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Combined search for anomalous pseudoscalar HVV couplings in VH production and H $\rightarrow$ VV decay

The CMS Collaboration*

Abstract

A search for anomalous pseudoscalar couplings of the Higgs boson H to electroweak vector bosons V (= W or Z) in a sample of proton-proton collision events corresponding to an integrated luminosity of $18.9\,\mathrm{fb}^{-1}$ at a center-of-mass energy of 8 TeV is presented. Events consistent with the topology of associated VH production, where the Higgs boson decays to a pair of bottom quarks and the vector boson decays leptonically, are analyzed. The consistency of data with a potential pseudoscalar contribution to the HVV interaction, expressed by the effective pseudoscalar cross section fractions f_{a_3}, is assessed by means of profile likelihood scans. Results are given for the VH channels alone and for a combined analysis of the VH and previously published H $\rightarrow$ VV channels. Assuming the standard model ratio of the coupling strengths of the Higgs boson to top and bottom quarks, $f_{a_3}^{ZZ} > 0.0034$ is excluded at 95% confidence level in the combination.

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*See Appendix 9 for the list of collaboration members

1 Introduction

The observation of a new boson [1–3] with a mass around 125 GeV and properties consistent with those of the standard model (SM) Higgs boson [4–10] has ushered in a new era of precision Higgs physics. The ATLAS and CMS collaborations at the CERN LHC have begun a comprehensive study of the boson properties. The spin-parity of the Higgs boson has been studied in $\mathrm{H} \to \mathrm{ZZ}, \mathrm{Z}\gamma^*, \gamma^*\gamma^* \to 4\ell$, $\mathrm{H} \to \mathrm{WW} \to \ell\nu\ell\nu$, and $\mathrm{H} \to \gamma\gamma$ decays [11–16], where ℓ is an electron or muon. The CDF and D0 collaborations have set limits on the $\mathrm{p}\overline{\mathrm{p}} \to \mathrm{VH}$ production cross section (with $\mathrm{V} = \mathrm{W}$ or Z) at the Tevatron, for two exotic spin-parity models of the Higgs boson [17]. In all cases, the spin-parity J^{CP} of the boson has been found to be consistent with the SM prediction. Based on a study of anomalous couplings in $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ decays, the CMS collaboration has excluded the hypothesis of a pure pseudoscalar spin-zero boson at 99.98% confidence level (CL), while an effective pseudoscalar cross section fraction $f_{a_3}^{\mathrm{ZZ}} > 0.43$ is excluded at 95% CL (assuming a positive, real valued ratio of scalar and pseudoscalar couplings) [15]. Under the same assumptions, the ATLAS collaboration has excluded $f_{a_3}^{\mathrm{ZZ}} > 0.11$ at 95% CL [18].

We present here the first search for anomalous pseudoscalar HVV couplings at the LHC in the topology of associated production, VH. It will be shown that the VH channels are strong probes of the structure of the HVV interaction, with sensitivity even to small anomalous couplings. The ultimate LHC sensitivity to a potential pseudoscalar interaction in these channels is expected to greatly exceed that of $\mathrm{H} \to \mathrm{VV}$ [19]. Due to the highly off-shell nature of the propagator in VH production, small anomalous couplings can lead to significant modifications of cross sections and kinematic features. In particular, the propagator mass, measured by the VH invariant mass, $m(\mathrm{VH})$, is highly sensitive to anomalous HVV couplings [20].

Results from the VH channels are ultimately combined with those from $\mathrm{H} \to \mathrm{VV}$ measurements [15]. The $\mathrm{q}\overline{\mathrm{q}} \to \mathrm{VH} \to \mathrm{V}\mathrm{b}\overline{\mathrm{b}}$ and $\mathrm{gg} \to \mathrm{H} \to \mathrm{VV}$ processes involve the Yukawa fermion coupling $\mathrm{H}\mathrm{f}\overline{\mathrm{f}}$ and the same HVV coupling, assuming gluon fusion production is dominated by the top-quark loop. The dominance of the gluon fusion production mechanism of the Higgs boson at the LHC is supported by experimental measurements [4–10]. It is interesting to consider models where the ratio of the $\mathrm{H}\mathrm{b}\overline{\mathrm{b}}$ and $\mathrm{H}\mathrm{t}\overline{\mathrm{t}}$ coupling strengths in the VH and $\mathrm{H} \to \mathrm{VV}$ processes is not affected by the presence of anomalous contributions [21]. In such a case, it is possible to relate the cross sections of the two processes for arbitrary anomalous HVV couplings and perform a combined analysis of the VH and $\mathrm{H} \to \mathrm{VV}$ processes, exploiting both kinematics and the relative signal strengths of the two processes. The $\mathrm{H} \to \mathrm{VV}$ signal strength is relatively well measured and can provide a strong constraint on the VH signal strength. For modest values of $f_{a_3}^{\mathrm{ZZ}}$, the VH signal strength is constrained to large values. The added constraint thereby significantly improves the sensitivity to anomalous couplings.

In the following, we consider only the interactions of a spin-zero boson with the W and Z bosons, for which the scattering amplitude is parameterized as

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{HVV}} + \frac{\kappa_1^{\mathrm{HVV}} q_{\mathrm{V}_1}^2 + \kappa_2^{\mathrm{HVV}} q_{\mathrm{V}_2}^2}{\left(\Lambda_1^{\mathrm{HVV}}\right)^2} \right] m_{\mathrm{V}_1}^2 \epsilon_{\mathrm{V}_1}^* \epsilon_{\mathrm{V}_2}^* + a_2^{\mathrm{HVV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{HVV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}, \tag{1}$$

where the a_i^{HVV} are arbitrary complex coupling parameters which can depend on the V_1 and V_2 squared four-momenta, $q_{\mathrm{V}_1}^2$ and $q_{\mathrm{V}_2}^2$; $f^{(i)\mu\nu}$ is the field strength tensor of a gauge boson with momentum q_{V_i} and polarization vector ϵ_{V_i}, given by $\epsilon_{\mathrm{V}_i}^{\mu} q_{\mathrm{V}_i}^{\nu} - \epsilon_{\mathrm{V}_i}^{\nu} q_{\mathrm{V}_i}^{\mu}$; $\tilde{f}_{\mu\nu}^{(i)}$ is the dual field strength tensor, given by $\frac{1}{2}\epsilon_{\mu\nu\rho\sigma}f^{(i)\rho\sigma}$; m_{V_1} is the pole mass of the vector boson; and Λ_1^{HVV} is the energy scale where phenomena not included in the SM become relevant [19]. The a_1^{HVV}, κ_i^{HVV} and a_2^{HVV} terms represent parity-conserving interactions of a scalar, while the a_3^{HVV} term represents a parity-conserving interaction of a pseudoscalar. In the SM, $a_1^{\mathrm{HVV}} = 2$, which is the only nonzero coupling at tree level. All other terms in Eq. (1) are generated within the SM by loop-induced processes at levels below current experimental sensitivity. Therefore, any evidence for these terms in the available data should be interpreted as evidence of new physics.

We search for an anomalous a_3^{HVV} term of the HVV interaction, assuming that the κ_i^{HVV} and a_2^{HVV} terms are negligible. The effective pseudoscalar cross section fraction for process j (WH, ZH, WW, or ZZ) is defined as

$$f_{a_3}^{j} = \frac{\left|a_3^{\mathrm{HVV}}\right|^2 \sigma_3^j}{\left|a_1^{\mathrm{HVV}}\right|^2 \sigma_1^j + \left|a_3^{\mathrm{HVV}}\right|^2 \sigma_3^j}, \tag{2}$$

where σ_i^j is the production cross-section for process j with $a_i^{\mathrm{HVV}} = 1$ and all other couplings assumed to be equal to zero. A superscript is not included when making a general statement not related to a particular process. The purely scalar (pseudoscalar) case corresponds to $f_{a_3} = 0$ ($f_{a_3} = 1$). The signal strength parameter μ^j for process j can also be defined in terms of the a_i^{HVV} as

$$\mu^j = \frac{\left|a_1^{\mathrm{HVV}}\right|^2 \sigma_1^j + \left|a_3^{\mathrm{HVV}}\right|^2 \sigma_3^j}{\left|a_{1,\mathrm{SM}}^{\mathrm{HVV}}\right|^2 \sigma_1^j}. \tag{3}$$

For a given set of coupling constants, the physical observables $f_{a_3}^j$ and μ^j vary for different processes as a result of the dependence on the σ_i^j. The $f_{a_3}^{\mathrm{ZH}}$ and $f_{a_3}^{\mathrm{WH}}$ variables are defined with respect to the ZH and WH production cross-sections in $\sqrt{s} = 8$ TeV pp collisions, whereas the $f_{a_3}^{\mathrm{VV}}$ variables are defined with respect to the cross-section times branching fraction for the corresponding pp → H → VV process. In the latter case, the dependence on the pp → H cross-section cancels.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the 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. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more 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. [22].

3 Analysis strategy

The analysis is based on a data sample of pp collisions corresponding to an integrated luminosity of 18.9 fb^{-1} at a center-of-mass energy of 8 TeV, collected with single-electron, single-muon, and double-electron triggers. The final states considered are $\ell\nu$jj and $\ell\ell$jj (where j represents a jet), targeting the WH and ZH signals respectively.

