Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state is presented. The analysis is based on proton-proton collision data recorded by the CMS detector in 2016–2018 at a centre-of-mass energy of 13 TeV at the CERN LHC, corresponding to an integrated luminosity of $138 \text{ fb}^{-1}$. The search is sensitive to resonances with masses between 1.3 and 6 TeV, decaying to bosons that are highly Lorentz-boosted such that each of the bosons forms a single large-radius jet. Machine learning techniques are employed to identify such jets. No significant excess over the estimated standard model background is observed. A maximum local significance of 3.6 standard deviations, corresponding to a global significance of 2.3 standard deviations, is observed at masses of 2.1 and 2.9 TeV. In a heavy vector triplet model, spin-1 $Z'$ and $W'$ resonances with masses below 4.8 TeV are excluded at the 95% confidence level (CL). These limits are the most stringent to date. In a bulk graviton model, spin-2 gravitons and spin-0 radions with masses below 1.4 and 2.7 TeV, respectively, are excluded at 95% CL. Production of heavy resonances through vector boson fusion is constrained with upper cross section limits at 95% CL as low as 0.1 fb.

Published in Physics Letters B as doi:10.1016/j.physletb.2023.137813.
1 Introduction

The CERN LHC allows the probing of new phenomena in interactions of elementary particles at energies of multiple TeV. While the standard model (SM) of particle physics describes these high-energy interactions very successfully, it leaves several questions unresolved, such as the nature of dark matter and the origin of the large difference between the electroweak and Planck scales. Theories beyond the SM that can address these questions introduce new particles and interactions that could be observed in proton-proton (pp) collisions at the LHC.

A wide range of models predict the production of new heavy resonances decaying to pairs of $W$, $Z$ (jointly referred to as $V$), and Higgs bosons (H). Examples of such resonances are spin-0 radions ($\text{Rad}$) and spin-2 gravitons ($G_{\text{bulk}}$) in the Randall–Sundrum model with warped extra dimensions [1–7], and spin-1 vector boson resonances ($W'$ and $Z'$) appearing in composite Higgs [10–14] and little Higgs [15, 16] models and forming a heavy vector triplet ($\text{HVT}$) [17].

Previous searches by the CMS Collaboration in the $VV$ [18–29] and $VH$ [18, 30–36] channels, and corresponding searches by the ATLAS Collaboration in the $VV$ [37–45] and $VH$ [46–49] channels, have not observed significant deviations from the SM. The most stringent lower limits at 95% confidence level (CL) [18, 37] for spin-1 resonances decaying to a $WZ$ ($WH$) boson pair exclude masses up to 4.3 (4.0) TeV in the HVT model B [17].

This Letter presents a search in the all-jets final state for new heavy resonances using a pp collision data set collected by the CMS experiment at a centre-of-mass energy of 13 TeV in 2016–2018 corresponding to an integrated luminosity of $138 \text{fb}^{-1}$. Resonances decaying to a $VV$ or $VH$ boson pair with masses between 1.3 and 6 TeV and produced via Drell–Yan (DY), gluon fusion (ggF), or vector boson fusion (VBF) are targeted. Representative Feynman diagrams for the aforementioned processes are shown in Fig. 1.

![Feynman diagrams](https://example.com/feynman_diagrams.png)

Figure 1: Feynman diagrams of the signal processes ggF or DY produced (upper) and VBF produced (lower): (left) graviton or radion decaying to $WW$ or $ZZ$; (center) $Z'$ and $W'$ decaying to $ZH$ and $WH$, respectively; (right) $Z'$ and $W'$ decaying to $WW$ and $WZ$, respectively.

Because of the large Lorentz boost of the $H$, $W$, and $Z$ bosons from the resonance decay, each boson decay is typically clustered as a single large-radius jet. The final state thus consists of
two large-radius jets (distance parameter $R = 0.8$) in the case of DY and ggF production, with two additional small-radius ($R = 0.4$) jets in the case of VBF production. The SM background estimation and signal extraction procedure is based on a three-dimensional (3D) maximum likelihood fit to the mass of the two large-radius jet systems and the two individual large-radius jet masses, as introduced in a previous search by the CMS Collaboration in the VV channel [19]. The sensitivity to VV and VH resonances is significantly improved compared to previous searches by categorizing events according to jet tagging algorithms based on machine learning [50] that analyze the substructure of the large-radius jets to separate jets that originate from boosted H, W, and Z bosons from other jets. Events are further categorized based on the presence of additional small-radius jets, enhancing the sensitivity to VBF-produced resonances.

2 The CMS detector and event reconstruction

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. Forward calorimeters extend the pseudorapidity 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. [51].

Event reconstruction is based on a particle flow algorithm [52], which reconstructs and identifies individual particles (photon, electron, muon, charged hadron, neutral hadron) with information from the various elements of the CMS detector. Jets are reconstructed from these particles, using the anti-$k_T$ jet clustering algorithm [53] with distance parameters of $R = 0.4$ (AK4 jets) and $R = 0.8$ (AK8 jets), as implemented in the FASTJET package [54]. To mitigate the effect of additional pp interactions within the same or nearby bunch crossings (pileup) on the reconstructed jet momentum, tracks identified as originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation studies. In situ measurements of the momentum balance in dijet, photon+jet, Z+jets, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [55]. Additional selection criteria are applied to each jet to remove jet measurements potentially arising from instrumental effects or reconstruction failures [56].

Events of interest are selected using a two-tiered trigger system [57]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed time interval of less than 4 µs. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. Events are selected online with a variety of different jet triggers based on the highest jet transverse momentum ($p_T$) or the $p_T$ sum of all jets in the event ($H_T$). For some of these triggers additional requirements on the trimmed jet mass [58] are applied to allow lower the $p_T$ and $H_T$ thresholds [19, 25]. The trigger efficiency as a function of the invariant mass of the two highest $p_T$ AK8 jets ($m_{j\bar{j}}^{AK8}$) is >99% above 1250 GeV for all three data-taking years, and the subsequent analysis thus requires $m_{j\bar{j}}^{AK8}$ to be above this threshold.
3 Signal and background simulation

Each signal model is characterized by key parameters. The bulk graviton model is characterized by two free parameters: the mass of the first Kaluza–Klein excitation of a spin-2 boson (the Kaluza–Klein bulk graviton), and the ratio $\tilde{\kappa} = \kappa / \sqrt{8 \pi} / M_{Pl}$, with $\kappa$ being the unknown curvature scale of the extra dimension and $M_{Pl}$ the Planck mass. A scenario with $\tilde{\kappa} = 0.5$, resulting in resonances with a width smaller than the detector resolution is considered in this analysis, as motivated in Ref. [59]. The radion model is also characterized by two parameters: $r_c$, the compactification radius, and $\Lambda_R$, the ultraviolet cutoff of the theory. The scenario with $kr_c \pi = 35$ and $\Lambda_R = 3 \text{TeV}$ [59] is considered in this analysis. The HVT model is characterized in terms of four parameters: the mass of the W $'$ and Z $'$ resonance; a coefficient $c_F$, which scales the couplings of the additional gauge bosons to fermions; $c_H$, which scales the couplings to the Higgs boson and longitudinally polarized SM vector bosons; and $g_V$, representing the typical strength of the new vector boson interaction. Two scenarios are considered in this analysis: HVT model B, corresponding to $g_V = 3$, $c_H = -0.98$, and $c_F = 1.02$ [17]; and HVT model C [17], corresponding to $g_V = 1$, $c_H = 1 - 3$, and $c_F = 0$. In both scenarios, the new resonances have a narrow decay width and large branching fraction to vector boson pairs, while the fermionic couplings are suppressed. In the HVT model C, which has no fermionic couplings, the resonances would be produced at the LHC exclusively via the VBF mode.

Monte Carlo (MC) simulated events of the radion, bulk graviton, and HVT resonance signal processes are generated at leading order (LO) in perturbative quantum chromodynamics (QCD) with MadGraph5_aMC@NLO versions 2.4.2 and 2.6.0 [60]. The parton showering and hadronization is simulated with Pythia versions 8.205 and 8.230 [61], for 2016 and 2017–2018 detector conditions, respectively. The NNPDF 3.0 [62] LO parton distribution functions (PDFs) are used together with the CUETP8M1 [63] and CT5 [64] underlying-event tunes in Pythia for 2016 and 2017–2018 conditions, respectively. The signal cross sections are computed at next-to-LO (NLO) with MadGraph5_aMC@NLO with the PDF4LHC15_100 PDF set [62,63,69].

Simulated event samples of the SM background processes are used to develop the analysis strategy and create templates for distributions used in the comparison with data. The QCD multijet production is simulated with three generator configurations: Pythia only, the LO mode of MadGraph5_aMC@NLO [70] interfaced with Pythia for the parton shower evolution and matching (MG+PYTHIA8 in the following), and HERWIG++ 2.7.1 [71] with the CUETHS1 tune [63]. Top quark pair (tt), single top quark, and boson pair production are modelled at NLO with POWHEG v2 [72] interfaced with PYTHIA. The production of W+jets and Z+jets (V+jets) is simulated at LO with MadGraph5_aMC@NLO interfaced with PYTHIA. The same underlying-event tunes as used in the signal event samples are used in the background event samples. A correction [73] is applied to the simulated V+jets events to match the $p_T$ distribution of the vector bosons computed at LO in QCD to the one predicted at NLO in QCD, and another correction [74] is used to account for NLO electroweak effects at high $p_T$. The NNPDF 3.1 [75] next-to-NLO (NNLO) PDFs are employed for simulated V+jets events.

All samples are processed through a Geant4-based [66] simulation of the CMS detector. To simulate the effect of pileup collisions, additional inelastic events are generated using Pythia and superimposed on the hard-scattering events. The simulated events are weighted to reproduce the distribution of the number of reconstructed pileup vertices observed in the 2016, 2017, and 2018 data separately. While the detector components and conditions varied across the three years of data taking, the detector performance relevant to this analysis, in particular with regard to the $m_{jj}^{A K S}$ and $m_{j e t}^{A K S}$ scale and resolution, was very similar [77,78]. We therefore combine the simulated event samples corresponding to the three years of data taking, weight-
ing them according to the corresponding integrated luminosity of 36.3, 41.5, and 59.7 fb\(^{-1}\) for 2016, 2017, and 2018 \cite{79,80,81}, respectively.

## 4 Event selection

All events are required to have at least one primary vertex reconstructed within a region extending 24 cm along the beam, centred on the centre of the detector, and extending 2 cm from the mean beam axis in the transverse direction \cite{82}. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. \cite{83}.

Events are selected by requiring at least two AK8 jets with \(p_T > 200\) GeV and \(|\eta| < 2.5\). The two AK8 jets with the highest \(p_T\) in the event are selected as potential vector boson or Higgs boson candidates and are required to have a separation of \(|\Delta\eta_{AK8}^j| < 1.3\) in order to reduce the QCD multijet background. The invariant mass of the two AK8 jets is required to fulfill \(m_{AK8}^{jj} > 1250\) GeV, based on the trigger selection discussed in Section 2. Given the \(m_{AK8}^{jj}\) resolution of about 10\%, the lowest resonance mass that passes this selection with high efficiency is 1.3 TeV. Jets originating from the misreconstruction of a high-momentum lepton are rejected by requiring an angular separation \(\Delta R = \sqrt{\left(\Delta\eta\right)^2 + \left(\Delta\phi\right)^2} > 0.8\) (where \(\phi\) is the azimuthal angle) from muons (electrons) with \(p_T > 20\) (35) GeV and satisfying identification criteria optimized for high-momentum leptons \cite{84,85}.

Hadronic decays of H, W, and Z bosons are identified using two variables computed from the AK8 jet constituents: the “groomed” mass of the jet and the score from the DeepAK8 neural network \cite{50} jet tagging algorithm. When computing these jet variables, the pileup per particle identification algorithm \cite{86,87} is used to mitigate the effect of pileup at the reconstructed particle level, making use of local shape information, event pileup properties, and tracking information.

To improve the resolution of the jet mass, the groomed jet mass (\(m_{AK8}^{\text{jet}}\)) is calculated with the soft drop algorithm \cite{88}, which removes soft and wide angular radiation by reclustering the jet constituents using the Cambridge–Aachen algorithm \cite{89,90} with parameters \(\beta = 0\), \(z_{\text{cut}} = 0.1\), and \(R_0 = 0.8\).

The DeepAK8 tagger is trained on multiple properties of the reconstructed jet constituents and secondary vertices. For each jet constituent, measured properties such as \(p_T\), charge, and angular separation between the particle and the jet axis, are included. Additional properties of charged particles and secondary vertices are used to extract features related to the presence of heavy-flavor (b or c) quarks. The DeepAK8 tagger features a two-step customized deep neural network architecture, developed to handle the high number of input features and their correlations. In the first step, two separate convolutional neural networks extract the helpful characteristics of the constituent particles and the secondary vertices. The jet categorization happens in the second step, where a simple, fully connected network combines and processes the output of the two convolutional networks.

Jets are categorized according to their origin from single quarks or gluons, or H, W, and Z bosons decaying to bottom, charm, or light quark pairs. Two tagger discriminants based on the DeepAK8 categorization are used in this search. The \(q\bar{q}\) tagger considers W and Z bosons decaying to light quark pairs as signal and single quarks and gluons as background. The \(b\bar{b}\) tagger considers H and Z bosons decaying to bottom quark pairs as signal and single quarks and gluons as background. As the background estimation procedure of this search relies on
Table 1: Summary of the event category definitions. The categories are listed from the highest to the lowest sensitivity in each production mode. The percentages correspond to the maximum misidentification rate associated with the high (HP) and low (LP) purity working points.

| Event category     | VBF    | AK8 jet1 or 2 tag | AK8 jet2 or 1 tag |
|--------------------|--------|-------------------|-------------------|
| VBF VH HPHP        | pass   | (5% qQ or 2% b\bar{b}) | 2% b\bar{b}     |
| VBF VV HPHP        | pass   | 5% qQ             | 5% qQ            |
| VBF VH LPHP        | pass   | (20% qQ or 10% b\bar{b}) | 2% b\bar{b}     |
| VBF VH HPLP        | pass   | 5% qQ             | 10% b\bar{b}    |
| VBF VV HPLP        | pass   | 5% qQ             | 20% qQ           |
| DY/ggF VH HPHP     | fail   | (5% qQ or 2% b\bar{b}) | 2% b\bar{b}     |
| DY/ggF VV HPHP     | fail   | 5% qQ             | 5% qQ            |
| DY/ggF VH LPHP     | fail   | (20% qQ or 10% b\bar{b}) | 2% b\bar{b}     |
| DY/ggF VH HPLP     | fail   | 5% qQ             | 10% b\bar{b}    |
| DY/ggF VV HPLP     | fail   | 5% qQ             | 20% qQ           |

To reduce the QCD multijet background, we require each AK8 jet mass to be between 55 and 215 GeV. Finally, a loose requirement of $\rho = \ln((m_{\text{AK8 jet}}^2)/p_T^2) < -1.8$ [91] is applied in order to veto events in which the jet mass is high, but the jet $p_T$ is low. In those cases, the cone size of $\Delta R = 0.8$ is too small to contain the full jet, affecting both the jet mass resolution and the qQ tagging efficiency, which are consequently not well modelled in the simulation.

To simplify the modelling of the 3D shapes in the $(m_{\text{AK8 jet1}}^2, m_{\text{AK8 jet2}}^2, m_{\text{AK8 jet3}}^2)$ space, the two AK8 jets are labelled at random so that the mass distributions of the first and second selected jet, $m_{\text{AK8 jet1}}$ and $m_{\text{AK8 jet2}}$, have the same shape. The selected events are subdivided to enhance sensitivity to VBF signal production. The VBF topology is selected by requiring at least two AK4 jets with $p_T > 30$ GeV and $|\eta| < 5.0$ that do not overlap within $\Delta R < 1.2$ with the leading two AK8 jets. A separation of $|\Delta \eta_{\text{AK4}}| > 4.5$ and an invariant mass of the two leading AK4 jets larger than 800 GeV is required to maximize the signal-to-background ratio and achieve the best sensitivity.

Events are further grouped into categories using the qQ and b\bar{b} taggers with different tagging rates, i.e. different signal-to-background ratios (high purity “HP” and low purity “LP”), to target specific signal decay modes, as summarized in Table 1. Purities are expressed in terms of the maximum allowed misidentification rate. To ensure that each event ends up only in one category, events are required to fail the selection of all previous categories in the order listed in Table 1. The overall signal efficiency depends on the resonance type and mass, and is estimated...
from simulation to be 12–26% and 2–18% for DY/ggF production and VBF production, respectively. For resonances decaying to a Higgs boson, the VH HPHP category contains 40–60% of the signal, while for the other resonances 10–40% of the signal is contained in the VH HPHP category and 15–40% in the VV HPHP category. The other DY/ggF categories contain 5–40% of the signal, depending on the resonance type and mass. The VBF categories contain 25–40% of the VBF signals and less than 5% of the DY/ggF signals.

5 Background estimation and signal extraction

To test for the presence of narrow resonances decaying to two bosons, a 3D maximum likelihood fit of signal and background templates to the data in the \((m_{\text{jj}}, m_{\text{jet1}}, m_{\text{jet2}})\) space is carried out in all event categories simultaneously. We give a brief explanation of the fit model in the following, and refer to Ref. [19] for more details.

The main SM background processes in this search are QCD multijet, \(t\bar{t}\), W+jets, and Z+jets production. The QCD multijet production is the largest background in all categories. While in the VV event categories the QCD multijet production is by far the most dominant, making up more than 75% of the background, in the VH categories \(t\bar{t}\) contributes up to 41% of the background. The background from W+jets and Z+jets contributes up to 4%, most significantly to the LP categories. The background contribution from single top quark and diboson production is less than 1.5 and 0.5%, respectively, and is modelled as a part of the \(t\bar{t}\) background. Signal and background templates in the \((m_{\text{jj}}, m_{\text{jet1}}, m_{\text{jet2}})\) space are built from simulation with the method described in Ref. [19] to prevent fluctuations due to the limited number of generated events.

While the signal is resonant in the \(m_{\text{jj}}, m_{\text{jet1}}, \) and \(m_{\text{jet2}}\) observables, all backgrounds are nonresonant in \(m_{\text{jj}}\). The QCD multijet background is nonresonant in all three dimensions. The remaining backgrounds have partly resonant components in \(m_{\text{jet1}}, \) modelled by separate templates, and partly nonresonant components that are absorbed in the QCD multijet background template. In the background model it is assumed that background components resonant in \(m_{\text{jet}}\) containing jets from genuine V bosons or top quarks can be reasonably well modelled by simulation calibrated with external measurements. Nonresonant background components with jets initiated by single quarks or gluons misidentified by the \(q\bar{q}\) and \(b\bar{b}\) taggers may be largely mismodelled in simulation, and are constrained in the likelihood fit to the data. Systematic uncertainties in the signal and background models are treated as nuisance parameters and profiled in the statistical interpretation of the data.

To account for discrepancies in the QCD multijet simulation and data, we allow the background model (template) to adapt to the data using physically motivated variations of the nominal shape of the distributions obtained from the PYTHIA8-only simulations. The templates are smooth versions of the simulations obtained from simulated events through a forward folding approach, as described in Ref. [19]. The alternative shapes described below are shown in Fig. 2 together with the PYTHIA8 templates and simulation. The normalization of the QCD multijet background is allowed to vary within 50% and is treated as uncorrelated between all event categories to let the fit constrain the yield in each of them separately. Alternative shapes with variations proportional to \(m_{\text{jj}}, 1/m_{\text{jj}}, m_{\text{jet}}, \) and \(1/m_{\text{jet}}\) allow for variations in the underlying jet \(p_T\) spectrum and jet mass scale. Two additional alternative shapes that simultaneously affect the resonance mass and the groomed jet mass are also added in order to take into account differences in the MC generation and modelling of the parton shower. These alternative templates are derived using the HERWIG++ and MG+PYTHIA8 QCD multijet simulation.

For events with a large \(m_{\text{jet}}\) (>175 GeV) and low \(m_{\text{jj}}\) (<1400 GeV), the distribution exhibits
Figure 2: Distributions of $m_{AK8}^{jj}$ (left) and $m_{AK8}^{jet1}$ (right) in the nominal QCD multijet simulation using PYTHIA8 (black markers) and three-dimensional templates (black solid line) in the DY/ggF VH HPHP category. Superimposed are the normalized up and down variations of five alternative shapes corresponding to shape nuisance parameters in the fit model. Each of the variations has a characteristic dependence on $m_{AK8}^{jet}$ to allow the necessary flexibility in the fit for the template to adapt to the data. We also allow an overall variation of the rate in the fit. The distribution of $m_{AK8}^{jet2}$ is not shown, as it is similar to the distribution of $m_{AK8}^{jet1}$. 

a turn-on close to the $\rho < -1.8$ threshold that is particularly difficult to model with the QCD multijet simulation. An additional smooth shape variation ($m_{AK8}^{jet}$ turn-on in Fig. 2) parameterizing any discrepancy between the 3D template and the QCD multijet simulation in this region is added to the fit. We neglect the uncertainties due to the choice of PDF in the QCD multijet simulation, since it was verified that these effects are covered by the included shape variations. All shape variations are treated as uncorrelated among the event categories with different tagger requirements and correlated among the VBF and DY/ggF categories.

Similarly, for the W+jets and Z+jets backgrounds, two alternative shapes of the $m_{AK8}^{jj}$ templates derived by a variation proportional to $m_{AK8}^{jj}$ and $1/m_{AK8}^{jj}$ are considered, and the normalization is allowed to vary within 50%, uncorrelated between all event categories. We neglect the uncertainties due to the NLO QCD+EW corrections to the V+jets simulation, since it was verified that these effects are covered by the included shape variations. The $t\bar{t}$ background normalization is allowed to vary within 6% [93, 94] and is considered correlated between the event categories as it is dominantly doubly-resonant in $m_{jet1}$ and $m_{jet2}$. An alternative shape where the top quark $p_T$ spectrum is reweighted to match the observed $p_T$ distribution in $t\bar{t}$ data [94] is also taken into account.

Systematic uncertainties in H, W, and Z boson reconstruction and identification are dominant for the signal, and are treated as correlated between the signal and the background components resonant in the $m_{jet}^{AK8}$ observable. The 3D fit constrains the corresponding nuisance parameters that are included with a prior uncertainty from external measurements of the H, W, and Z boson reconstruction and identification performance. Uncertainties in the jet mass scale, jet mass resolution, and the $q\bar{q}$ and $b\bar{b}$ tagging efficiencies are estimated from their calibration in a semileptonic $t\bar{t}$ event sample [50] and in a sample enriched with $g \to b\bar{b}$ jets using a
double-muon tag\[92\]. The jet mass scale and resolution are allowed to vary within 2 and 8%, respectively. The tagging efficiency of the 5% q\(\bar{q}\), 20% q\(\bar{q}\), 2% b\(\bar{b}\), and 10% b\(\bar{b}\) taggers are allowed to vary within 7–15%, 7–9%, 3–9%, and 2–7%, respectively, depending on the year of data taking. Uncertainties equal to 1.5 times the nominal tagging uncertainty values are included in the fit as additional nuisance parameters to account for the potential mismodelling of the \(p_T\) dependence of the tagging efficiency beyond the range of the data-to-simulation scale factor measurement. Finally, the q\(\bar{q}\) tagger’s rate for misidentification of hadronically decaying top quarks in the tf sample is allowed to vary within 3–7%.

The uncertainty in the signal acceptance and in the mean and width of the \(m_{\text{AK8}}^{\text{jj}}, m_{\text{AK8}}^{\text{jet1}},\) and \(m_{\text{AK8}}^{\text{jet2}}\) distributions originating from the PDFs for the signal processes are determined from the LO NNPDF set, where the root-mean-square of 100 pseudo-experiments obtained from the PDF set provides the uncertainty envelope. Uncertainties related to the jet energy scale and resolution are taken into account as nuisance parameters varying the \(m_{\text{AK8}}^{\text{jj}}\) mean and width.

The uncertainty in the integrated luminosity amounts to 1.6%\[79–81\].

![Figure 3](image-url)  

Figure 3: Comparison between the background post-fit and the data distributions of \(m_{\text{AK8}}^{\text{jet}}\) (left) and \(m_{\text{AK8}}^{\text{jj}}\) (right) in the DY/ggF VH HPHP category. The background shape uncertainty is shown as a gray shaded band around the result of the maximum likelihood fit to the data under the background-only assumption (gray solid line), and the statistical uncertainties in the data are represented as vertical bars. The various background components contributing to the total background fit are also shown with different line colors. An example of a signal distribution is overlaid, where the number of expected events is scaled by an arbitrary normalization factor of 20. Shown below each mass plot is the difference between the data and the fit divided by the statistical uncertainty in the data; the uncertainty bar represents the statistical uncertainty only. The total uncertainty in the background estimate fitted to the data divided by the statistical uncertainty in the data is shown as a band.

Figure 3 shows the \(m_{\text{jet}}^{\text{AK8}}\) and \(m_{\text{jj}}^{\text{AK8}}\) spectra in data in the category most sensitive to the DY/ggF VH signal. The solid gray histograms represent the results of the maximum likelihood fit to the data under the background-only assumption. The resonant background components are shown separately. A signal is superimposed onto all projections corresponding to a signal yield as expected from the theoretical prediction and the analysis selection efficiency, and scaled by an arbitrary factor. The lower panels in Fig. 3 show the difference between the data and the
Figure 4: Projections of the data and background post-fit distributions onto the $m_{\text{AK8}}$ dimension in regions enriched in background ($m_{\text{AK8}}^{\text{jet1}} < 65$ or $> 140$ GeV, and $m_{\text{AK8}}^{\text{jet2}} < 65$ or $> 140$ GeV), for the HPHP VH (left) and VV (right) DY/ggF categories. The background shape uncertainty is shown as a gray shaded band around the result of the maximum likelihood fit to the data under the background-only assumption (gray solid line), and the statistical uncertainties in the data are shown as vertical bars. The various background components contributing to the total background fit are also shown with different line colors. Shown below each mass plot is the difference between the data and the fit divided by the statistical uncertainty in the data; the uncertainty bar represents the statistical uncertainty only. The total uncertainty in the background estimate fitted to the data divided by the statistical uncertainty in the data is shown as a band.

Prior to the analysis of the full 3D spectra in data, the fit model was validated as follows. The capability of the fit model to extract, without a significant bias, the cross section and significance of a potential signal resonance was confirmed with toy data distributions obtained from simulation with signal injected. In data event samples enriched in QCD multijet and tt events, obtained by excluding events with $65 < m_{\text{AK8}}^{\text{jet1}} < 140$ GeV and $65 < m_{\text{AK8}}^{\text{jet2}} < 140$ GeV in all categories of the analysis, a good description of the $m_{\text{AK8}}^{\text{jet1}}$, $m_{\text{AK8}}^{\text{jet2}}$, and $m_{\text{AK8}}^{\text{jj}}$ was found. Figure 4 shows an example validation for the $m_{\text{AK8}}^{\text{jj}}$ spectra in data in the DY/ggF HPHP categories. Finally, a goodness of fit test based on the saturated model is performed, comparing the full 3D spectra in data with the result of a maximum likelihood fit to the data under the background-only assumption. In this test, all uncertainties and their correlations are taken into account. A $p$-value of 0.35 is estimated w.r.t. the expected goodness of fit, indicating a good compatibility between the observed data and the background-only model.

6 Results

Figure 5 shows the $m_{\text{AK8}}^{\text{jj}}$ spectra in data for selected regions in $m_{\text{jet1}}^{\text{AK8}}$ and $m_{\text{jet2}}^{\text{AK8}}$ enriched in signal from DY/ggF VV in the two categories most sensitive to the DY/ggF VV signal. The
DY/ggF VH HPHP category exhibits an excess of data events over the background prediction in the 1.7–3.2 TeV range, while in the DY/ggF VV HPHP category excesses of data events around 2 and 3 TeV are visible. In Fig. 5, additional distributions of the difference between the data and the fit divided by the statistical uncertainty in the data in the \( m_{\text{AKS}} \) spectra are shown for selected regions in \( m_{\text{AKS}} \) and \( m_{\text{AKS}} \) enriched in signal from DY/ggF VV, DY/ggF VH, and VBF VV/VH, representing the most sensitive regions of the 3D phase space.

For the statistical evaluation, we follow the CL_{s} prescription, using the asymptotic approximation described in Refs. [96, 98]. It was verified that limits computed with a full CL_{s} method agree with the asymptotic approximation approach within one standard deviation.

To check for the presence of a signal, we first compute asymptotic significances for all signal mass hypotheses in each signal scenario. A maximum local significance of 3.6 standard deviations is observed at masses of 2.1 and 2.9 TeV under the \( W' \rightarrow WZ \) hypothesis, corresponding to excesses in the spectra of the VV HPLP and VV HPHP event categories, respectively. The size of the excess remains above two standard deviations when increasing significantly the V+jets and \( t\bar{t} \) background uncertainties or using a looser (10%) q\( \bar{q} \) tagger requirement for the definition of the categories. Taking into account the look-elsewhere effect, a global significance of 2.3 standard deviations is found. Searches in the semileptonic final states [18, 37] did not observe any excesses at 2.1 and 2.9 TeV.

Upper exclusion limits on the production cross section at 95% CL are set. Figure 7 shows the
Figure 6: Distributions of the difference between the data and the background-only fit divided by the statistical uncertainty in the data. The total uncertainty in the background estimate fitted to data divided by the statistical uncertainty in the data is shown as a band. It should be noted that these two uncertainties are partially correlated. Three projections of the 3D phase space are shown in regions enriched in signal from DY/ggF VV (65 < m_{AK8} < 105 GeV, 65 < m_{jeti} < 105 GeV) (upper left), DY/ggF VH (65 < m_{AK8 jet1/2} < 105 GeV, 110 < m_{AK8 jet2/1} < 140 GeV) (upper right) and VBF VV/VH (65 < m_{AK8 jet} < 140 GeV, 65 < m_{jet2} < 140 GeV) (lower). Examples of expected signal shapes added to the fit are overlaid, where the number of expected events is scaled by an arbitrary normalization factor stated in the legend.
exclusion limits as functions of the resonance mass, compared to theoretical predictions of the product of the production cross section and the branching fraction $B$. The theoretical cross sections shown in Fig. 7 are calculated at NLO in QCD with the models detailed in Ref. [17,59]. Table 2 summarizes the resonance mass limits at 95% CL for all considered models. The limits presented in this letter are the most stringent to date in the all-jets final state. The limits on spin-1 resonances decaying to a WZ (WH) boson pair in the HVT model B match or exceed by 0.1 TeV the previous published most stringent limits from the semileptonic final states [18,37]. Considering an HVT model with VV and VH resonances, this search sets the most stringent limit of 4.8 TeV. The improvement by 15% in the cross section exclusion limits for these resonances compared to the previous result by the CMS Collaboration in this channel [19] arises in roughly equal measure from the increased size of the data set and the improved boson tagging techniques. Tabulated results are provided in the HEPData record for this analysis [99].

Figure 7: Observed and expected 95% CL upper limits on the product of the production cross section ($\sigma$) and the branching fraction, obtained after combining all categories with 138 fb$^{-1}$ of data at $\sqrt{s} = 13$ TeV, for Rad $\rightarrow$ VV (upper left), G_{bulk} $\rightarrow$ VV (upper right), HVT model B $V' \rightarrow$ VV+VH (lower left), HVT model C $V' \rightarrow$ VV+VH (lower right) signals. For each signal scenario the theoretical prediction and its uncertainty associated with the choice of PDF set is shown.
Table 2: Summary of the exclusion limits on the resonance masses for the considered models. The numbers show the lower limit at 95% CL, with the exception of the ones given in parentheses quoting the ranges of exclusion.

| Model     | Decay channel | Observed limit (TeV) | Expected limit (TeV) |
|-----------|---------------|----------------------|----------------------|
| Radion ggF | VV            | 2.7                  | 3.4                  |
| $G_{bulk} (\tilde{\kappa} = 0.5)$ ggF | VV            | 1.4                  | 1.5                  |
| HVT (B) $W'$  | WZ            | 4.4                  | 4.3                  |
| HVT (B) $W'$  | WH            | 4.0                  | 4.3                  |
| HVT (B) $Z'$  | WW (1.3–3.1, 3.3–3.5) | 3.8                  |
| HVT (B) $Z'$  | ZH            | 3.9                  | 3.8                  |
| HVT (B) $V'$  | VV            | 4.5                  | 4.5                  |
| HVT (B) $V'$  | VH            | 4.2                  | 4.5                  |
| HVT (B) $V'$  | VV + VH       | 4.8                  | 4.8                  |

7 Summary

A search has been presented for resonances with masses between 1.3 and 6 TeV that decay to $WW$, $WZ$, $ZZ$, $WH$, or $ZH$ boson pairs. Each of the two boson decays is clustered into one large-radius jet, yielding a dijet final state from Drell–Yan and gluon fusion production, complemented by two additional jets for vector boson fusion production. The hadronic decays of $H$, $W$, and $Z$ bosons are identified using machine learning-based jet taggers that reduce the background from quantum chromodynamics multijet production. No evidence of a departure from the expected background is found. A maximum local significance of 3.6 standard deviations from the standard model prediction, corresponding to a global significance of 2.3 standard deviations, is observed at masses of 2.1 and 2.9 TeV. Upper limits at 95% confidence level on the resonance production cross section are set as a function of the resonance mass. In a heavy vector triplet model, spin-1 $Z'$ and $W'$ resonances with masses below 4.8 TeV are excluded. These limits are the most stringent to date. In a bulk graviton model, spin-2 gravitons and spin-0 radions with masses below 1.4 and 2.7 TeV, respectively, are excluded. Furthermore, the exclusive production of new heavy resonances through the vector boson fusion mode is constrained with upper cross section limits as low as 0.1 fb.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INI/FN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM
Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium); the Ministry of Education and Science, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TPK2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium); the Ministry of Education and Science, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TPK2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fondação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan

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

Universität Antwerpen, Antwerpen, Belgium
M.R. Darwish, T. Janssens, T. Kello, H. Rejeb Sfar, P. Van Mechelen

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

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, K. Lee, M. Mahdavikhorrami, I. Makarenko, A. Malara, S. Paredes, L. Pétre, N. Postiaux, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaere

Ghent University, Ghent, Belgium
D. Dobur, J. Knolle, L. Lambrecht, G. Mestdagh, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovper, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, G. Brunc, F. Bury, C. Caputa, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Branda Malbouisson, W. Carvalho, J. Chinellato, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins, C. Mora Herrera, K. Mota Amarildo, L. Mundim, H. Nogima, A. Santoro, A.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes, L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novae, Sandra S. Padula

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

University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka
Beihang University, Beijing, China
T. Cheng, T. Javaid, M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer, Z. Hu, S. Lezki, K. Yi

Institute of High Energy Physics, Beijing, China
G.M. Chen, H.S. Chen, M. Chen, F. Iemmi, C.H. Jiang, A. Kapoor, H. Liao, Z.-A. Liu, V. Milosevic, F. Monti, R. Sharma, J. Tuc, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ar, Y. Bart, C. Chen, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xian, H. Yang

Sun Yat-Sen University, Guangzhou, China
J. Li, M. Lu, Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao, D. Leggat, H. Okawa, Y. Zhang

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

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

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

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

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

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

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

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian
| Institution                                                                 | Authors                                                                                   |
|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Network of High Energy Physics, Cairo, Egypt                              | A.A. Abdelalim, E. Salama                                                                |
| Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt | A. Lotfy, Y. Mohammed                                                                        |
| National Institute of Chemical Physics and Biophysics, Tallinn, Estonia  | S. Bhowmik, R.K. Dewanjee, K. Ehaath, M. Kadastik, T. Lange, S. Nandar, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken |
| Department of Physics, University of Helsinki, Helsinki, Finland         | P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen                                    |
| Helsinki Institute of Physics, Helsinki, Finland                         | S. Bharthuar, E. Brucceler, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampert, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Myllymäki, J. Ott, M. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi |
| Lappeenranta-Lahti University of Technology, Lappeenranta, Finland       | P. Luukka, H. Petrow, T. Tuuva                                                              |
| IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France               | C. Amendola, M. Besancon, F. Coudre, M. Dejardin, D. Denegri, J.L. Faure, F. Ferré, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.O. Sahin, A. Savoy-Navarro, P. Simkina, M. Titov |
| Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France | C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damast, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnara, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, J. Rembser, R. Salerni, U. Sarkar, J.B. Sauvar, Y. Siros, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche |
| Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France       | J.-L. Agram, J. Andrea, D. Apparu, D. Block, G. Bourgatte, J.-M. Brown, E.C. Chabert, C. Collard, D. Darej, U. Goerlach, C. Grimault, A.-C. Le Bihar, P. Van Hove |
| Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France  | S. Beauceron, C. Bernet, B. Blancor, G. Boudou, A. Carle, N. Chanor, J. Choisy, D. Contard, P. Depasse, C. Dozen, H. El Mamouni, J. Fay, S. Gasco, M. Gouzevitch, G. Grienere, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torerotot, M. Vander Donckt, P. Verdier, S. Viret |
| Georgian Technical University, Tbilisi, Georgia                          | D. Chokhe, L. I. Lomidzé, Z. Tsamalaizde                                                  |
| RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany      | V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuseler, A. Pauls, N. Röwer, M. Teroerde      |
| RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany   | S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey                   |
Institute, Bhubaneswar, Odisha, India
S. Bahinipati, A.K. Das, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair, Bindhu, A. Nayak, P. Saha, N. Sur, S.K. Swain, D. Vats

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

Istfahan University of Technology, Istfahan, Iran
H. Bakhshiansohi, E. Khazaie, M. Sedghi

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, S.M. Etesami, D. Ramos, A. Rastogi, P. Mal

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, R. Aly, C. Aruta, A. Colaleo, D. Creanza, N. De Filippis, M. De Palma, A. Di Florio, W. Elmetenawee, F. Errico, L. Fiore, G. Iaselli, M. Incere, G. Maggi, M. Maggi, I. Margjeka, V. Mastrapasqua, S. My, S. Nuzzo, A. Pellecchia, A. Pompili, G. Pugliese, R. Radogna, D. Ramos, A. Ranieri, G. Selvaggi, L. Silvestris, F.M. Simone, U. Süzbilir, A. Stamerra, R. Venditti, P. Verw尹ligen

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
G. Abbiendi, C. Battilana, D. Bonacorsi, L. Borgonovi, L. Brigliadori, R. Campanini, P. Capiluppi, A. Castro, F.R. Cavallo, M. Cuffiani, G.M. Dallavalle, T. Diotalevi, F. Fabbri, A. Fanfani, P. Giacomelli, L. Giommi, C. Grandi, L. Guiducci, S. Lo Meo, L. Lunerti, S. Marcellini, G. Masetti, F.L. Navarra, A. Perrotta, F. Pramawera, A.M. Rossi, T. Rovelli, G.P. Sirolı, G.

INFN Sezione di Catania, Università di Catania, Catania, Italy
S. Costa, A. Di Mattia, R. Potenza, A. Tricomi, T. Tuve

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

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

INFN Sezione di Genova, Università di Genova, Genova, Italy
M. Bozzo, F. Ferro, R. Mulargia, E. Robutti, S. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
A. Benaglia, G. Boldrini, F. Brivio, F. Cetorelli, F. De Guio, M.E. Dinardo, P. Dini, S. Gennai, A. Ghezzi, P. Govoni, L. Guzzì, M.T. Lucchini, M. Malberti, S. Malvezzi, A. Massironi, M. Menasce, L. Moroni, M. Paganoni, D. Pedrini, B.S. Pinolini, S. Ragazzi, N. Redaelli, T. Tabarelli de Fatis, D. Zuolo

INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy; Università della
Basilicata, Potenza, Italy; Università G. Marconi, Rome, Italy
S. Buontempo, F. Carnevali, N. Cavallo, A. De Iorio, F. Fabozzi, O.M. Iorio, L. Lista, P. Paolucci, B. Rossi, C. Sciacca

INFN Sezione di Padova, Università di Padova, Padova, Italy; Università di Trento, Trento, Italy
P. Azzi, N. Bacchetta, D. Bisello, P. Bortignon, A. Bragagnolo, R. Carlin, P. Checcia, T. Dorigo, F. Gasparini, F. Gonella, G. Govi, A. Gozzelino, G. Grosso, L. Laycin, E. Lusiani, M. Margoni, J. Pazzini, P. Ronchese, R. Rossini, G. Strong, M. Tosi, H. Yarar, M. Zanetti, P. Zotto, A. Zucchetta, G. Zumerle

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
S. Abu Zeid, C. Aimé, A. Braghieri, S. Calzaferri, D. Fiorina, P. Montagna, V. Re, C. Riccardi, P. Salvini, I. Vai, P. Vitulo

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
P. Asenov, G.M. Bilei, D. Ciangottini, F. Fano, M. Magherini, G. Mantovani, V. Mariani, M. Menichelli, F. Moscatelli, A. Piccinelli, M. Presilla, A. Rossi, A. Santocchia, D. Spiga, T. Tedeschi

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy; Università di Siena, Siena, Italy
P. Azzurri, G. Bagliesi, V. Bertacchi, R. Bhattacharya, L. Bianchini, T. Boccali, E. Bossini, D. Bruschi, R. Castaldi, M.A. Ciocci, V. D’Amante, R. Dell’Orso, M.R. Di Domenico, S. Donato, A. Giassi, F. Ligabue, E. Manca, G. Mandorli, D. Matos Figueiredo, A. Messineo, M. Musich, F. Palla, S. Parolai, G. Ramirez-Sanchez, A. Rizzi, G. Rolandi, S. Roy Chowdhury, T. Sarkar, A. Scribano, N. Shafiei, P. Spagnolo, R. Tenchini, G. Tonelli, N. Turini, A. Venturi, P.G. Verdini

INFN Sezione di Roma, Sapienza Università di Roma, Roma, Italy
P. Barria, M. Campana, F. Cavallari, D. Del Re, E. Di Marco, M. Diemoz, E. Longo, P. Meridiani, G. Organtini, F. Pandolfi, R. Paramatti, C. Quaranta, S. Rahatlou, C. Rovelli, F. Santanastasio, L. Soffi, R. Tramontano

INFN Sezione di Torino, Università di Torino, Torino, Italy; Università del Piemonte Orientale, Novara, Italy
N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, N. Bartosik, R. Bellan, A. Bellora, J. Berenguer, Antequera, C. Biuno, N. Cartiglia, M. Costa, R. Covarelli, N. Demaria, M. Grippi, B. Kiani, F. Legger, C. Mariotti, S. Maselli, A. Mecca, E. Migliore, E. Monteil, M. Monteno, M.M. Obertino, G. Ortonta, L. Pacher, N. Pastrone, M. Pelliccioni, M. Ruspa, K. Shchelina, F. Siviero, V. Sola, A. Solano, D. Soldi, A. Staiano, M. Tornago, D. Trocino, G. Umore, A. Vagnerini

INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, A. Da Rold, G. Della Ricca, G. Sorrentino

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmer, Y.C. Yang

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

Hanyang University, Seoul, Korea
E. Asilar, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, H. Han, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

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

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

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

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

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

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

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

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, A. Potrebko, T. Torims, V. Veckalns

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, S.Y. