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# Constraints on anomalous Higgs boson couplings using production and decay information in the four-lepton final state

The CMS Collaboration *

*CERN, Switzerland*

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A search is performed for anomalous interactions of the recently discovered Higgs boson using matrix element techniques with the information from its decay to four leptons and from associated Higgs boson production with two quark jets in either vector boson fusion or associated production with a vector boson. The data were recorded by the CMS experiment at the LHC at a center-of-mass energy of 13 TeV and correspond to an integrated luminosity of $38.6\,\mathrm{fb}^{-1}$. They are combined with the data collected at center-of-mass energies of 7 and 8 TeV, corresponding to integrated luminosities of 5.1 and $19.7\,\mathrm{fb}^{-1}$, respectively. All observations are consistent with the expectations for the standard model Higgs boson.

## 1. Introduction

The observation of a boson with a mass of about 125 GeV by the ATLAS and CMS Collaborations [1–3] is consistent with the prediction of the standard model (SM) Higgs (H) boson [4–10]. It has been established that the spin-parity quantum numbers of the H boson are consistent with $J^{PC} = 0^{++}$ [11–18]. However, the data still leave room for anomalous interactions or *CP* violation in the interactions of the H boson. The kinematics of leptons ($\ell = \mu^\pm$ and $e^\pm$) from $H \to ZZ/Z\gamma^*/\gamma^*\gamma^* \to 4\ell$ decays (through virtual photons or Z bosons), of quark jets produced in association with the H boson in vector boson fusion (VBF), and of the decays of Z or W bosons produced in association with H (VH) allow studies of anomalous interactions of the H boson [19–36].

The CMS Collaboration analyzed the data collected at the CERN LHC at center-of-mass energies of 7 and 8 TeV (Run 1), corresponding to integrated luminosities of 5.1 and $19.7\,\mathrm{fb}^{-1}$, measuring the spin-parity properties of the H boson and searching for anomalous HVV couplings using the H boson's decay modes to two electroweak gauge bosons [13]. That study focused on testing for the presence of anomalous effects in HZZ, HZ$\gamma$, H$\gamma\gamma$, and HWW interactions under spin-zero, -one, and -two hypotheses. The spin-one hypotheses were excluded at greater than 99.999% confidence level (CL) in the ZZ and WW modes; they were also excluded via the Landau–Yang theorem [37,38] by the observation of the $\gamma\gamma$ decay mode with $5.7\sigma$ significance. The spin-two boson hypothesis with gravity-like minimal couplings was excluded at 99.87% CL, and nine other possible hypotheses of spin-two tensor structure of HVV interactions were excluded at 99% CL or higher. Given the exclusion of the spin-one and -two scenarios, constraints were set on the contribution of eleven anomalous couplings to the HZZ, HZ$\gamma$, H$\gamma\gamma$, and HWW interactions under the hypothesis of a spin-zero state. Among others, these results constrained a *CP*-violation parameter $f_{a3}$, the fractional pseudoscalar cross section in the $H \to ZZ$ channel, which will be described in more detail in Section 2. The pure pseudoscalar hypothesis was excluded at 99.98% CL, and the limit $f_{a3} < 0.43$ was set at 95% CL. Similar results, for a smaller number of parameters and fewer exotic-spin models, were obtained by ATLAS [17].

All the above studies considered the decay of an on-shell H boson to two vector bosons. The accumulated data in Run 1 were not sufficient for precision tests of anomalous interactions in associated production, in off-shell production, or with fermions. Nonetheless, both CMS [14] and ATLAS [18] performed analyses of anomalous HVV interactions in VH and VBF production, respectively. Finally, the CMS experiment searched for anomalous HVV interactions in off-shell production of the H boson in $pp \to H \to ZZ$ with Run 1 data [15]. Further measurements probing the tensor structure of the HVV and H$f\bar{f}$ interactions can test *CP* invariance and, more generally, any small anomalous contributions [39].

In this Letter, the analysis approach follows our previous Run 1 publication [13], expanded in two important ways. Information from the kinematic correlations of quark jets from VBF and VH

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

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production is used together with $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 4\ell$ decay information for the first time, applying the relevant techniques discussed in Ref. [33]. Moreover, data sets corresponding to integrated luminosities of 2.7 and $35.9\,\mathrm{fb}^{-1}$ collected at a center-of-mass energy of 13 TeV in Run 2 of the LHC during 2015 and 2016, respectively, are combined with the Run 1 data, increasing the data sample of $\mathrm{H} \to 4\ell$ events by approximately a factor of four.

In what follows, the phenomenology of anomalous HVV interactions is discussed in Section 2. The CMS detector, reconstruction techniques, and Monte Carlo (MC) simulation are introduced in Section 3. Details of the analysis are discussed in Section 4, and results are presented in Section 5. We summarize in Section 6.

## 2. Phenomenology of anomalous H boson interactions

We assume that the H boson couples to two gauge bosons VV, such as ZZ, $\mathrm{Z}\gamma$, $\gamma\gamma$, WW, or gg, which in turn couple to quarks or leptons [19–34]. Three general tensor structures that are allowed by Lorentz symmetry are tested. Each term includes a form factor $F_i(q_1^2, q_2^2)$, where $q_1$ and $q_2$ are the four-momenta of the two difermion states, such as $\mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ in the $\mathrm{H} \to \mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$ decay. The H boson coupling to fermions is assumed not to be mediated by a new heavy state V′, generating the so-called contact terms [35,36]. We therefore study the process $\mathrm{H} \to \mathrm{VV} \to 4\mathrm{f}$ and the equivalent processes in production, rather than $\mathrm{H} \to \mathrm{VV}' \to 4\mathrm{f}$ or equivalent processes. Nonetheless, those contact terms are equivalent to the anomalous HVV couplings already tested using the $f_{\Lambda 1}$ and $f_{\Lambda 1}^{\mathrm{Z}\gamma}$ parameters, defined below. It is assumed that all lepton and quark couplings to vector bosons follow the SM predictions. Relaxing this requirement would be equivalent to allowing the contact terms to vary with flavor, which would result in too many unconstrained parameters to be tested with the present amount of data. Only the lowest order operators, or lowest order terms in the $(q_j^2/\Lambda^2)$ form-factor expansion, are tested, where $\Lambda$ is an energy scale of new physics.

Anomalous interactions of a spin-zero H boson with two spin-one gauge bosons VV, such as ZZ, $\mathrm{Z}\gamma$, $\gamma\gamma$, WW, and gg, are parameterized with a scattering amplitude that includes three tensor structures with expansion of coefficients up to $(q^2/\Lambda^2)$:

$$A(\mathrm{HVV}) \sim \left[ a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}, \tag{1}$$

where $q_i$, $\epsilon_{\mathrm{V}i}$, and $m_{\mathrm{V1}}$ are the four-momentum, polarization vector, and pole mass of a gauge boson, $f^{(i)\mu\nu} = \epsilon_{\mathrm{V}i}^{\mu} q_i^{\nu} - \epsilon_{\mathrm{V}i}^{\nu} q_i^{\mu}$, $\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} f^{(i),\rho\sigma}$ [13,33], and $a_i^{\mathrm{VV}}$ and $\kappa_i^{\mathrm{VV}}/\left(\Lambda_1^{\mathrm{VV}}\right)^2$ are parameters to be determined from data.