The trigger, object and event selection criteria, and background modeling are identical to those of Ref. [23]. Using the selected events, the two-dimensional template method described in Ref. [15] is used to determine f_{a_3} confidence intervals. The discriminant of the boosted decision tree (BDT) described in Ref. [23] serves as one dimension of the templates. This BDT is trained separately for the WH and ZH channels to exploit various kinematic features typical of signal and background, and the correlations among observables. The b-tagging likelihood discriminants of the jets used to construct the Higgs boson candidate, the invariant mass of the Higgs boson candidate, and the angular separation between final state leptons and jets are the most important variables in terms of background rejection. Although initially trained to separate background from a scalar Higgs boson signal, it has been demonstrated with simulated events that the BDT is also effective for signals with anomalous f_{a_3} values. The second dimension of the templates is $m(\mathrm{VH})$. Effectively, the BDT dimension provides a background-depleted region at high values of the BDT discriminant with which to test various signal hypotheses using the $m(\mathrm{VH})$ distribution.

Signal templates in the $\vec{x} = \{\mathrm{BDT}, m(\mathrm{VH})\}$ plane are constructed for arbitrary values of f_{a_3} from a linear superposition of templates representing the pure scalar ($\mathcal{P}_{0^+}(\vec{x})$) and pseudoscalar ($\mathcal{P}_{0^-}(\vec{x})$) hypotheses and a template ($\mathcal{P}^{\mathrm{int}}_{0^+,0^-}(\vec{x};\phi_{a_3})$) that accounts for interference between the a_1^{HVV} and a_3^{HVV} terms in Eq. (1), as follows:

$$\mathcal{P}_{\mathrm{sig}}(\vec{x}; f_{a_3}, \phi_{a_3}) = (1 - f_{a_3})\, \mathcal{P}_{0^+}(\vec{x}) + f_{a_3}\, \mathcal{P}_{0^-}(\vec{x}) + \sqrt{f_{a_3}(1 - f_{a_3})}\, \mathcal{P}^{\mathrm{int}}_{0^+,0^-}(\vec{x}; \phi_{a_3})\,. \tag{4}$$

The phase between the a_1^{HVV} and a_3^{HVV} couplings is represented by ϕ_{a_3}. The interference contributions to the BDT discriminant and $m(\mathrm{VH})$ distributions are negligible, as verified with simulated events. Therefore the last term in Eq. (4) is ignored in the VH channels. Anomalous couplings that result from loops with particles much heavier than the Higgs boson are real valued, allowing phases of 0 and π. In the H $\to$ VV channels, we assume $\phi_{a_3} = 0$. The resulting templates are used to perform profile likelihood scans [24] to assess the consistency of various signal hypotheses with the data. One-dimensional profile likelihood scans of f_{a_3} are performed (where μ is profiled), as well as two-dimensional scans in the μ versus f_{a_3} plane.

In order to combine channels that depend on the a_i^{HZZ} with those depending on the a_i^{HWW}, some assumption on the relationship between the couplings is required, and custodial symmetry is assumed ($a_1^{\mathrm{HZZ}} = a_1^{\mathrm{HWW}}$). It is further assumed that $a_3^{\mathrm{HWW}} = a_3^{\mathrm{HZZ}}$. With these assumptions, the f_{a_3} and μ values in the WH and ZH channels are related by

$$f_{a_3}^{\mathrm{WH}} = \left[1 + \frac{1}{\Omega^{\mathrm{ZH,WH}}}\left(\frac{1}{f_{a_3}^{\mathrm{ZH}}} - 1\right)\right]^{-1} \tag{5}$$

and

$$\mu^{\mathrm{WH}} = \mu^{\mathrm{ZH}}\left[1 + f_{a_3}^{\mathrm{ZH}}\left(\Omega^{\mathrm{ZH,WH}} - 1\right)\right], \tag{6}$$

where

$$\Omega^{\mathrm{ZH,WH}} = \frac{\sigma_1^{\mathrm{ZH}}/\sigma_3^{\mathrm{ZH}}}{\sigma_1^{\mathrm{WH}}/\sigma_3^{\mathrm{WH}}}. \tag{7}$$

The translation constants given by the JHUGEN 4.3 [19, 25, 26] event generator are $\sigma_1^{\mathrm{WH}}/\sigma_3^{\mathrm{WH}} = 0.0174$ and $\sigma_1^{\mathrm{ZH}}/\sigma_3^{\mathrm{ZH}} = 0.0239$. Values of $\Omega^{i,j}$ are given in Table 1. In order to improve the sen-

Table 1: Values of $\Omega^{i,j}$ which relate the channels studied in this paper, as defined in Eq. (7).

$i\,,j$	$\Omega^{i,j}$
ZH , WH	1.37
ZZ , WW	2.11
ZZ , ZH	266
WW , WH	173

sitivity to anomalous couplings, results from the VH channels are combined with those from H → VV [15]. We assume the signal yield in the H → VV analysis to be dominated by gluon fusion production with negligible contamination from vector boson fusion or VH production, as in Ref. [15]. Provided that the ratio of the $\mathrm{Hb\overline{b}}$ and $\mathrm{Ht\bar{t}}$ coupling strengths is given by the SM prediction, Eq. (6) can be used to relate the signal strength in the VH and H → VV analyses, with an appropriate change of indices (replacing 'WH' with 'ZZ' to relate the ZZ and ZH channels, or 'ZH' with 'WW' to relate the WW and WH channels). For the H → VV channels, JHUGEN gives $\sigma_1^{\mathrm{WW}}/\sigma_3^{\mathrm{WW}} = 3.01$ and $\sigma_1^{\mathrm{ZZ}}/\sigma_3^{\mathrm{ZZ}} = 6.36$. The corresponding $\Omega^{i,j}$ values are given in Table 1. In the combination of the WH and H → WW channels, the ratio of the signal strengths $\mu^{\mathrm{WH}}/\mu^{\mathrm{WW}}$ increases linearly from 1 to 173 as $f_{a_3}^{\mathrm{WW}}$ increases from 0 to 1, according to Eq. (6). The WH signal strength has been measured by CMS to be 1.1 ± 0.9 [23], and for H → WW it has been measured to be 0.76 ± 0.21 [13]. Thus, for intermediate and large values of $f_{a_3}^{\mathrm{WW}}$ it is not possible to reconcile the expected signal yield with data in both channels simultaneously. A similar effect occurs in a combination of the ZH and H → ZZ channels, where the ratio of the signal strengths $\mu^{\mathrm{ZH}}/\mu^{\mathrm{ZZ}}$ rises sharply with $f_{a_3}^{\mathrm{ZZ}}$.

However, an anomalous ratio of the $\mathrm{Hb\overline{b}}$ and $\mathrm{Ht\bar{t}}$ coupling strengths spoils the relationship in Eq. (6). We therefore perform two interpretations of the VH and H → VV combination; one interpretation in which this relationship is enforced, and one interpretation in which the signal strengths in the VH and H → VV channels are allowed to vary independently. These are referred to as the 'correlated-μ' and 'uncorrelated-μ' combinations, respectively.

4 Simulation

Simulated qq → VH signal events are generated for pure scalar and pseudoscalar hypotheses with the leading-order (LO) event generator JHUGEN, and assuming a mass $m_{\mathrm{H}} = 125.6\,\mathrm{GeV}$. The simulated event sample is reweighted to include corrections up to next-to-next-to-LO and next-to-LO (NLO) in the QCD and electroweak (EW) couplings respectively [27–31]. These corrections are derived for a scalar Higgs boson, and applied to both scalar and pseudoscalar simulated event samples.

The gg → ZH process includes diagrams with quark triangle and box loops, as shown in Fig. 1. These diagrams interfere destructively with one another [32]. The box diagram contains no HVV vertex. The triangle diagram does, but is unaffected by the a_3^{HVV} term in Eq. (1). The triangle diagram mediated by a CP-odd HVV interaction is completely anti-symmetric under the reversal of the direction of loop momentum flow; the diagrams with opposite loop momentum flow therefore perfectly cancel one another. As the a_1^{HZZ} coupling varies within a profile likelihood scan, the box contribution remains fixed while the triangle contribution and the interference must be varied accordingly. This is accomplished by reweighting the simulated gg → ZH event sample to have the correct $m(\mathrm{VH})$ distribution at the generator level, including interference effects. This reweighting is based on results obtained with the VBFNLO event generator [32, 33], modified for this analysis to allow variation of the $\mathrm{Hf\bar{f}}$ and HZZ coupling strengths.

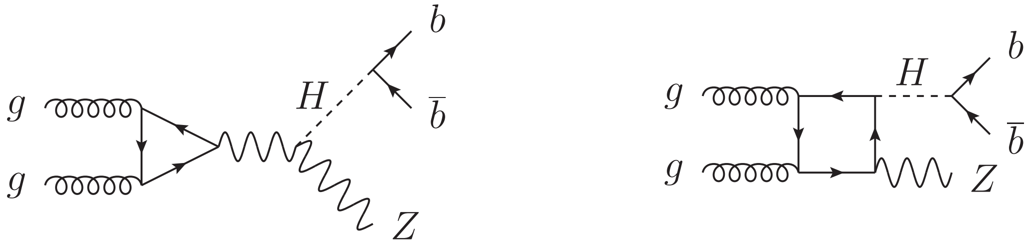

Figure 1: Feynman diagrams representing gluon-initiated ZH production via a quark triangle (left) and box (right) loop.

Simulated background event samples are generated with a variety of event generators. Diboson, W+jets, Z+jets, and $\mathrm{t\bar{t}}$ samples are generated with MADGRAPH 5.1 [34], while POWHEG 1.0 [35] is used to generate single top quark samples, as well as the gluon-initiated contribution to ZH production (gg → ZH). The HERWIG++ 2.5 [36] generator is used along with alternative matrix element generators to produce additional simulated background samples to assess the systematic uncertainty related to event simulation accuracy, as described in Section 6.

The PYTHIA 6.4 [37] and HERWIG++ generators are used to simulate parton showering and hadronization. Detector simulation is performed with GEANT4 [38]. Uncorrelated proton-proton collisions occurring in the same bunch crossing as the signal event (pileup) are overlayed on top of the hard interaction, in accord with the distribution observed. Corrections are applied to the simulation in order to account for differences in object reconstruction efficiencies and resolutions with respect to the data.

Control regions in data are defined in Ref. [23], from which normalization scale factors for the dominant backgrounds are derived. A simultaneous fit to data across control regions is performed to extract the scale factors, which are applied here. The shape of the W (V) boson transverse momentum p_{T} distribution is corrected in the simulated $\mathrm{t\bar{t}}$ (V+jets) event sample, based on a fit to data in a background-enriched control region.

5 Object and event selection

All objects are reconstructed using a particle-flow (PF) approach [39, 40]. Among all reconstructed primary vertices satisfying basic quality criteria, the vertex with the largest value of $\sum p_{\mathrm{T}}^2$ is selected. Electrons are reconstructed from inner detector tracks matched to calorimeter superclusters, and selected with a multivariate identification algorithm [41]. Electrons are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and pseudorapidity $|\eta| < 2.5$, with a veto applied to the barrel-endcap transition region ($1.44 < |\eta| < 1.57$) where electron reconstruction is sub-optimal. Muons are reconstructed from inner detector tracks matched to tracks reconstructed in the muon system, and selected with a cut-based identification algorithm [42]. Muons are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.4$. Both electrons and muons are required to be well isolated from other reconstructed objects. Jets are reconstructed using the anti-k_t algorithm [43], with a distance parameter of 0.5, from the reconstructed objects, after removing charged objects with a trajectory inconsistent with production at the primary vertex. Additionally, the energy

Table 2: Summary of the event selection criteria. Numbers in parentheses refer to the high-boost region defined in the text.

Variable	$W \to \ell\nu$	$Z \to \ell\ell$
$p_T(j_1)$ [GeV]	>30	>20
$p_T(j_2)$ [GeV]	>30	>20
max(CSV(j_1),CSV(j_2))	>0.40	>0.50 (>0.244)
min(CSV(j_1),CSV(j_2))	>0.40	>0.244
p_T(H) [GeV]	>100	—
m(H) [GeV]	<250	40 – 250 (<250)
m(V) [GeV]	—	75 – 105
p_T(V) [GeV]	130 – 180 (>180)	50 – 100 (>100)
E_T^{miss} [GeV]	>45	—
$\Delta\Phi(E_T^{miss}, \ell)$	$<\pi/2$	—

contribution from neutral pileup activity is subtracted with an area-based approach [44]. Jets are tagged as originating from the fragmentation and hadronization of bottom quarks with the combined secondary vertex (CSV) algorithm [45], which exploits both the track impact parameter and secondary vertex information. Missing transverse energy E_T^{miss} is reconstructed as the negative vector p_T sum of all reconstructed objects.

Events are categorized based on the flavour and number of charged leptons into four channels. Events with two same-flavour, opposite-sign electrons (muons) are assigned to the $Z \to ee$ ($Z \to \mu\mu$) channel. Events with one electron (muon) and large E_T^{miss} are assigned to the $W \to e\nu$ ($W \to \mu\nu$) channel. In the $W \to \ell\nu$ ($Z \to \ell\ell$) channels, Higgs boson candidates are constructed from the pair of jets (referred to as j_1 and j_2) with the largest vector p_T sum among jets with $p_T >$ 30 (20) GeV and $|\eta| < 2.5$. The Z boson candidates are constructed from lepton pairs whose invariant mass is consistent with the Z boson mass. The W boson candidates are constructed by combining the momentum of the identified lepton with the event E_T^{miss}, and calculating the neutrino momentum along the beam axis based on a W boson mass constraint. To suppress contributions from QCD multijet events, in the $W \to \ell\nu$ channels the magnitude of the E_T^{miss} vector must exceed 45 GeV and it must be separated in direction from the charged lepton by less than $\pi/2$ radians in azimuth. In addition, the Higgs boson candidate p_T must exceed 100 GeV.

The analysis sensitivity is increased further by categorizing events into medium- and high-boost regions based on the p_T of the vector boson candidate to increase the analysis sensitivity. The bulk of the sensitivity comes from the high-boost region. These regions are later combined statistically. In the $W \to \ell\nu$ channels, the medium- and high-boost regions are defined by $130 < p_T(W) < 180$ GeV and $p_T(W) > 180$ GeV, respectively. In the $Z \to \ell\ell$ channels, the regions are instead defined by $50 < p_T(Z) < 100$ GeV and $p_T(Z) > 100$ GeV. The low-boost region described in Ref. [23] is not included because of its negligible sensitivity to anomalous couplings. Requirements on the Higgs boson candidate mass and the b-tagging likelihood discriminants of the jets used to construct the Higgs boson candidate are also applied. The selection criteria are summarized in Table 2.

The expected scalar, pseudoscalar, and total background templates for the high-boost $W \to e\nu$ channel are shown in Fig. 2. One-dimensional projections of the templates for the high-boost $W \to \mu\nu$ and $Z \to ee$ channels onto the m(VH) axis are shown in Fig. 3. The discrimination power of $m(\mathrm{VH})$ for the scalar and pseudoscalar hypotheses can be seen clearly; the pseudoscalar hypothesis tends to produce larger values of $m(\mathrm{VH})$ than the scalar hypothesis.

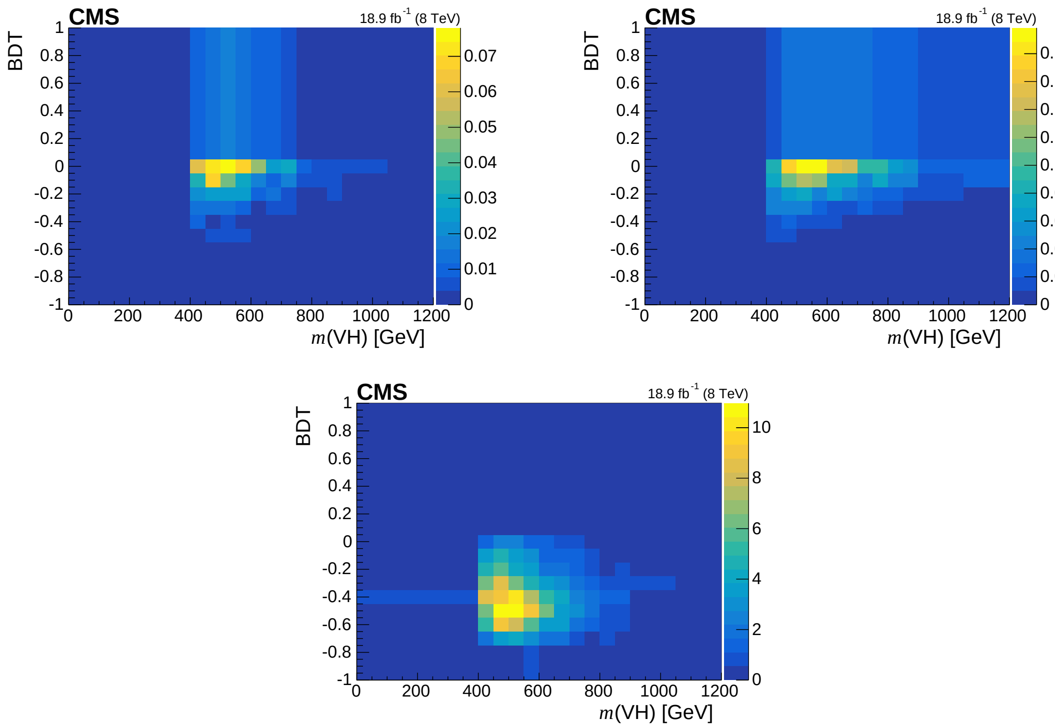

Figure 2: The scalar (left), pseudoscalar (right), and total background (bottom) templates for the high-boost W $\rightarrow e\nu$ channel. Bin content is normalized according to the bin area.

6 Systematic uncertainties

A variety of sources of uncertainty are considered in this analysis. These include the energy scale, energy resolution, and reconstruction efficiencies of the relevant physics objects; integrated luminosity determination; cross section and background normalization scale factor uncertainties; and the accuracy and finite size of the simulated event samples. The treatment of most uncertainties is identical to that of Ref. [23], with the exceptions discussed below. All uncertainties are summarized in Table 3.

Uncertainties are assigned to both the scalar and pseudoscalar signal yields, related to the calculation of higher-order QCD and EW corrections. In the pseudoscalar case, the uncertainty in the NLO EW corrections is taken to be the size of the corrections for a scalar Higgs boson. A slight mismodeling of the $m(\mathrm{VH})$ distribution is observed in a sideband of the medium-boost regions with values of the BDT discriminant less than -0.3. This sideband has negligible signal content. The ratio of data to the background prediction has an approximately constant, positive slope. As a result, an additional $m(\mathrm{VH})$ modeling systematic uncertainty is included, which allows for a linear correction of the background model. The size of this uncertainty is taken as twice the size of the fitted slope in the associated sideband, and the uncertainty in each of the four regions is treated as uncorrelated.

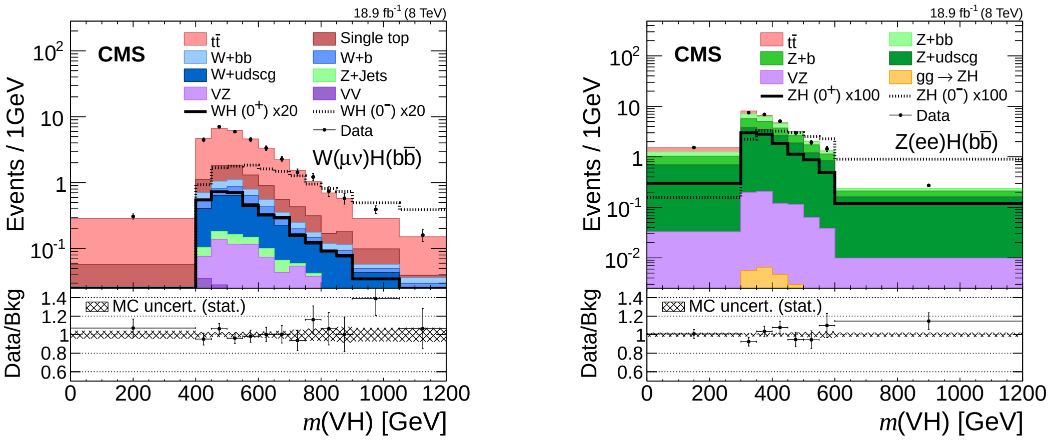

Figure 3: The $m(\mathrm{VH})$ distributions for the high-boost region of the $\mathrm{W} \to \mu\nu$ (left) and $\mathrm{Z} \to \mathrm{ee}$ (right) channels. The distribution observed in data is represented by points with error bars. SM backgrounds are represented by filled histograms. A pure scalar (pseudoscalar) Higgs boson signal is represented by the solid (dotted) histogram. The statistical uncertainty related to the finite size of the simulated background event samples is represented by the hatched region. Values of $m(\mathrm{VH}) > 1200\,\mathrm{GeV}$ are included in the last bin. The bin content is normalized according to the bin width. The lower panel shows the ratio of the observed and expected background yields.

Table 3: Summary of the sources of systematic uncertainty on the background and signal yields. The size of the uncertainties that only affect normalizations are given. Uncertainties that also affect the shapes are implemented with template morphing, a smooth vertical interpolation between the nominal shape and systematic shape variations.

Source	Pre-fit uncertainty
Normalization uncertainties	
Integrated luminosity	2.6%
Lepton reconstruction and trigger efficiency	3% per ℓ
Missing transverse energy scale and resolution	3%
Signal and background cross section (scale)	4–6%
Signal and background parton distribution functions	1%
0^+ (0^-) EW/QCD signal corrections	2%/5% (10%/5%)
tt̄ and V +jets data-driven scale factors	10%
Single top quark cross section	15%
Diboson cross section	15%
gg → ZH cross section	$^{+35\%}_{-25\%}$
Normalization + shape uncertainties	
Jet energy scale	$\pm 1\sigma$
Jet energy resolution	$\pm 1\sigma$
b tagging efficiency	$\pm 1\sigma$
b tagging mistag rate	$\pm 1\sigma$
Simulated event statistics	$\pm 1\sigma$
Event simulation accuracy (V+jets and tt̄)	Alternate event simulation
$m(\mathrm{VH})$ modeling	$\pm 2 \times$ fitted slope

7 Results

Results of one-dimensional profile likelihood scans in the VH channels are shown in Fig. 4, in terms of $f_{a_3}^{\mathrm{ZH}}$. Throughout the paper, expected results are derived from an Asimov data set [46] for a pure scalar Higgs boson with $\mu = 1$. This dataset represents the expectation for an SM Higgs boson in the asymptotic limit of large statistics. The combined VH scan assumes $a_i^{\mathrm{HWW}} = a_i^{\mathrm{HZZ}}$.

The expected $-2\Delta\ln\mathcal{L}$ values reach a plateau above $f_{a_3}^{\mathrm{ZH}} \approx 0.3$, as a result of the small σ_1/σ_3 values in the VH channels. Even for modest values of $f_{a_3}^{\mathrm{ZH}}$, the total signal cross section, and therefore the $m(\mathrm{VH})$ shape, is dominated by the pseudoscalar contribution. Increasing $f_{a_3}^{\mathrm{ZH}}$ further has little impact on the $m(\mathrm{VH})$ shape, and therefore the likelihood.

Based on the available data, the VH channels alone do not have sufficient sensitivity to derive any constraint on f_{a_3} at 95% CL. Although there is some discrepancy between the expected and observed scans, all observed results are consistent with the SM prediction of $f_{a_3} = 0$. This discrepancy is driven by a modest excess (deficit) at high (low) values of $m(\mathrm{VH})$ in a selected number of background-depleted bins in the high-boost $\mathrm{Z} \to \mathrm{ee}$ and $\mathrm{W} \to \mu\nu$ channels, which is consistent with the SM prediction within statistical and systematic uncertainties.

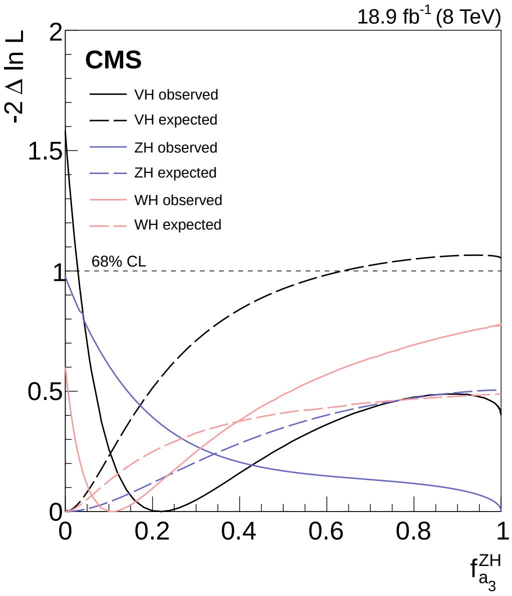

Figure 4: Results of profile likelihood scans for the WH and ZH channels, as well as the combination (VH). The dotted (solid) lines show the expected (observed) -2Δln$\mathcal{L}$ value as a function of $f_{a_3}^{\mathrm{ZH}}$. A horizontal dashed line is shown, representing the 68% CL.

Results from the VH channels are combined with results from the $\mathrm{H} \to \mathrm{VV}$ channels [15], with and without assuming the SM ratio of the $\mathrm{Hb\bar{b}}$ and $\mathrm{Ht\bar{t}}$ coupling strengths. Combined profile likelihood scans are shown in Figs. 5 and 6, in terms of $f_{a_3}^{\mathrm{ZZ}}$ or $f_{a_3}^{\mathrm{WW}}$. The $-2\Delta\ln\mathcal{L}$ distributions shown here for the VH channels alone are the same as those shown in Fig. 4, after a transformation of the x-axis to $f_{a_3}^{\mathrm{WW}}$ or $f_{a_3}^{\mathrm{ZZ}}$. These transformations compress (stretch) the low (high) f_{a_3} region, resulting in the distributions shown. The position of the $-2\Delta\ln\mathcal{L}$ minima and f_{a_3} confidence intervals are given in Table 4.

The WH (ZH) channel is first combined with the H → WW (H → ZZ) channel, enhancing the sensitivity to anomalous HWW (HZZ) interactions, without the need to introduce any assumption on the relationship between HWW and HZZ couplings. These results are shown in the upper (lower) portion of Fig. 5. The H → WW channel alone is not able to constrain f_{a_3} at 68% CL. However, in the uncorrelated-μ combination of the WH and H → WW channels, $f_{a_3}^{\mathrm{WW}} > 0.21$ is disfavoured at 68% CL. Due to the modest preference in the ZH channel for large f_{a_3}, the uncorrelated-μ combination of the ZH and H → ZZ channels results in a bound on f_{a_3} that is slightly weaker than that from the H → ZZ channel alone.

All four channels are combined under the assumption $a_i^{\mathrm{HWW}} = a_i^{\mathrm{HZZ}}$. The results of this uncorrelated-μ combination are shown in the top of Fig. 6. A slight improvement over the constraint from the H → VV channels alone is observed, with $f_{a_3}^{\mathrm{ZZ}} > 0.25$ excluded at 95% CL.

Correlated-μ combinations of the VH and H → VV channels are performed as well, which are based on the assumption of the SM ratio of the $\mathrm{Hb\bar{b}}$ and $\mathrm{Ht\bar{t}}$ coupling strengths. This assumption fixes the relationship between the signal strengths in the VH and H → VV channels. As a result of the relatively well measured signal strengths in the H → VV channels, for intermediate and large values of f_{a_3} the signal strengths in the VH channels are constrained to large values, and such a signal cannot be accommodated by the data. The results are shown in the bottom of Fig. 6. Relative to the f_{a_3} exclusions obtained from the H → VV channels alone, the results obtained here are significantly stronger, with $f_{a_3}^{\mathrm{ZZ}} > 0.0034$ excluded at 95% CL in the full combination of all channels.

The future power of the VH channels at probing small anomalous HVV couplings is demonstrated on the right side of Figs. 5 and 6. Although the expected exclusion of anomalous couplings in these channels is only at the ~ 68 % CL level with the current 8 TeV dataset, the $-2\Delta\ln\mathcal{L}$ values increase sharply for small, non-zero values of $f_{a_3}^{\mathrm{ZZ}}$ and reach a plateau at $f_{a_3}^{\mathrm{ZZ}} \approx 0.05$. With the inclusion of $\sqrt{s} = 13\,\mathrm{TeV}$ collision data from the ongoing LHC run, the shape of these $-2\Delta\ln\mathcal{L}$ distributions will not change significantly, but the plateau will reach larger values of $-2\Delta\ln\mathcal{L}$. As soon as the exclusion of a pure pseudoscalar becomes possible, it will be possible to exclude small values of $f_{a_3}^{\mathrm{ZZ}}$ as well.

Results of two-dimensional profile likelihood scans in the μ^{ZH} versus $f_{a_3}^{\mathrm{ZH}}$ plane based on a combination of WH and ZH channels are shown in Fig. 7. Smaller μ^{ZH} values are preferred with increasing $f_{a_3}^{\mathrm{ZH}}$ as a result of increasing signal efficiency, due to the harder $m(\mathrm{VH})$ distribution of a potential pseudoscalar signal compared to that of a scalar. The minimum of the -2Δln$\mathcal{L}$ values corresponds to $\mu^{\mathrm{ZH}} = 1.11$ and $f_{a_3}^{\mathrm{ZH}} = 0.22$.

Finally, we allow for the modification of the a_3^{HVV} couplings by a momentum-dependent form factor [19], given by

$$\left[\left(1+\frac{q_{\mathrm{V}_1}^2}{\Lambda^2}\right)^2\left(1+\frac{q_{\mathrm{V}_2}^2}{\Lambda^2}\right)^2\right]^{-1}, \tag{8}$$

where Λ represents a scale of new physics at which the a_3^{HVV} coupling can no longer be treated as a constant. Unlike earlier results in H → VV [15] where the vector boson q^2 is restricted to $\lesssim 100\,\mathrm{GeV}$, in VH production much larger values are accessible. This fact is responsible for much of the sensitivity of this analysis, but also necessitates the consideration of form factor effects. Profile likelihood scans based on a combination of the WH and ZH channels for various values of Λ are shown in Fig. 8.

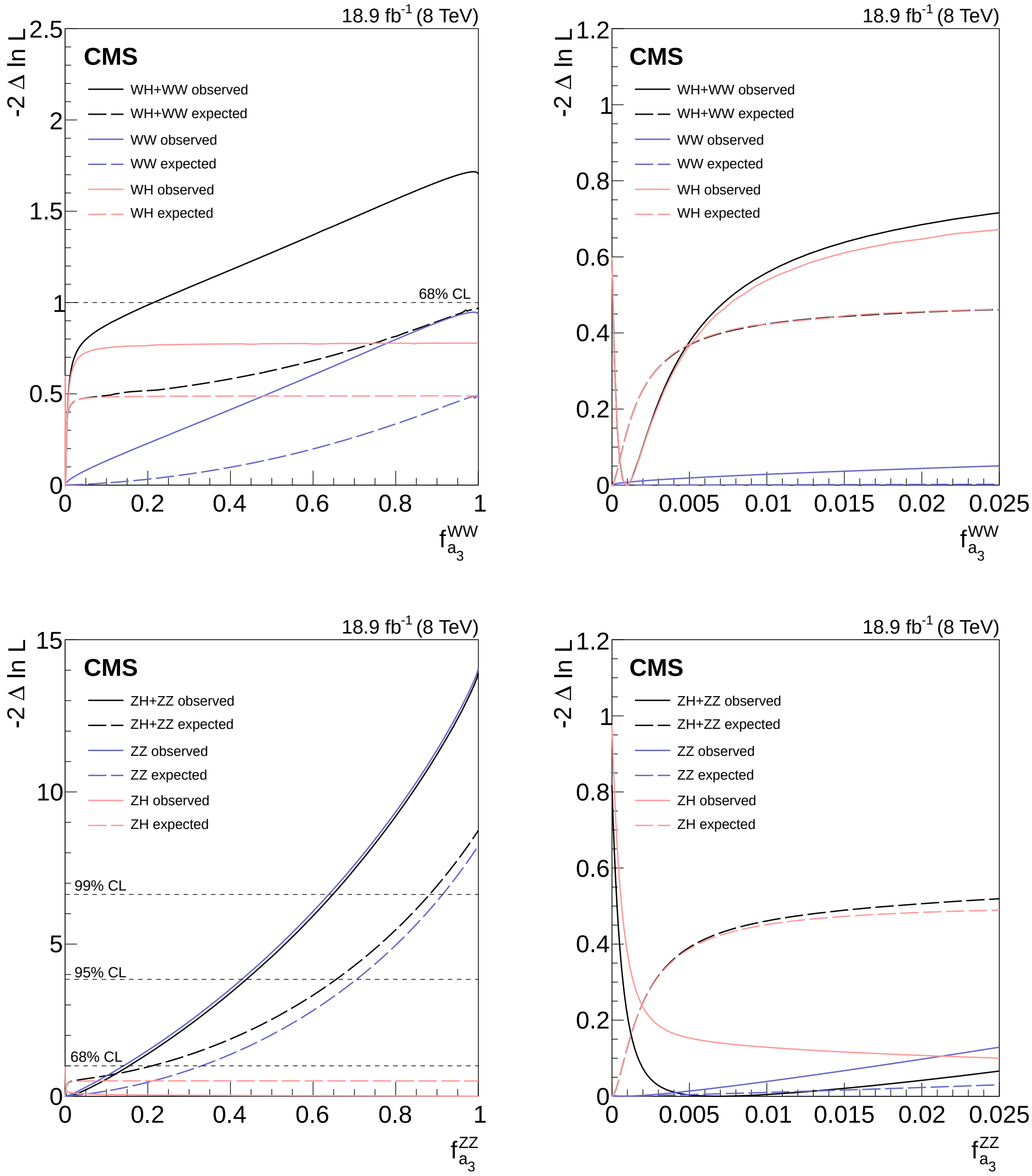

Figure 5: Results of profile likelihood scans for the VH and VV channels, plus their combination. The dotted (solid) lines show the expected (observed) -2$\Delta\ln\mathcal{L}$ value as a function of f_{a_3}. The full range of f_{a_3} is shown on the left, with the low f_{a_3} region highlighted on the right. Horizontal dashed lines represent the 68%, 95%, and 99% CL.

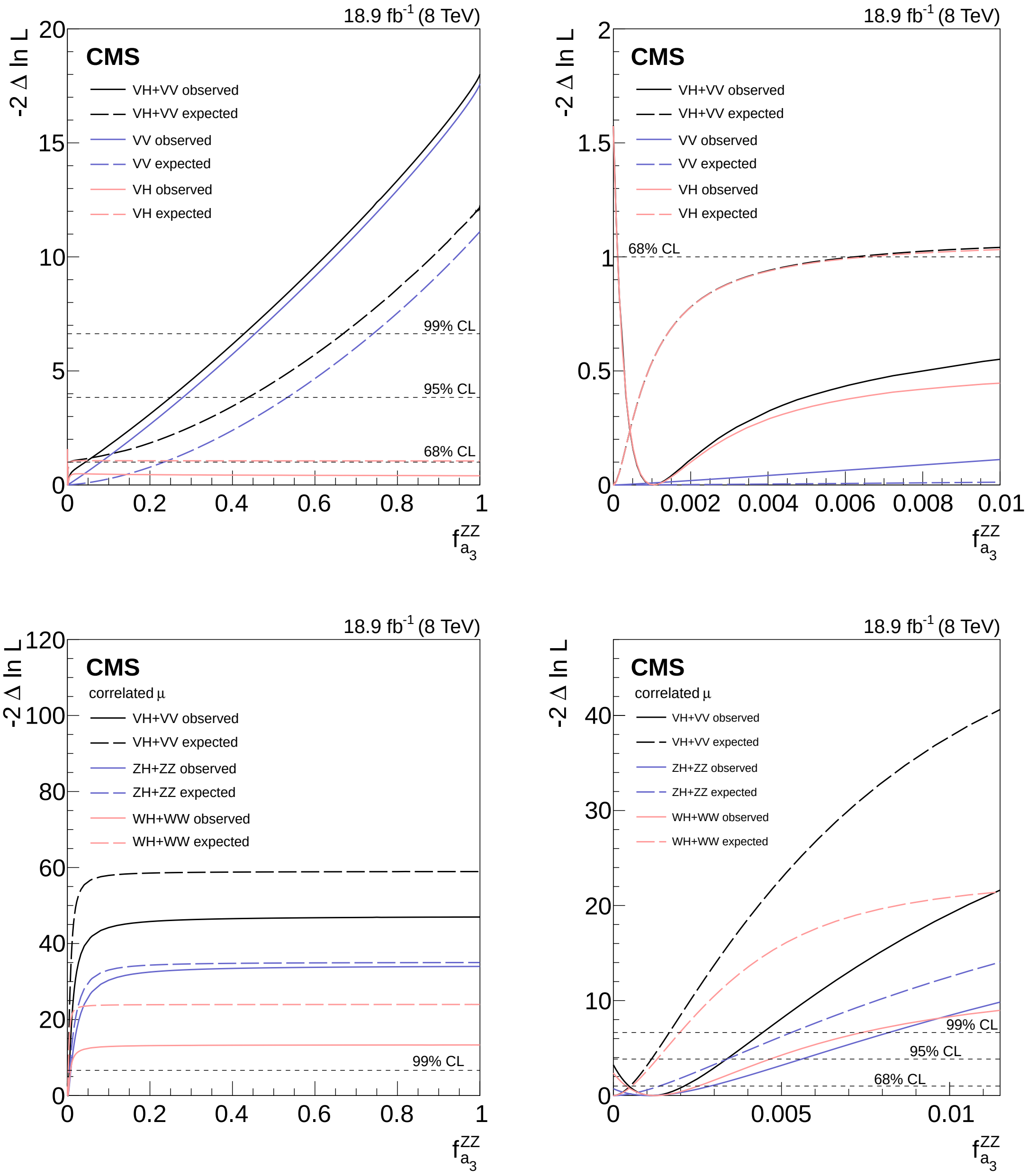

Figure 6: Results of profile likelihood scans for the VH and VV channels, as well as their combination. The dotted (solid) lines show the expected (observed) -2$\Delta\ln\mathcal{L}$ value as a function of f_{a_3}. The full range of f_{a_3} is shown on the left, with the low f_{a_3} region highlighted on the right. The bottom plots contain the results of correlated-μ scans. Horizontal dashed lines represent the 68%, 95%, and 99% CL. In the legend, VH refers to the combination of the WH and ZH channels, and VV refers to the combination of the H → WW and H → ZZ channels.

Table 4: A summary of the locations of the minimum -2$\Delta\ln\mathcal{L}$ values in one-dimensional f_{a_3} profile likelihood scans. Parentheses contain 68% CL intervals, and brackets contain 95% CL intervals. The ranges are truncated at the physical boundaries $0 < f_{a_3} < 1$. The results of combinations which involve both VH and H → VV channels are given with and without assuming the SM ratio of the coupling strengths of the Higgs boson to top and bottom quarks.

Channel	Parameter	Expected	Observed
VH	$f_{a_3}^{\mathrm{ZH}}$	0 (0, 0.64) [0, 1]	0.22 (0.029, 1) [0, 1]
		Correlated-μ combination	
WH + H → WW	$f_{a_3}^{\mathrm{WW}}$	0 (0, 0.0012) [0, 0.0027]	0.0026 (0.00082, 0.0053) [0, 0.0098]
ZH + H → ZZ	$f_{a_3}^{\mathrm{ZZ}}$	0 (0, 0.0014) [0, 0.0034]	0.0011 (0, 0.0029) [0, 0.0056]
VH + H → VV	$f_{a_3}^{\mathrm{ZZ}}$	0 (0, 0.00050) [0, 0.0011]	0.0012 (0.00047, 0.0021) [0, 0.0034]
		Uncorrelated-μ combination	
WH + H → WW	$f_{a_3}^{\mathrm{WW}}$	0 (0, 1) [0, 1]	0.00088 (0, 0.21) [0, 1]
ZH + H → ZZ	$f_{a_3}^{\mathrm{ZZ}}$	0 (0, 0.21) [0, 0.66]	0.0067 (0, 0.16) [0, 0.44]
VH + H → VV	$f_{a_3}^{\mathrm{ZZ}}$	0 (0, 0.0062) [0, 0.44]	0.0010 (0.00011, 0.043) [0, 0.25]

For $\Lambda \gtrsim 10$ TeV, a potential momentum-dependent form factor has a negligible impact on the analysis. But for smaller values of Λ, the tail of the $m(\mathrm{VH})$ distribution is diminished, and along with it the sensitivity to anomalous couplings. However, even for Λ values as small as 1 TeV, the VH channels maintain significant sensitivity.

8 Summary

A search has been performed for anomalous pseudoscalar HVV interactions in $\sqrt{s} = 8$ TeV pp data collected with the CMS detector. This is the first study of such interactions at the LHC in associated VH production. The VH channels alone do not currently have sufficient sensitivity to constrain the effective pseudoscalar cross section fractions f_{a_3} at 95% CL. In a combination of the VH and H → VV channels, when assuming the absence of additional anomalous Higgs boson couplings and treating the scalar a_1^{HVV} and pseudoscalar a_3^{HVV} couplings as constants, $f_{a_3}^{\mathrm{ZZ}} > 0.0034$ is excluded at 95% CL. This exclusion represents a significant improvement with respect to previous results.

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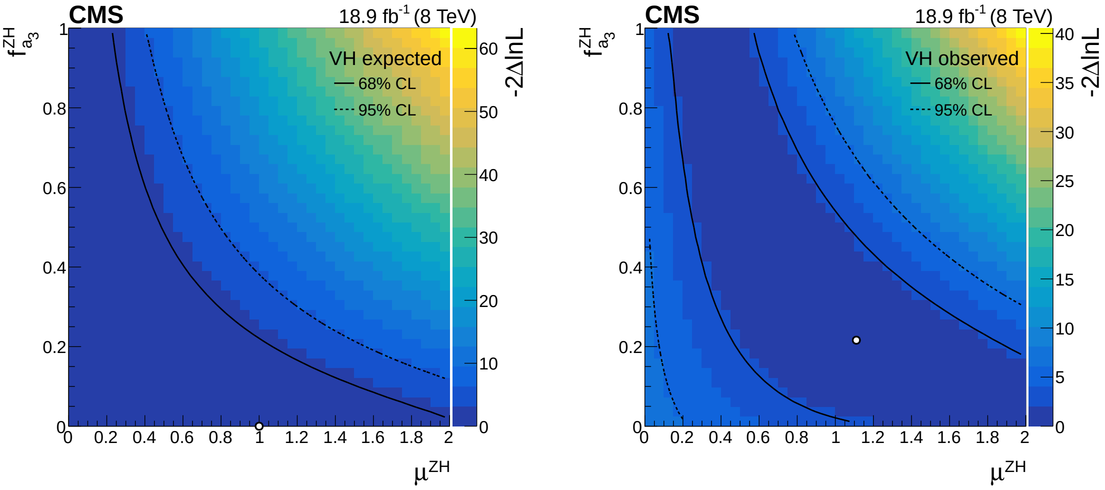

Figure 7: Expected (left) and observed (right) two-dimensional profile likelihood scans based on a combination of the WH and ZH channels in the $f_{a_3}^{ZH}$ versus μ^{ZH} plane. The colour coding represents $-2\Delta\ln\mathcal{L}$ calculated with respect to the global minimum. The scan minimum is indicated by a white dot. The 68% and 95% CL contours at $-2\Delta\ln\mathcal{L} = 2.30$ and 5.99, respectively, are shown. The observed result includes upper and lower bounds while the expected result contains only upper bounds, as the expected result is consistent with $f_{a_3}^{ZH} = 0$ at 68% CL.

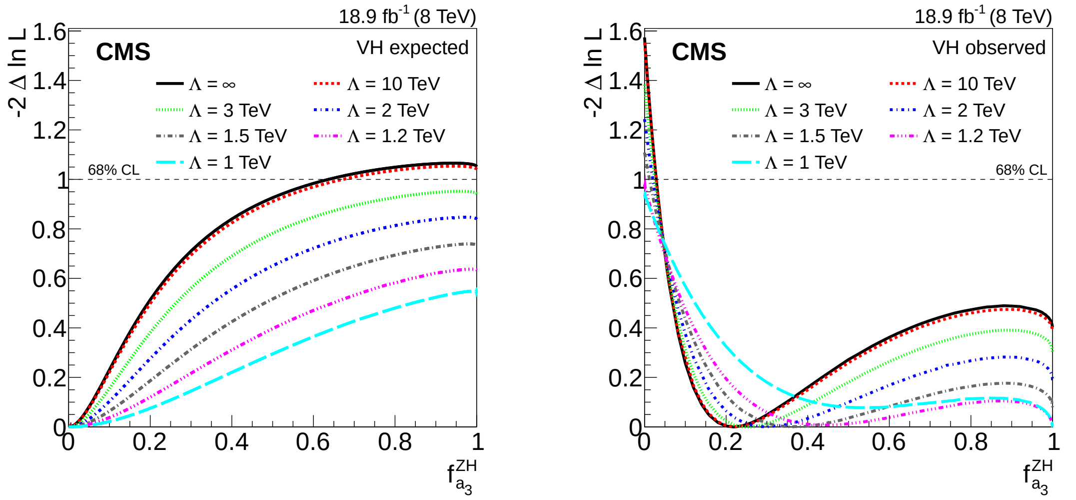

Figure 8: Results of expected (left) and observed (right) $f_{a_3}^{ZH}$ scans based on a combination of the WH and ZH channels, with various scales of new physics Λ. The coloured lines show the -2Δln$\mathcal{L}$ value as a function of $f_{a_3}^{ZH}$. The horizontal dashed line represents the 68% CL.

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References

[1] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, `doi:10.1016/j.physletb.2012.08.020`, `arXiv:1207.7214`.

[2] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, `doi:10.1016/j.physletb.2012.08.021`, `arXiv:1207.7235`.

[3] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **06** (2013) 081, `doi:10.1007/JHEP06(2013)081`, `arXiv:1303.4571`.

[4] S. L. Glashow, "Partial-symmetries of weak interactions", *Nucl. Phys.* **22** (1961) 579, `doi:10.1016/0029-5582(61)90469-2`.

[5] F. Englert and R. Brout, "Broken symmetry and the mass of gauge vector mesons", *Phys. Rev. Lett.* **13** (1964) 321, `doi:10.1103/PhysRevLett.13.321`.

[6] P. W. Higgs, "Broken symmetries, massless particles and gauge fields", *Phys. Lett.* **12** (1964) 132, `doi:10.1016/0031-9163(64)91136-9`.

[7] P. W. Higgs, "Broken symmetries and the masses of gauge bosons", *Phys. Rev. Lett.* **13** (1964) 508, `doi:10.1103/PhysRevLett.13.508`.

[8] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, "Global conservation laws and massless particles", *Phys. Rev. Lett.* **13** (1964) 585, `doi:10.1103/PhysRevLett.13.585`.

[9] S. Weinberg, "A model of leptons", *Phys. Rev. Lett.* **19** (1967) 1264, `doi:10.1103/PhysRevLett.19.1264`.

[10] A. Salam, "Weak and electromagnetic interactions", in *Elementary particle physics: relativistic groups and analyticity*, N. Svartholm, ed., p. 367. Almqvist & Wiksell, Stockholm, 1968. Proceedings of the eighth Nobel symposium.

[11] CMS Collaboration, "On the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs", *Phys. Rev. Lett.* **110** (2013) 081803, `doi:10.1103/PhysRevLett.110.081803`, `arXiv:1212.6639`.

[12] CMS Collaboration, "Measurement of the properties of a Higgs boson in the four-lepton final state", *Phys. Rev. D* **89** (2014) 092007, `doi:10.1103/PhysRevD.89.092007`, `arXiv:1312.5353`.

[13] CMS Collaboration, "Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states", *JHEP* **01** (2014) 096, `doi:10.1007/JHEP01(2014)096`, `arXiv:1312.1129`.

[14] CMS Collaboration, "Observation of the diphoton decay of the Higgs boson and measurement of its properties", *Eur. Phys. J. C* **74** (2014) 3076, `doi:10.1140/epjc/s10052-014-3076-z`, `arXiv:1407.0558`.

[15] CMS Collaboration, "Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV", *Phys. Rev. D* **92** (2015) 012004, `doi:10.1103/PhysRevD.92.012004`, `arXiv:1411.3441`.

[16] ATLAS Collaboration, "Evidence for the spin-0 nature of the Higgs boson using ATLAS data", *Phys. Lett. B* **726** (2013) 120, `doi:10.1016/j.physletb.2013.08.026`, `arXiv:1307.1432`.

[17] CDF and D0 Collaborations, "Tevatron constraints on models of the Higgs boson with exotic spin and parity using decays to bottom-antibottom quark pairs", *Phys. Rev. Lett.* **114** (2015) 151802, `doi:10.1103/PhysRevLett.114.151802`, `arXiv:1502.00967`.

[18] ATLAS Collaboration, "Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector", *Eur. Phys. J. C* **75** (2015) 476, `doi:10.1140/epjc/s10052-015-3685-1`, `arXiv:1506.05669`.

[19] I. Anderson et al., "Constraining anomalous HVV interactions at proton and lepton colliders", *Phys. Rev. D* **89** (2014) 035007, `doi:10.1103/PhysRevD.89.035007`, `arXiv:1309.4819`.

[20] J. Ellis, D. S. Hwang, V. Sanz, and T. You, "A fast track towards the 'Higgs' spin and parity", *JHEP* **11** (2012) 134, `doi:10.1007/JHEP11(2012)134`, `arXiv:1208.6002`.

[21] R. M. Barnett, G. Senjanović, L. Wolfenstein, and D. Wyler, "Implications of a light Higgs scalar", *Phys. Lett. B* **136** (1984) 191, `doi:10.1016/0370-2693(84)91179-1`.

[22] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, `doi:10.1088/1748-0221/3/08/S08004`.

[23] CMS Collaboration, "Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks", *Phys. Rev. D* **89** (2014) 012003, `doi:10.1103/PhysRevD.89.012003`, `arXiv:1310.3687`.

[24] ATLAS and CMS Collaborations, "Procedure for the LHC Higgs boson search combination in summer 2011", Technical Report ATL-PHYS-PUB-2011-011, CMS NOTE-2011/005, (2011).

[25] S. Bolognesi et al., "On the spin and parity of a single-produced resonance at the LHC", *Phys. Rev. D* **86** (2012) 095031, `doi:10.1103/PhysRevD.86.095031`, `arXiv:1208.4018`.

[26] Y. Gao et al., "Spin determination of single-produced resonances at hadron colliders", *Phys. Rev. D* **81** (2010) 075022, `doi:10.1103/PhysRevD.81.075022`, `arXiv:1001.3396`.

[27] T. Han and S. Willenbrock, "QCD correction to the pp → WH and ZH total cross-sections", *Phys. Lett. B* **273** (1991) 167, `doi:10.1016/0370-2693(91)90572-8`.

[28] W. L. van Neerven and E. B. Zijlstra, "The $\mathcal{O}(\alpha_S^2)$ corrected Drell-Yan K-factor in the DIS and MS schemes", *Nucl. Phys. B* **382** (1992) 11, `doi:10.1016/0550-3213(92)90078-P`.

[29] O. Brein, R. V. Harlander, M. Wiesemann, and T. Zirke, "Top-quark mediated effects in hadronic Higgs-Strahlung", *Eur. Phys. J. C* **72** (2012) 1, `doi:10.1140/epjc/s10052-012-1868-6`, `arXiv:1111.0761`.

[30] LHC Higgs Cross Section Working Group, "Handbook of LHC Higgs cross sections: 2. Differential distributions", CERN Report CERN-2012-002, 2012. `arXiv:1201.3084`.

[31] M. L. Ciccolini, S. Dittmaier, and M. Kramer, "Electroweak radiative corrections to associated WH and ZH production at hadron colliders", *Phys. Rev. D* **68** (2003) 073003, `doi:10.1103/PhysRevD.68.073003`, `arXiv:hep-ph/0306234`.

[32] C. Englert, M. McCullough, and M. Spannowsky, "Gluon-initiated associated production boosts Higgs physics", *Phys. Rev. D* **89** (2014) 013013, `doi:10.1103/PhysRevD.89.013013`, `arXiv:1310.4828`.

[33] K. Arnold et al., "VBFNLO: A parton level Monte Carlo for processes with Electroweak bosons", *Comput. Phys. Commun.* **180** (2009) 1661, `doi:10.1016/j.cpc.2009.03.006`, `arXiv:0811.4559`. See also `arXiv:1404.3940` and `arXiv:1107.4038`.

[34] J. Alwall et al., "MadGraph 5: going beyond", *JHEP* **06** (2011) 128, `doi:10.1007/JHEP06(2011)128`, `arXiv:1106.0522`.

[35] S. Frixione, P. Nason, and C. Oleari, "Matching NLO QCD computations with parton shower simulations: the POWHEG method", *JHEP* **11** (2007) 070, `doi:10.1088/1126-6708/2007/11/070`, `arXiv:0709.2092`.

[36] M. Bähr et al., "Herwig++ physics and manual", *Eur. Phys. J. C* **58** (2008) 639, `doi:10.1140/epjc/s10052-008-0798-9`, `arXiv:0803.0883`.

[37] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, `doi:10.1088/1126-6708/2006/05/026`, `arXiv:hep-ph/0603175`.

[38] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, `doi:10.1016/S0168-9002(03)01368-8`.

[39] CMS Collaboration, "Particle-flow event reconstruction in CMS and performance for jets, taus, and $E_{\mathrm{T}}^{\mathrm{miss}}$", CMS Physics Analysis Summary CMS-PAS-PFT-09-001, CERN, 2009.

[40] CMS Collaboration, "Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector", CMS Physics Analysis Summary CMS-PAS-PFT-10-001, CERN, 2010.

[41] CMS Collaboration, "Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$", *JINST* **10** (2015) P06005, `doi:10.1088/1748-0221/10/06/P06005`, `arXiv:1502.02701`.

[42] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7\,\mathrm{TeV}$", *JINST* **7** (2012) P10002, `doi:10.1088/1748-0221/7/10/P10002`, `arXiv:1206.4071`.

[43] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_t jet clustering algorithm", *JHEP* **04** (2008) 063, `doi:10.1088/1126-6708/2008/04/063`, `arXiv:0802.1189`.

[44] M. Cacciari and G. P. Salam, "Pileup subtraction using jet areas", *Phys. Lett. B* **659** (2008) 119, `doi:10.1016/j.physletb.2007.09.077`, `arXiv:0707.1378`.

[45] CMS Collaboration, "Identification of b-quark jets with the CMS experiment", *JINST* **8** (2013) P04013, `doi:10.1088/1748-0221/8/04/P04013`, `arXiv:1211.4462`.

[46] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1, `doi:10.1140/epjc/s10052-011-1554-0`, `arXiv:1007.1727`.

9 The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], V. Knünz, A. König, M. Krammer[1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady[2], N. Rad, B. Rahbaran, H. Rohringer, J. Schieck[1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

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

Vrije Universiteit Brussel, Brussel, 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

Université Libre de Bruxelles, Bruxelles, Belgium
P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[3]

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[4], O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, C. Delaere, D. Favart, L. Forthomme, A. Giammanco[5], A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, M. Musich, C. Nuttens, L. Perrini, K. Piotrzkowski, A. Popov[6], L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[7], 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, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[7], A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[b], A. De Souza Santos[b], S. Dogra[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], C.S. Moon[a,8], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, D. Leggat, R. Plestina[9], F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

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

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger[10], M. Finger Jr.[10]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[11,12], S. Elgammal[11], A. Ellithi Kamel[13,13], M.A. Mahmoud[14,14]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

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

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, N. Filipovic, R. Granier de Cassagnac, M. Jo, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[15], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[15], X. Coubez, J.-C. Fontaine[15], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin[2], K. Skovpen, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, 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

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[16]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, V. Zhukov[6]

RWTH Aachen University, III. Physikalisches Institut A, 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, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, K. Borras[17], A. Burgmeier, A. Campbell, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo[18], J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel[19], H. Jung, A. Kalogeropoulos, O. Karacheban[19], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[19], R. Mankel, 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, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

University of Hamburg, 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, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo[2], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, C. Scharf, P. Schleper, E. Schlieckau, A. Schmidt, S. Schumann, J. Schwandt, V. Sola, H. Stadie, G. Steinbrück, F.M. Stober, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann[2], S.M. Heindl, U. Husemann, I. Katkov[6], A. Kornmayer[2], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

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

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath[20], F. Sikler, V. Veszpremi, G. Vesztergombi[21], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[22], J. Molnar, Z. Szillasi[2]

University of Debrecen, Debrecen, Hungary
M. Bartók[23], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
S. Choudhury[24], P. Mal, K. Mandal, D.K. Sahoo, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, 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, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik[25], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu[26], Sa. Jain, G. Kole, S. Kumar, B. Mahakud, M. Maity[25], G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar[25], N. Sur, B. Sutar, N. Wickramage[27]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, A. Kapoor, K. Kothekar, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami[28], A. Fahim[29], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh[30], M. Zeinali

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

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[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], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,2], R. Venditti[a,b]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[2], 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], S.S. Chhibra[a,b], 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,2], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
G. Cappello[a], M. Chiorboli[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], L. Viliani[a,b,2]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[2]

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M.R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
L. Brianza, M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b],

S. Malvezzi[a], R.A. Manzoni[a,b,2], B. Marzocchi[a,b], 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]

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], 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

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a,2], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], A. Branca[a,b], R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b,2], T. Dorigo[a], U. Dosselli[a], F. Fanzago[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,2], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], M. Zanetti, P. Zotto[a,b], A. Zucchetta[a,b,2], G. Zumerle[a,b]

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

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
L. Alunni Solestizi[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]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a,31], P. Azzurri[a,2], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,31], R. Dell'Orso[a], S. Donato[a,c,2], G. Fedi, L. Foà[a,c†], A. Giassi[a], M.T. Grippo[a,31], 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,32], A.T. Serban[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], G. D'imperio[a,b,2], D. Del Re[a,b,2], M. Diemoz[a], S. Gelli[a,b], C. Jorda[a], E. Longo[a,b], F. Margaroli[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], P. Traczyk[a,b,2]

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,2], S. Argiro[a,b], M. Arneodo[a,c], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], 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], E. Monteil[a,b], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], 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], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea
J.A. Brochero Cifuentes, H. Kim, T.J. Kim

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

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, B. Hong, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
H.D. Yoo

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[33], F. Mohamad Idris[34], W.A.T. Wan Abdullah, M.N. Yusli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[35], A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

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

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho,

M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[37,38], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[39], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[38], I. Dremin[38], M. Kirakosyan, A. Leonidov[38], G. Mesyats, S.V. Rusakov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[40], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[41], P. Cirkovic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, 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, J. Santaolalla, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, 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[42], M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli[43], L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandi[44], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas[45], J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres[21], N. Wardle, H.K. Wöhri, A. Zagozdzinska[36], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov[46], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[47], L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, F.J. Ronga, D. Salerno, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, 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

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, S. Cerci[48], Z.S. Demiroglu, C. Dozen, I. Dumanoglu, F.H. Gecit, S. Girgis,

G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal[49], A. Kayis Topaksu, G. Onengut[50], M. Ozcan, K. Ozdemir[51], S. Ozturk[52], B. Tali[48], H. Topakli[52], C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, S. Bilmis, B. Isildak[53], G. Karapinar[54], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya[55], O. Kaya[56], E.A. Yetkin[57], T. Yetkin[58]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen[59], F.I. Vardarlı

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
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. Newbold[60], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[61], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, 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, S.D. Worm

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, D. Futyan, G. Hall, G. Iles, R. Lane, R. Lucas[60], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko[46], J. Pela, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta[62], T. Virdee, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
J. Alimena, E. Berry, D. Cutts, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean,

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, Los Angeles, USA
R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, M. Derdzinski, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[63], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA
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, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, K. Stenson, S.R. Wagner

Cornell University, Ithaca, 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, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, 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, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, S.V. Gleyzer, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev,

H. Mei, P. Milenovic[64], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi[65], M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, 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, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, USA
B. Bilki[66], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[67], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[68], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B.A. Barnett, B. Blumenfeld, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, A. Sady, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, 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, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA
B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, 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

Northwestern University, Evanston, USA
S. Bhattacharya, K.A. Hahn, A. Kubik, J.F. Low, N. Mucia, N. Odell, B. Pollack, M. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[37], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, 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, D. Stickland, C. Tully, A. Zuranski

University of Puerto Rico, Mayaguez, USA
S. Malik

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, A. Kumar, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak

Rice University, Houston, 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

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-

Bellido, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, G. Petrillo, P. Tan, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
J.P. Chou, E. Contreras-Campana, D. Ferencek, Y. Gershtein, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali[69], A. Castaneda Hernandez[69], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[70], V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer[2]

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA
D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, P. Verwilligen, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at British University in Egypt, Cairo, Egypt
12: Now at Suez University, Suez, Egypt
13: Also at Cairo University, Cairo, Egypt

14: Also at Fayoum University, El-Fayoum, Egypt
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Tbilisi State University, Tbilisi, Georgia
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Eötvös Loránd University, Budapest, Hungary
22: Also at University of Debrecen, Debrecen, Hungary
23: Also at Wigner Research Centre for Physics, Budapest, Hungary
24: Also at Indian Institute of Science Education and Research, Bhopal, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Now at King Abdulaziz University, Jeddah, Saudi Arabia
27: Also at University of Ruhuna, Matara, Sri Lanka
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Purdue University, West Lafayette, USA
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
43: Also at National Technical University of Athens, Athens, Greece
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
47: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
48: Also at Adiyaman University, Adiyaman, Turkey
49: Also at Mersin University, Mersin, Turkey
50: Also at Cag University, Mersin, Turkey
51: Also at Piri Reis University, Istanbul, Turkey
52: Also at Gaziosmanpasa University, Tokat, Turkey
53: Also at Ozyegin University, Istanbul, Turkey
54: Also at Izmir Institute of Technology, Izmir, Turkey
55: Also at Marmara University, Istanbul, Turkey
56: Also at Kafkas University, Kars, Turkey
57: Also at Istanbul Bilgi University, Istanbul, Turkey
58: Also at Yildiz Technical University, Istanbul, Turkey
59: Also at Hacettepe University, Ankara, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom

61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
63: Also at Utah Valley University, Orem, USA
64: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
65: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
66: Also at Argonne National Laboratory, Argonne, USA
67: Also at Erzincan University, Erzincan, Turkey
68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
69: Also at Texas A&M University at Qatar, Doha, Qatar
70: Also at Kyungpook National University, Daegu, Korea