Hyderabad, India*
[37] *Also at Indian Institute of Science (IISc), Bangalore, India*
[38] *Also at Indian Institute of Technology (IIT), Mumbai, India*
[39] *Also at IIT Bhubaneswar, Bhubaneswar, India*
[40] *Also at Institute of Physics, Bhubaneswar, India*
[41] *Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[42] *Also at Sharif University of Technology, Tehran, Iran*
[43] *Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*

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[44] Also at Helwan University, Cairo, Egypt
[45] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[46] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[47] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[48] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[49] Also at Università di Napoli 'Federico II', Napoli, Italy
[50] Also at Ain Shams University, Cairo, Egypt
[51] Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[52] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[53] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[54] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[55] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
[56] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[57] Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[58] Also at National and Kapodistrian University of Athens, Athens, Greece
[59] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[60] Also at Universität Zürich, Zurich, Switzerland
[61] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[62] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[63] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[64] Also at Konya Technical University, Konya, Turkey
[65] Also at Izmir Bakircay University, Izmir, Turkey
[66] Also at Adiyaman University, Adiyaman, Turkey
[67] Also at Istanbul Gedik University, Istanbul, Turkey
[68] Also at Necmettin Erbakan University, Konya, Turkey
[69] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[70] Also at Marmara University, Istanbul, Turkey
[71] Also at Milli Savunma University, Istanbul, Turkey
[72] Also at Kafkas University, Kars, Turkey
[73] Also at Hacettepe University, Ankara, Turkey
[74] Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[75] Also at Yildiz Technical University, Istanbul, Turkey
[76] Also at Vrije Universiteit Brussel, Brussel, Belgium
[77] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[78] Also at University of Bristol, Bristol, United Kingdom
[79] Also at IPPP Durham University, Durham, United Kingdom
[80] Also at Monash University, Faculty of Science, Clayton, Australia
[81] Also at Università di Torino, Torino, Italy
[82] Also at Bethel University, St. Paul, Minnesota, USA
[83] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[84] Also at California Institute of Technology, Pasadena, California, USA
[85] Also at United States Naval Academy, Annapolis, Maryland, USA
[86] Also at Bingol University, Bingol, Turkey
[87] Also at Georgian Technical University, Tbilisi, Georgia
[88] Also at Sinop University, Sinop, Turkey
[89] Also at Erciyes University, Kayseri, Turkey
[90] Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
[91] Also at Texas A&M University at Qatar, Doha, Qatar

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[92] *Also at Kyungpook National University, Daegu, Korea*
[93] *Also at another institute or international laboratory covered by a cooperation agreement with CERN*
[94] *Also at Yerevan Physics Institute, Yerevan, Armenia*
[95] *Now at University of Florida, Gainesville, Florida, USA*
[96] *Also at Imperial College, London, United Kingdom*
[97] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*

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