In Eq. (1), the only leading tree-level contributions are $a_1^{\mathrm{ZZ}} \neq 0$ and $a_1^{\mathrm{WW}} \neq 0$, and we assume custodial symmetry, so that $a_1^{\mathrm{ZZ}} = a_1^{\mathrm{WW}}$. The rest of the couplings are considered anomalous contributions. Tiny anomalous terms arise in the SM due to loop effects, and new, beyond standard model (BSM) contributions could make them larger. The SM values of those couplings are not yet accessible experimentally. Considerations of gauge invariance and symmetry between two identical bosons require $\kappa_1^{\mathrm{ZZ}} = \kappa_2^{\mathrm{ZZ}} = -\exp(i\phi_{\Lambda 1}^{\mathrm{ZZ}})$, $\kappa_{1,2}^{\gamma\gamma} = \kappa_{1,2}^{\mathrm{gg}} = \kappa_1^{\mathrm{Z}\gamma} = 0$, and $\kappa_2^{\mathrm{Z}\gamma} = -\exp(i\phi_{\Lambda 1}^{\mathrm{Z}\gamma})$, where $\phi_{\Lambda 1}^{\mathrm{VV}}$ is the phase of the corresponding coupling. The $a_{2,3}^{\mathrm{Z}\gamma}$ and $a_{2,3}^{\gamma\gamma}$ terms were tested in the Run 1 analysis [13], but have tighter constraints from on-shell photon measurements in $\mathrm{H} \to \mathrm{Z}\gamma$ and $\gamma\gamma$. We therefore do not repeat those measurements. The HWW couplings appear in VBF and WH production. We relate those couplings to the HZZ measurements assuming $a_i^{\mathrm{WW}} = a_i^{\mathrm{ZZ}}$ and drop the ZZ labels in what follows. Four anomalous couplings are left to be tested: $a_2$, $a_3$, $\kappa_2/\Lambda_1^2$, and $\kappa_2^{\mathrm{Z}\gamma}/\left(\Lambda_1^{\mathrm{Z}\gamma}\right)^2$. The generic notation $a_i$ refers to all four of these couplings, as well as the SM coupling $a_1$.

Equation (1) parameterizes both the $\mathrm{H} \to \mathrm{VV}$ decay and the production of the H boson via either VBF or VH. All three of these processes, which are illustrated in Fig. 1, are considered. While $q_i^2$ in the $\mathrm{H} \to \mathrm{VV}$ process does not exceed $(100\,\mathrm{GeV})^2$ due to the kinematic bound, in associated production no such bound exists. In the present analysis it is assumed that the $q_i^2$ range is not restricted within the allowed phase space.

The effective fractional cross sections $f_{ai}$ and phases $\phi_{ai}$ are defined as follows:

$$f_{ai} = |a_i|^2\sigma_i \Big/ \sum |a_j|^2\sigma_j, \text{ and } \phi_{ai} = \arg\left(a_i/a_1\right). \tag{2}$$

This definition of $f_{ai}$ is valid for both the SM coupling $a_1$ and the anomalous couplings, but there is no need for a separate measurement of $f_{a1}$ because $\sum f_{ai} = 1$. The cross sections $\sigma_i$ in Eq. (2) are calculated for each corresponding coupling $a_i$. They are evaluated for the $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 2\mathrm{e}2\mu$ process, where $a_i = 1$ and all other $a_j = 0$ in Eq. (1). The resulting ratios are $\sigma_1/\sigma_3 = 6.53$, $\sigma_1/\sigma_2 = 2.77$, $\sigma_1/\sigma_{\Lambda 1} = 1.47 \times 10^4\,\mathrm{TeV}^{-4}$, and $\sigma_1/\sigma_{\Lambda 1}^{\mathrm{Z}\gamma} = 5.80 \times 10^3\,\mathrm{TeV}^{-4}$. In the case of the $\mathrm{HZ}\gamma$ coupling the requirement $\sqrt{|q_i^2|} \geq 4\,\mathrm{GeV}$ is introduced in the cross section calculations to avoid infrared divergence. Equation (2) can be inverted to recover the coupling ratio,

$$\left|\frac{a_i}{a_1}\right| = \sqrt{\frac{f_{ai}}{f_{a1}}}\sqrt{\frac{\sigma_1}{\sigma_i}}. \tag{3}$$

It is convenient to measure the effective cross-section ratios ($f_{ai}$) rather than the anomalous couplings themselves ($a_i$). First of all, most systematic uncertainties cancel in the ratio. Moreover, the effective fractions are conveniently bounded by 0 and 1 and do not depend on the normalization convention in the definition of the couplings. Until the effects of interference become important, the statistical uncertainties in these measurements scale with the integrated luminosity as $1/\sqrt{\mathcal{L}}$, in the same way as cross section measurements. The $f_{ai}$ values have a simple interpretation as the fractional size of the BSM contribution for the $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 2\mathrm{e}2\mu$ decay. For example, $f_{ai} = 0$ indicates a pure SM Higgs boson, $f_{ai} = 1$ gives a pure BSM particle, and $f_{ai} = 0.5$ means that the two couplings contribute equally to the $\mathrm{H} \to \mathrm{ZZ}/\mathrm{Z}\gamma^*/\gamma^*\gamma^* \to 2\mathrm{e}2\mu$ process. In particular, $f_{a3}$ is the fractional pseudoscalar cross section in the $\mathrm{H} \to \mathrm{ZZ} \to 2\mathrm{e}2\mu$ channel. A value $0 < f_{a3} < 1$ would indicate *CP* violation, with a possible mixture of scalar and pseudoscalar states, while $f_{a3} = 1$ would indicate that the H boson is a pure pseudoscalar resonance, which has been excluded at 99.98% CL [13].

The above approach allows a general test of the kinematic distributions associated with the couplings of H to 4 fermions, whether in the decay or in the associated production channels, as shown in Fig. 1. If deviations from the SM are detected, a more detailed study of the $(q_j^2/\Lambda^2)$ form-factor expansion can be performed, eventually providing a measurement of the double-differential cross section for each tested tensor structure. Under the assumption that the couplings are constant and real (i.e., $\phi_{ai} = 0$ or $\pi$), the above formulation is equivalent to an effective Lagrangian [13]. It is also equivalent to the formulation involving contact terms [35,36] if the contact terms are assumed to satisfy lepton universality.

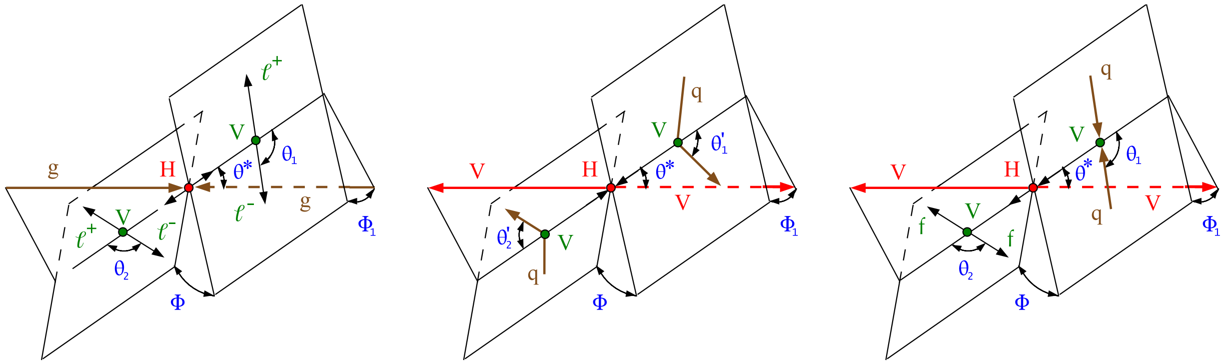

**Fig. 1.** Illustration of H boson production and decay in three topologies: gluon fusion $gg \to H \to VV \to 4\ell$ (left); vector boson fusion $qq \to VV(qq) \to H(qq) \to VV(qq)$ (middle); and associated production $qq \to V \to VH \to (ff)H \to (ff)VV$ (right). In the latter two cases, although the full H decay chain is not shown in the figure, the production and decay $H \to VV$ may be followed by the same four-lepton decay shown in the first case. The five angles shown in blue and the invariant masses of the two vector bosons shown in green fully characterize either the production or the decay chain. The angles are defined in either the H or V boson rest frames [26,33]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 3. The CMS detector, simulation, and reconstruction

The $H \to 4\ell$ decays are reconstructed in the CMS detector, which is composed of a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections, all within a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Outside the solenoid are the gas-ionization detectors for muon measurements, which are embedded in the steel flux-return yoke. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Events of interest are selected using a two-tiered trigger system. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [40].

A dedicated MC program, JHUGen 7.0.2 [26,29,33,41], is used to simulate the effect of anomalous couplings in the production and decay $H \to ZZ$ / $Z\gamma^*$ / $\gamma^*\gamma^* \to 4\ell$. The gluon fusion production of an H boson is simulated with the POWHEG 2.0 [42–44] event generator at next-to-leading order (NLO) in quantum chromodynamics (QCD). The associated gluon fusion production of an H boson with two jets is affected by anomalous Hgg interactions. These effects are modeled with JHUGen. It is also found that the NLO QCD effects that are relevant for the analysis of a spin-zero state are well described by a combination of leading-order (LO) matrix elements and parton showering [33]. For the SM case, JHUGen simulations at LO in QCD and POWHEG simulations at NLO in QCD, with parton showering applied in both cases, are explicitly compared, and no significant differences are found. Therefore, JHUGen at LO in QCD is adopted for the simulation of VBF, VH, and $t\bar{t}H$ production with anomalous couplings. The MELA package [2,26,29,33,41] contains a library of matrix elements from JHUGen for the H boson signal and MCFM 7.0 [45–47] for the SM background and is used to apply weights to events in any MC sample to model any other set of couplings.

The main background in this analysis, $q\bar{q} \to ZZ/Z\gamma^* \to 4\ell$, is estimated from simulation with POWHEG, with the next-to-NLO (NNLO) K-factor, which is approximately 1.1 at $m_{4\ell} = 125\,\text{GeV}$ [48], applied to the NLO cross section. The $gg \to ZZ/Z\gamma^* \to 4\ell$ background process is simulated with MCFM 7.0, where the Higgs boson production K-factor at NNLO in QCD, which is approximately 2.3 at $m_{4\ell} = 125\,\text{GeV}$, is applied to the LO cross section [49]. The VBF and triple-gauge-boson (VVV) backgrounds are estimated at LO with PHANTOM 1.2.8 [50]. The parton distribution functions (PDFs) used for all of these samples are NNPDF3.0 [51]. All MC samples are interfaced with PYTHIA 8.212 [52] tune CUETP8M1 [53] for parton showering and further processed through a dedicated simulation of the CMS detector based on Geant4 [54].

The selection of the $H \to 4\ell$ events and associated particles closely follows the methods used in the analyses of Run 1 [12,13] and Run 2 [48] data. The main triggers for this analysis select a pair of leptons passing loose identification and isolation requirements, with $p_T$ of the leading and subleading electron (muon) at least 23 (17) and 12 (8) GeV, respectively. To maximize the signal acceptance, triggers requiring three leptons with lower $p_T$ thresholds and no isolation requirement are also used, as are isolated single-electron and single-muon triggers with higher $p_T$ thresholds. Electrons (muons) are reconstructed within the geometrical acceptance defined by $|\eta| < 2.5$ (2.4) for transverse momentum $p_T > 7\,(5)\,\text{GeV}$ with an algorithm that combines information from the ECAL (muon system) and the tracker. It is required that the ratio of each lepton track's impact parameter in three dimensions, computed with respect to the chosen primary vertex position, to its uncertainty be less than 4. The primary vertex is defined as the vertex with the highest sum of $p_T^2$ of physics objects defined by a jet-finding algorithm. To discriminate prompt leptons from $Z/\gamma^*$ boson decays from those arising from hadron decays within jets, an isolation requirement for leptons is imposed. An algorithm is used to collect the final-state radiation (FSR) of leptons. An FSR photon is associated to the closest selected lepton in the event if its angular separation from the lepton is below the required threshold, as discussed in Ref. [48]. Three mutually exclusive channels are considered: $H \to 4e$, $4\mu$, and $2e2\mu$. At least two leptons are required to have $p_T > 10\,\text{GeV}$, and at least one is required to have $p_T > 20\,\text{GeV}$. All four pairs of oppositely charged leptons that can be built with the four leptons, irrespective of flavor, are required to satisfy $m_{\ell^+\ell'^-} > 4\,\text{GeV}$. The $Z/\gamma^*$ candidates are required to satisfy the condition $12\,\text{GeV} < m_{\ell\ell} < 120\,\text{GeV}$; the invariant mass of at least one of the $Z/\gamma^*$ candidates must be larger than 40 GeV. The four-lepton invariant mass $m_{4\ell}$ must be between 105 and 140 GeV.

Jets are reconstructed using the particle-flow (PF) algorithm [55], with PF candidates clustered by the anti-$k_T$ algorithm [56,57] with a distance parameter of 0.4, and with the constraint that the charged particles be compatible with the primary vertex. The jet momentum is determined as the vectorial sum of all PF candidate momenta in the jet. Jets must satisfy $p_T > 30\,\text{GeV}$ and $|\eta| < 4.7$ and be separated from all selected lepton candidates and any selected FSR photons by an angular distance $\Delta R(\ell/\gamma, \text{jet}) > 0.4$, where the angular distance between two particles $i$ and $j$ is $\Delta R(i, j) = \sqrt{(\eta^i - \eta^j)^2 + (\phi^i - \phi^j)^2}$.

**Table 1**
Summary of the three production categories in the analysis of 2016 data. The discriminants $\mathcal{D}$ are calculated from Eqs. (4) and (5), as discussed in more detail in the text. For each analysis, the appropriate BSM model is considered in the definition of the categories: $f_{a3}=1$, $f_{a2}=1$, $f_{\Lambda1}=1$, or $f_{\Lambda1}^{Z\gamma}=1$. Three observables (abbreviated as obs.) are listed for each analysis and for each category. They are described in more detail later in the text.

| Category | VBF-jet | VH-jet | Untagged |
|---|---|---|---|
| Target | $\mathrm{qq'VV} \to \mathrm{qq'H} \to (\mathrm{jj})(4\ell)$ | $\mathrm{q\overline{q}} \to \mathrm{VH} \to (\mathrm{jj})(4\ell)$ | $\mathrm{H} \to 4\ell$ |
| Selection | $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF}}$ or $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF,BSM}} > 0.5$ | $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{ZH}}$ or $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{ZH,BSM}}$ or<br>$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{WH}}$ or $\mathcal{D}_{\mathrm{2jet}}^{\mathrm{WH,BSM}} > 0.5$ | not VBF-jet<br>not VH-jet |
| $f_{a3}$ obs. | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0-}^{\mathrm{VBF+dec}}, \mathcal{D}_{CP}^{\mathrm{VBF}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0-}^{\mathrm{VH+dec}}, \mathcal{D}_{CP}^{\mathrm{VH}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0-}^{\mathrm{dec}}, \mathcal{D}_{CP}^{\mathrm{dec}}$ |
| $f_{a2}$ obs. | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VBF}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VH}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{dec}}$ |
| $f_{\Lambda1}$ obs. | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda1}^{\mathrm{VBF+dec}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda1}^{\mathrm{VH+dec}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda1}^{\mathrm{dec}}, \mathcal{D}_{0h+}^{\mathrm{dec}}$ |
| $f_{\Lambda1}^{Z\gamma}$ obs. | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\mathrm{VBF+dec}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\mathrm{VH+dec}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}$ | $\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\mathrm{dec}}, \mathcal{D}_{0h+}^{\mathrm{dec}}$ |

## 4. Analysis techniques

The full kinematic information from each event is extracted using the matrix element calculations in the MELA package. For either the H boson decay or associated production with two jets, up to seven kinematic observables, five angles and two invariant masses, are defined, as shown in Fig. 1 [26,33]. In the 2 → 6 process of associated H boson production via either VBF, ZH, or WH and its subsequent decay to a four-fermion final state, up to 13 independent observables $\vec{\Omega}$ remain. In the following, we use either the production kinematics, the decay kinematics, or both, as appropriate. The $\vec{p}_{\mathrm{T}}$ of the system of the H boson and two jets, which would appear at NLO in QCD, is not included in the input observables in order to reduce associated QCD uncertainties. The MELA approach retains all relevant kinematic information in a minimal set of discriminants $\mathcal{D}$, computed from ratios of probabilities $\mathcal{P}$. We use two types of discriminants,

$$\mathcal{D}_{\mathrm{alt}}\left(\vec{\Omega}\right) = \frac{\mathcal{P}_{\mathrm{sig}}\left(\vec{\Omega}\right)}{\mathcal{P}_{\mathrm{sig}}\left(\vec{\Omega}\right) + \mathcal{P}_{\mathrm{alt}}\left(\vec{\Omega}\right)} \qquad (4)$$

and

$$\mathcal{D}_{\mathrm{int}}\left(\vec{\Omega}\right) = \frac{\mathcal{P}_{\mathrm{int}}\left(\vec{\Omega}\right)}{\mathcal{P}_{\mathrm{sig}}\left(\vec{\Omega}\right) + \mathcal{P}_{\mathrm{alt}}\left(\vec{\Omega}\right)}, \qquad (5)$$

where "sig" stands for the SM signal; "alt" denotes an alternative hypothesis [29], which could be background ("bkg"), an alternative H boson production mechanism ("2jet"), or an alternative H boson coupling model ("$a_i$"); and "int" represents the contribution to the probability from the interference between "sig" and "alt" [33]. By the Neyman–Pearson lemma [58], the $\mathcal{D}_{\mathrm{alt}}$ discriminant contains all the information available from the kinematics to separate the SM signal hypothesis from the alternative hypothesis. Because all intermediate hypotheses are a linear combination of the SM hypothesis and the alternative hypothesis, the combination of $\mathcal{D}_{\mathrm{alt}}$ with $\mathcal{D}_{\mathrm{int}}$ also contains all the information available to separate the interference component. The discriminants used in this analysis are summarized in Table 1 and described in more detail below.

The selected events in the 2016 data sample are split into three categories: VBF-jet, VH-jet, and untagged. The VBF-jet category requires exactly four leptons with either two or three jets of which at most one is b quark flavor-tagged, or at least four jets and no b-tagged jets. The VH-jet category requires exactly four leptons and two or more jets; if there are four or more jets, none of them should be b tagged. The requirements on the number of b-tagged jets are applied to reduce cross-feed from $\mathrm{t\bar{t}H}$ production. In order to separate the target production mode for each category from gluon fusion production, the requirement $\mathcal{D}_{\mathrm{2jet}} > 0.5$ is applied following Eq. (4), where $\mathcal{P}_{\mathrm{sig}}$ corresponds to the signal probability for the VBF (ZH or WH) production hypothesis in the VBF-jet (VH-jet) category, and $\mathcal{P}_{\mathrm{alt}}$ corresponds to the gluon fusion production of the H boson in association with two jets. In each of the four $f_{ai}$ analyses, the requirement $\mathcal{D}_{\mathrm{2jet}} > 0.5$ is tested with both the $f_{ai}=0$ and $f_{ai}=1$ signal hypotheses in $\mathcal{P}_{\mathrm{sig}}$. Thus, this categorization differs slightly in the four analyses. The two highest $p_{\mathrm{T}}$ jets are used in the calculation of the matrix elements. All events not assigned to the VBF-jet or VH-jet categories are assigned to the untagged category. The above requirements are summarized in Table 1. Due to the small size of the 2015 data sample, those events were not categorized and were all treated as untagged, as was done in the analysis of 2011 and 2012 data [13]. The expected and observed numbers of events are listed in Table 2.

**Table 2**
The numbers of events expected for the SM (or $f_{a3}=1$, in parentheses) for different signal and background modes and the total observed numbers of events across the three $f_{a3}$ categories in 2016 and 2015 data.

| | VBF-jets | VH-jets | Untagged | 2015 |
|---|---|---|---|---|
| VBF signal | 2.4 (1.6) | 0.1 (0.1) | 2.2 (0.3) | 0.4 (0.2) |
| ZH signal | 0.1 (0.2) | 0.3 (0.5) | 0.7 (1.0) | 0.1 (0.1) |
| WH signal | 0.1 (0.3) | 0.3 (1.0) | 0.8 (2.2) | 0.1 (0.3) |
| $\mathrm{gg} \to \mathrm{H}$ signal | 3.2 (3.3) | 1.9 (2.0) | 49.6 (49.4) | 4.6 (4.6) |
| $\mathrm{t\bar{t}H}$ signal | 0.1 (0.1) | 0.0 (0.0) | 0.5 (0.6) | 0.1 (0.1) |
| $\mathrm{q\bar{q}} \to 4\ell$ bkg | 0.9 | 1.1 | 56.3 | 5.4 |
| $\mathrm{gg} \to 4\ell$ bkg | 0.1 | 0.1 | 5.5 | 0.5 |
| VBF/VVV bkg | 0.1 | 0.0 | 0.4 | 0.0 |
| Z+X bkg | 3.6 | 2.0 | 29.1 | 1.7 |
| Total expected | 10.7 | 5.8 | 145.2 | 12.9 |
| Total observed | 11 | 2 | 145 | 11 |

We perform an unbinned extended maximum likelihood fit to the events split into the categories according to the lepton flavor and production topology. An independent fit is performed for each parameter defined in Table 3. In each category of events, three observables $\vec{\mathcal{D}} = \{\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{ai}, \mathcal{D}_{\mathrm{int}}\}$ are defined following Eqs. (4) and (5), as summarized in Table 1.

The first observable, $\mathcal{D}_{\mathrm{bkg}}$ (shown in Fig. 2(a)), is common to all events and is designed to separate the signal from the dominant $\mathrm{q\bar{q}} \to 4\ell$ background, for which $\mathcal{P}_{\mathrm{bkg}}$ is calculated. The signal and

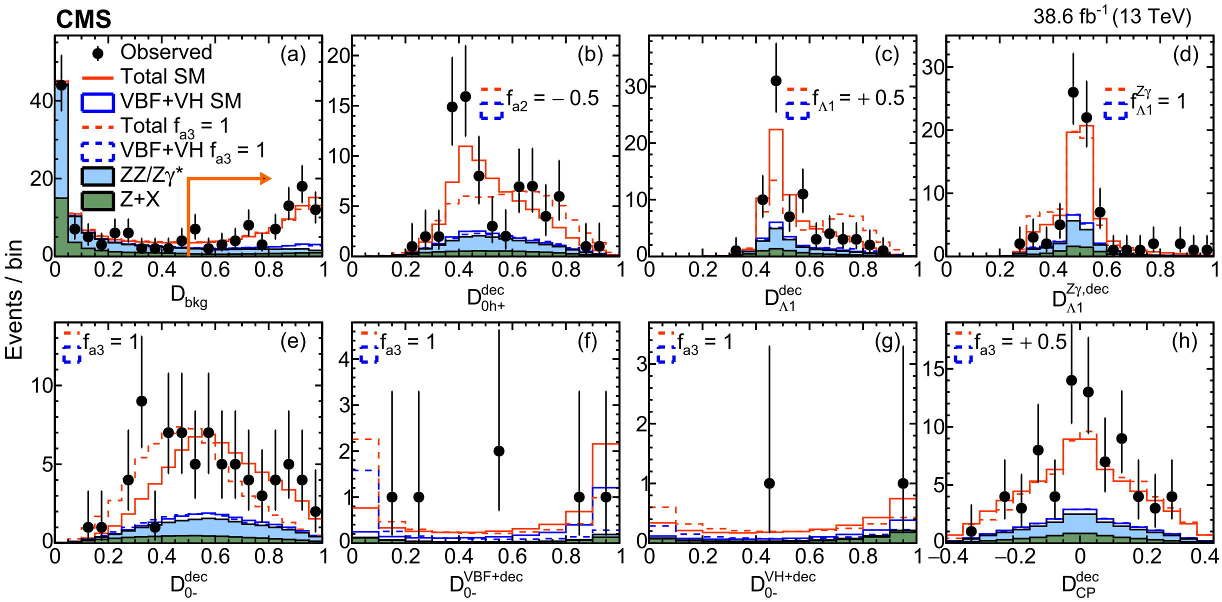

**Fig. 2.** Distributions of $\mathcal{D}_{\rm bkg}$ (a) for all events in Run 2; $\mathcal{D}_{0h+}$ (b), $\mathcal{D}_{\Lambda1}$ (c), $\mathcal{D}^{Z\gamma}_{\Lambda1}$ (d), $\mathcal{D}_{0-}$ (e), and $\mathcal{D}_{CP}$ (h) for the untagged and 2015 events; $\mathcal{D}_{0-}$ in the VBF-jet (f) and VH-jet (g) categories. The arrow in (a) indicates the requirement $\mathcal{D}_{\rm bkg} > 0.5$, used to suppress background on all other plots. Points with error bars show data and histograms show expectations for background and signal, as indicated in the legend in (a). The dashed lines show expectations for BSM hypotheses, as indicated in the individual legends.

**Table 3**
Summary of allowed 68% CL (central values with uncertainties) and 95% CL (in square brackets) intervals on anomalous coupling parameters obtained from the combined Run 1 and Run 2 data analysis.

| Parameter | Observed | Expected |
|---|---|---|
| $f_{a3}\cos(\phi_{a3})$ | $0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$ | $0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$ |
| $f_{a2}\cos(\phi_{a2})$ | $0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$ | $0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$ |
| $f_{\Lambda1}\cos(\phi_{\Lambda1})$ | $0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$ | $0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$ |
| $f^{Z\gamma}_{\Lambda1}\cos(\phi^{Z\gamma}_{\Lambda1})$ | $0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$ | $0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$ |

background probabilities include both the matrix element probability based on lepton kinematics and the $m_{4\ell}$ probability parameterization extracted from simulation of detector effects. The signal $m_{4\ell}$ parameterization assumes that $m_{\rm H} = 125\,\text{GeV}$.

The second observable, $\mathcal{D}_{ai}$, separates the SM hypothesis $f_{ai} = 0$ from the alternative hypothesis $f_{ai} = 1$. It is defined following Eq. (4), with $\mathcal{P}_{\rm sig}$ calculated for $f_{ai} = 0$ and $\mathcal{P}_{\rm alt}$ for the alternative H boson coupling hypothesis with $f_{ai} = 1$. In the untagged category the probabilities are calculated using only the decay information, but in the VBF-jet and VH-jet categories both the production and decay probabilities are used, with the matrix elements calculated for either VBF × decay or (ZH + WH) × decay, respectively. This observable is called $\mathcal{D}_{0-}$ in the $f_{a3}$, $\mathcal{D}_{0h+}$ in the $f_{a2}$, $\mathcal{D}_{\Lambda1}$ in the $f_{\Lambda1}$, and $\mathcal{D}^{Z\gamma}_{\Lambda1}$ in the $f^{Z\gamma}_{\Lambda1}$ analyses [13]. Superscripts are added to the discriminant name to indicate the processes used to calculate the matrix elements: either dec, VBF+dec, or VH+dec to denote decay, VBF × decay, or (ZH + WH) × decay, respectively. Distributions of $\mathcal{D}_{0-}$ in the three categories are shown in Fig. 2(e), (f), (g). Fig. 2(b), (c), (d) also shows the distributions of $\mathcal{D}_{0h+}$, $\mathcal{D}_{\Lambda1}$, and $\mathcal{D}^{Z\gamma}_{\Lambda1}$, respectively, for the untagged events.

The third observable, $\mathcal{D}_{\rm int}$ from Eq. (5), separates the interference of the two amplitudes corresponding to the SM coupling and the alternative H boson coupling model. In the case of the $f_{a3}$ analysis, this observable is called $\mathcal{D}_{CP}$ because if *CP* is violated it would exhibit a distinctive forward–backward asymmetry between $\mathcal{D}_{CP} > 0$ and $\mathcal{D}_{CP} < 0$, as illustrated in Fig. 2(h) for the untagged category of events. In the untagged category, decay information is used in the calculation of $\mathcal{D}_{\rm int}$. In the VBF-jet and VH-jet categories, production information is used. As in the case of $\mathcal{D}_{ai}$, superscripts indicate which processes were used to calculate the matrix elements. In the $f_{\Lambda1}$ and $f^{Z\gamma}_{\Lambda1}$ analyses, the interference discriminant does not provide additional separation, and $\mathcal{D}_{0h+}$ is used as the third observable.

In the likelihood fit, the signal probability density function (pdf) is parameterized for each production mode and in each category as

$$P_{\rm sig}\left(\vec{\mathcal{D}}; f_{ai}, \phi_{ai}\right) \propto \sum_n \left|\frac{a_i}{a_1}\right|^n \mathcal{T}_n\left(\vec{\mathcal{D}}\right)\cos^n(\phi_{ai}), \qquad (6)$$

where $\mathcal{T}_n$ is the three-dimensional template probability obtained from MC simulation, $|a_i/a_1|$ is calculated from $f_{ai}$ through Eq. (3), and $\cos(\phi_{ai}) = \pm 1$. The sum runs over five values $n = 0, \ldots, 4$ in the case of VBF and VH, where the HVV coupling appears on both the production and decay sides, and over three contributions $n = 0, 1$, and 2 for the other signal modes. The background pdf is also parameterized with templates extracted from simulation, except for the reducible background, Z+X, which is dominated by the Z+jets process but also includes the $t\bar{t}$+jets, Zγ+jets, WZ+jets, and WW+jets processes. The Z+X background is estimated using independent control regions in data with loose identification requirements on two leptons.

The yields of signal events in 2016 data are expressed with two unconstrained parameters $\mu_V$ and $\mu_F$, which are the ratios of the observed yields to the expectation in the SM for the production mechanisms driven by the HVV couplings (VBF and VH) and for the other modes (gluon fusion and $t\bar{t}$H), respectively. The signal yield in 2015 data is expressed with a single parameter $\mu_{13\,\rm TeV}$, which is a linear combination of $\mu_V$ and $\mu_F$. The fit is also performed simultaneously with the 2011 and 2012 data from Ref. [13], where the two signal strength parameters $\mu_{7\,\rm TeV}$ and $\mu_{8\,\rm TeV}$ are also linear combinations of $\mu_V$ and $\mu_F$ including the effects of the cross section scaling for each value of $f_{ai}$.

Most uncertainties in the signal yields cancel in this analysis because measurements of anomalous couplings are expressed as relative cross sections. Statistical uncertainties dominate over any systematic uncertainties in this analysis. In the decay-only observables the main effects come from lepton momentum uncertainties

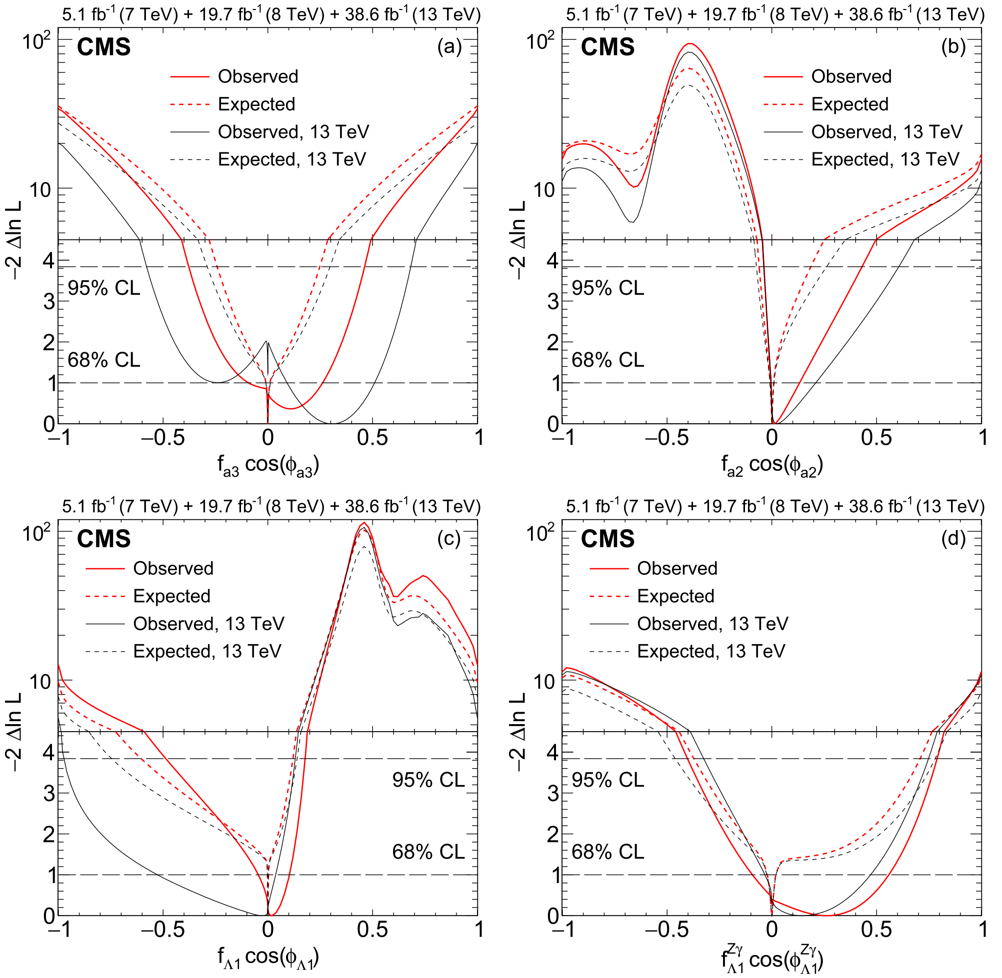

**Fig. 3.** Observed (solid) and expected (dashed) likelihood scans of $f_{a3}\cos(\phi_{a3})$ (a), $f_{a2}\cos(\phi_{a2})$ (b), $f_{\Lambda1}\cos(\phi_{\Lambda1})$ (c), and $f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$ (d). Results of the Run 2 only and the combined Run 1 and Run 2 analyses are shown.

and are propagated into the template uncertainties as in the previous analyses [13], where the main effect is on the $m_{4\ell}$ resolution affecting the $\mathcal{D}_{\mathrm{bkg}}$ parameterization.

The primary new feature in this analysis, compared to Run 1 [13], is the categorization based on jets and the kinematic discriminants using jet information. Both the shapes and the yields are varied according to uncertainties obtained from the jet energy variations. In addition, uncertainties in renormalization and factorization scales, PDFs, and the modeling of hadronization and the underlying event in MC simulation are propagated to the template and relative yield uncertainties. As part of these studies, comparisons were made between QCD production at NLO and LO, with matched PYTHIA hadronization in each case, for the VBF, VH, and $\mathrm{t\bar{t}H}$ processes. In all cases, only small differences were observed. The uncertainties in the migration of signal and background events between categories amount to 3–13% for the signal and 4–25% for the background, depending on the category. Among the signal processes, the largest uncertainties arise from the prediction of the $\mathrm{gg} \to \mathrm{H}$ yield in the VBF-jet category. In $\mathrm{t\bar{t}H}$ and gluon fusion production, anomalous couplings on the production side are not generally related to the HVV anomalous couplings considered here. There is a negligible effect on the observed distributions with large variations in the couplings.

Backgrounds from the $\mathrm{q\bar{q}} \to 4\ell$, $\mathrm{gg} \to 4\ell$, VBF, and $\mathrm{V}+(4\ell)$ processes are estimated using MC simulation. Theoretical uncertainties in the background estimation include uncertainties from the renormalization and factorization scales, the PDFs, and the K-factors described above. An additional 10% uncertainty is assigned to the $\mathrm{gg} \to 4\ell$ background K-factor to cover potential differences between signal and background.

## 5. Results and discussion

Four $f_{ai}$ parameters sensitive to anomalous H boson interactions, as defined in Eqs. (2) and (3), are tested in the observed data using the pdf in Eq. (6). The results of the likelihood scans of the $f_{ai}$ parameters on 13 TeV data only and on the full, combined data set from collisions at 13, 8, and 7 TeV are shown in Fig. 3. The combined results are listed in Table 3 and supersede our previous measurement in Ref. [13].

The expected 68% CL constraints improve by nearly an order of magnitude compared to the Run 1 analysis [13], as is evident from the narrow minima at $f_{ai}=0$ in the expectations in Fig. 3. This effect comes from utilizing production information, because the cross section in VBF and VH production increases quickly with $f_{ai}$ due to larger $q^2$ values contributing in Eq. (1) [33]. The narrow minima are shallower than expected, which may be understood by examining the best fitted $(\mu_V, \mu_F)$ values in the four analyses under the assumption that $f_{ai}=0$: $(0.76^{+1.10}_{-0.76}, 1.08^{+0.21}_{-0.20})$ at $f_{a3}=0$, $(0.01^{+0.89}_{-0.01}, 1.24^{+0.20}_{-0.18})$ at $f_{a2}=0$, $(0.20^{+0.94}_{-0.20}, 1.20^{+0.21}_{-0.20})$ at $f_{\Lambda1}=0$, and $(0.24^{+0.84}_{-0.24}, 1.20^{+0.20}_{-0.19})$ at $f_{\Lambda1}^{Z\gamma}=0$. The values obtained for the different analyses vary due to the different categorization and observables. The overall behavior with $\mu_V$ less than 1 is consistent with a downward statistical fluctuation in the small number of VBF and VH events, with the total observed number of untagged events similar to the expectation. Because fewer VBF and VH events are observed than expected, the narrow minima of $-2\ln(\mathcal{L})$ at $f_{ai}=0$, which come from the production information in these events, are observed to be less pronounced than expected. The minimum is most pronounced in the $f_{a3}$ analysis in Fig. 3(a) due to the largest observed $\mu_V$ value.

The improvement in the 95% CL constraints with respect to Run 1 is mostly due to the increase in the number of events with $\mathrm{H}\to 4\ell$ decay information by about a factor of four. Another factor of four increase in the data sample size is expected by the end of 2018, under similar running conditions. At that time, the inclusion of production information is expected to result in improvements to the 95% CL constraints in line with the improvements already seen in the 68% CL constraints.

Other features in Fig. 3 can be explained by examining the kinematic distributions in Fig. 2. The $\mathcal{D}_{0-}^{\text{dec}}$ distribution in Fig. 2(e) favors a mixture of the $f_{a3}=0$ and $f_{a3}=1$ models, resulting in the best fit value of $f_{a3}=0.30\pm0.21$ in Run 2. The $\mathcal{D}_{CP}^{\text{dec}}$ distribution in Fig. 2(h) has a small forward–backward asymmetry, with more events at $\mathcal{D}_{CP}^{\text{dec}}>0$ than $\mathcal{D}_{CP}^{\text{dec}}<0$, which gives preference to the $f_{a3}\cos(\phi_{a3})=+0.30$ value as opposed to $-0.30$. The narrow local minimum at $f_{a3}=0$ corresponds to the distribution of events in the tagged categories in Fig. 2(f), (g), which favors the SM hypothesis. The Run 1 result [13] favors the SM strongly, and therefore combining the two data sets results in a global minimum at $f_{a3}=0$.

Certain values of anomalous couplings, such as $f_{a2}\cos(\phi_{a2})\sim -0.5$ and $f_{\Lambda1}\cos(\phi_{\Lambda1})\sim +0.5$, lead to strong interference effects between the SM and anomalous amplitudes in Eq. (1). Therefore, kinematic distributions of such models are easily distinguished from SM distributions, and they are excluded at high CL in Fig. 3. Such anomalous models are shown in Fig. 2(b), (c). The $f_{a3}=1$ and $f_{\Lambda1}^{Z\gamma}=1$ models are shown in other cases in Fig. 2, as the most distinct from SM, except for (h), where maximal forward–backward asymmetry in $\mathcal{D}_{CP}$ is shown for $f_{a3}=0.5$. In all cases, the observed distributions in Fig. 2 are consistent with the SM expectations.

## 6. Summary

We study anomalous interactions of the H boson using novel techniques with a matrix element likelihood approach to simultaneously analyze the $\mathrm{H}\to 4\ell$ decay and associated production with two quark jets. Three categories of events are analyzed, targeting events produced in vector boson fusion, with an associated vector boson, and in gluon fusion, respectively. The data collected at a center-of-mass energy of 13 TeV in Run 2 of the LHC are combined with the Run 1 data, collected at 7 and 8 TeV. No deviations from the standard model are observed and constraints are set on the four anomalous HVV contributions, including the *CP*-violation parameter $f_{a3}$, summarized in Table 3.

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## The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

*Yerevan Physics Institute, Yerevan, Armenia*

W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler [1], A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck [1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz [1], M. Zarucki

*Institut für Hochenergiephysik, Wien, Austria*

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

*Institute for Nuclear Problems, Minsk, Belarus*

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

*Universiteit Antwerpen, Antwerpen, Belgium*

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

*Vrije Universiteit Brussel, Brussel, Belgium*

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang [2]

*Université Libre de Bruxelles, Bruxelles, Belgium*

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

*Ghent University, Ghent, Belgium*

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

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

N. Beliy

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [3], A. Custódio, E.M. Da Costa, G.G. Da Silveira [4], D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida,

C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

S. Ahuja[a], C.A. Bernardes[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J.C. Ruiz Vargas[a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, S. Stoykova, G. Sultanov

*Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences, Bulgaria*

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

*University of Sofia, Sofia, Bulgaria*

W. Fang[5], X. Gao[5]

*Beihang University, Beijing, China*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, S. Zhang, J. Zhao

*Institute of High Energy Physics, Beijing, China*

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

*Universidad de Los Andes, Bogota, Colombia*

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

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

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov[6], T. Susa

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

M. Finger[7], M. Finger Jr.[7]

*Charles University, Prague, Czech Republic*

E. Carrera Jarrin

*Universidad San Francisco de Quito, Quito, Ecuador*

Y. Assran[8,9], S. Elgammal[9], A. Mahrous[10]

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

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, J. Pekkanen, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

*Helsinki Institute of Physics, Helsinki, Finland*

J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*

J.-L. Agram[11], J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[11], X. Coubez, J.-C. Fontaine[11], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[12], V. Sordini, M. Vander Donckt, S. Viret

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

A. Khvedelidze[7]

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze[7]

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl[13]

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[14], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo[15], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel[16], H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann[16], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo[13], T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann[13], S.M. Heindl, U. Husemann, F. Kassel[13], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

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

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

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

*National and Kapodistrian University of Athens, Athens, Greece*

K. Kousouris

*National Technical University of Athens, Athens, Greece*

I. Evangelou, C. Foudas, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

*University of Ioánnina, Ioánnina, Greece*

M. Csanad, N. Filipovic, G. Pasztor, G.I. Veres[17]

*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*

G. Bencze, C. Hajdu, D. Horvath[18], Á. Hunyadi, F. Sikler, V. Veszpremi, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi[19], A. Makovec, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók[17], P. Raics, Z.L. Trocsanyi, B. Ujvari

*Institute of Physics, University of Debrecen, Debrecen, Hungary*

S. Choudhury, J.R. Komaragiri

*Indian Institute of Science (IISc), Bangalore, India*

S. Bahinipati[20], S. Bhowmik, P. Mal, K. Mandal, A. Nayak[21], D.K. Sahoo[20], N. Sahoo, S.K. Swain

*National Institute of Science Education and Research, Bhubaneswar, India*

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

*Panjab University, Chandigarh, India*

Ashok Kumar, Shah Aashaq, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma

*University of Delhi, Delhi, India*

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*

P.K. Behera

*Indian Institute of Technology Madras, Madras, India*

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[13], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

*Tata Institute of Fundamental Research-A, Mumbai, India*

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity[22], G. Majumder, K. Mazumdar, T. Sarkar[22], N. Wickramage[23]

*Tata Institute of Fundamental Research-B, Mumbai, India*

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani[24], E. Eskandari Tadavani, S.M. Etesami[24], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[25], F. Rezaei Hosseinabadi, B. Safarzadeh[26], M. Zeinali

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

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b],

A. Sharma [a], L. Silvestris [a,13], R. Venditti [a], P. Verwilligen [a]

[a] INFN Sezione di Bari, Bari, Italy
[b] Università di Bari, Bari, Italy
[c] Politecnico di Bari, Bari, Italy

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

[a] INFN Sezione di Bologna, Bologna, Italy
[b] Università di Bologna, Bologna, Italy

S. Albergo [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]

[a] INFN Sezione di Catania, Catania, Italy
[b] Università di Catania, Catania, Italy

G. Barbagli [a], K. Chatterjee [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], L. Russo [a,27], G. Sguazzoni [a], D. Strom [a], L. Viliani [a,b,13]

[a] INFN Sezione di Firenze, Firenze, Italy
[b] Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera [13]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli [a,b], F. Ferro [a], E. Robutti [a], S. Tosi [a,b]

[a] INFN Sezione di Genova, Genova, Italy
[b] Università di Genova, Genova, Italy

A. Benaglia [a], L. Brianza [a,b], F. Brivio [a,b], V. Ciriolo [a,b], M.E. Dinardo [a,b], S. Fiorendi [a,b], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], M. Malberti [a,b], S. Malvezzi [a], R.A. Manzoni [a,b], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], K. Pauwels [a,b], D. Pedrini [a], S. Pigazzini [a,b,28], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b]

[a] INFN Sezione di Milano-Bicocca, Milano, Italy
[b] Università di Milano-Bicocca, Milano, Italy

S. Buontempo [a], N. Cavallo [a,c], S. Di Guida [a,d,13], F. Fabozzi [a,c], F. Fienga [a,b], A.O.M. Iorio [a,b], W.A. Khan [a], L. Lista [a], S. Meola [a,d,13], P. Paolucci [a,13], C. Sciacca [a,b], F. Thyssen [a]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli 'Federico II', Napoli, Italy
[c] Università della Basilicata, Potenza, Italy
[d] Università G. Marconi, Roma, Italy

P. Azzi [a,13], N. Bacchetta [a], L. Benato [a,b], D. Bisello [a,b], A. Boletti [a,b], R. Carlin [a,b], A. Carvalho Antunes De Oliveira [a,b], P. Checchia [a], M. Dall'Osso [a,b], P. De Castro Manzano [a], T. Dorigo [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], S. Lacaprara [a], P. Lujan, M. Margoni [a,b], A.T. Meneguzzo [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], E. Torassa [a], M. Zanetti [a,b], P. Zotto [a,b], G. Zumerle [a,b]

[a] INFN Sezione di Padova, Padova, Italy
[b] Università di Padova, Padova, Italy
[c] Università di Trento, Trento, Italy

A. Braghieri [a], A. Magnani [a,b], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], M. Ressegotti, C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, Italy

L. Alunni Solestizi [a,b], M. Biasini [a,b], G.M. Bilei [a], C. Cecchi [a,b], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], E. Manoni [a], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a], P. Azzurri [a,13], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], L. Borrello, R. Castaldi [a], M.A. Ciocci [a,b], R. Dell'Orso [a], G. Fedi [a], L. Giannini [a,c], A. Giassi [a], M.T. Grippo [a,27], F. Ligabue [a,c], T. Lomtadze [a], E. Manca [a,c], G. Mandorli [a,c], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,29], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], D. Del Re [a,b,13], E. Di Marco [a,b], M. Diemoz [a], S. Gelli [a,b], E. Longo [a,b], F. Margaroli [a,b], B. Marzocchi [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a,b], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], F. Cenna [a,b], M. Costa [a,b], R. Covarelli [a,b], A. Degano [a,b], N. Demaria [a], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M. Monteno [a], 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], K. Shchelina [a,b], V. Sola [a], A. Solano [a,b], A. Staiano [a], P. Traczyk [a,b]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale, Novara, Italy*

S. Belforte [a], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], A. Zanetti [a]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

*Kyungpook National University, Daegu, Republic of Korea*

A. Lee

*Chonbuk National University, Jeonju, Republic of Korea*

H. Kim, D.H. Moon, G. Oh

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

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

*Hanyang University, Seoul, Republic of Korea*

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

*Korea University, Seoul, Republic of Korea*

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

*Seoul National University, Seoul, Republic of Korea*

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

*University of Seoul, Seoul, Republic of Korea*

Y. Choi, C. Hwang, J. Lee, I. Yu

*Sungkyunkwan University, Suwon, Republic of Korea*

V. Dudenas, A. Juodagalvis, J. Vaitkus

*Vilnius University, Vilnius, Lithuania*

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali [30], F. Mohamad Idris [31], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

R. Reyes-AlmanzaG. Ramirez-SanchezM.C. Duran-OsunaH. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [32], R.I. Rabadan-TrejoR. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

A. Morelos Pineda

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

D. Krofcheck

*University of Auckland, Auckland, New Zealand*

P.H. Butler

*University of Canterbury, Christchurch, New Zealand*

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

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

*National Centre for Nuclear Research, Swierk, Poland*

K. Bunkowski, A. Byszuk [33], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev [34,35], V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

Y. Ivanov, V. Kim[36], E. Kuznetsova[37], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

*Institute for Nuclear Research, Moscow, Russia*

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

*Institute for Theoretical and Experimental Physics, Moscow, Russia*

T. Aushev, A. Bylinkin[35]

*Moscow Institute of Physics and Technology, Moscow, Russia*

M. Chadeeva[38], O. Markin, P. Parygin, D. Philippov, S. Polikarpov, V. Rusinov

*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*

V. Andreev, M. Azarkin[35], I. Dremin[35], M. Kirakosyan[35], A. Terkulov

*P.N. Lebedev Physical Institute, Moscow, Russia*

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[39], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin

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

V. Blinov[40], Y. Skovpen[40], D. Shtol[40]

*Novosibirsk State University (NSU), Novosibirsk, Russia*

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

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

P. Adzic[41], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, 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, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Álvarez Fernández

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

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

*Universidad Autónoma de Madrid, Madrid, Spain*

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol,

F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban[16], J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer[13], M.J. Kortelainen, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[42], F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi[43], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[44], A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns[45], M. Verweij, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

W. Bertl[†], L. Caminada[46], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*

T.K. Aarrestad, C. Amsler[47], M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Takahashi, A. Zucchetta

*Universität Zürich, Zurich, Switzerland*

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

*National Central University, Chung-Li, Taiwan*

Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

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

F. Boran, S. Cerci[48], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos[49], E.E. Kangal[50], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut[51], K. Ozdemir[52], D. Sunar Cerci[48], B. Tali[48], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Bilin, G. Karapinar[53], K. Ocalan[54], M. Yalvac, M. Zeyrek

*Middle East Technical University, Physics Department, Ankara, Turkey*

E. Gülmez, M. Kaya[55], O. Kaya[56], S. Tekten, E.A. Yetkin[57]

*Bogazici University, Istanbul, Turkey*

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold[58], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev[59], 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

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

G. Auzinger, R. Bainbridge, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko[6], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[60], T. Virdee[13], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

*Imperial College, London, United Kingdom*

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

*Brunel University, Uxbridge, United Kingdom*

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

*Baylor University, Waco, USA*

R. Bartek, A. Dominguez

*Catholic University of America, Washington DC, USA*

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

*The University of Alabama, Tuscaloosa, USA*

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

*Boston University, Boston, USA*

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

*Brown University, Providence, USA*

R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett,

J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang

*University of California, Davis, Davis, USA*

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev

*University of California, Los Angeles, USA*

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

*University of California, Riverside, Riverside, USA*

J.G. Branson, S. Cittolin, M. Derdzinski, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[61], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

*University of California, Santa Barbara – Department of Physics, Santa Barbara, USA*

D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

*Cornell University, Ithaca, USA*

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, 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

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

*University of Florida, Gainesville, USA*

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

*Florida International University, Miami, USA*

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

*Florida State University, Tallahassee, USA*

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

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

B. Bilki[62], W. Clarida, K. Dilsiz[63], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[64], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[65], Y. Onel, F. Ozok[66], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, USA*

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

*Johns Hopkins University, Baltimore, USA*

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, R. Stringer, J.D. Tapia Takaki, Q. Wang

*The University of Kansas, Lawrence, USA*

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

*Kansas State University, Manhattan, USA*

F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, 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. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

*Massachusetts Institute of Technology, Cambridge, USA*

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

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

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

*Northeastern University, Boston, USA*

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

*Northwestern University, Evanston, USA*

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[34], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

*Princeton University, Princeton, USA*

S. Malik, S. Norberg

*University of Puerto Rico, Mayaguez, USA*

A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

*Purdue University, West Lafayette, USA*

T. Cheng, N. Parashar, J. Stupak

*Purdue University Northwest, Hammond, USA*

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

*Rice University, Houston, USA*

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

*University of Rochester, Rochester, USA*

R. Ciesielski, K. Goulianos, C. Mesropian

*The Rockefeller University, New York, USA*

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

*University of Tennessee, Knoxville, USA*

O. Bouhali[67], A. Castaneda Hernandez[67], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[68], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

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

N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

*Texas Tech University, Lubbock, USA*

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

*Vanderbilt University, Nashville, USA*

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

*University of Virginia, Charlottesville, USA*

R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

*Wayne State University, Detroit, USA*

M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

*University of Wisconsin – Madison, Madison, WI, USA*

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[†] Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[3] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[4] Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[5] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[6] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[7] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[8] Also at Suez University, Suez, Egypt.
[9] Now at British University in Egypt, Cairo, Egypt.
[10] Now at Helwan University, Cairo, Egypt.
[11] Also at Université de Haute Alsace, Mulhouse, France.
[12] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[13] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[14] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

[15] Also at University of Hamburg, Hamburg, Germany.
[16] Also at Brandenburg University of Technology, Cottbus, Germany.
[17] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[18] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[19] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[20] Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
[21] Also at Institute of Physics, Bhubaneswar, India.
[22] Also at University of Visva-Bharati, Santiniketan, India.
[23] Also at University of Ruhuna, Matara, Sri Lanka.
[24] Also at Isfahan University of Technology, Isfahan, Iran.
[25] Also at Yazd University, Yazd, Iran.
[26] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[27] Also at Università degli Studi di Siena, Siena, Italy.
[28] Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy.
[29] Also at Purdue University, West Lafayette, USA.
[30] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[31] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[32] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[33] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[34] Also at Institute for Nuclear Research, Moscow, Russia.
[35] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[36] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[37] Also at University of Florida, Gainesville, USA.
[38] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[39] Also at California Institute of Technology, Pasadena, USA.
[40] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[41] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[42] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[43] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[44] Also at National and Kapodistrian University of Athens, Athens, Greece.
[45] Also at Riga Technical University, Riga, Latvia.
[46] Also at Universität Zürich, Zurich, Switzerland.
[47] Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
[48] Also at Adiyaman University, Adiyaman, Turkey.
[49] Also at Istanbul Aydin University, Istanbul, Turkey.
[50] Also at Mersin University, Mersin, Turkey.
[51] Also at Cag University, Mersin, Turkey.
[52] Also at Piri Reis University, Istanbul, Turkey.
[53] Also at Izmir Institute of Technology, Izmir, Turkey.
[54] Also at Necmettin Erbakan University, Konya, 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 Rutherford Appleton Laboratory, Didcot, United Kingdom.
[59] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[60] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[61] Also at Utah Valley University, Orem, USA.
[62] Also at Beykent University, Istanbul, Turkey.
[63] Also at Bingol University, Bingol, Turkey.
[64] Also at Erzincan University, Erzincan, Turkey.
[65] Also at Sinop University, Sinop, Turkey.
[66] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[67] Also at Texas A&M University at Qatar, Doha, Qatar.
[68] Also at Kyungpook National University, Daegu, Korea.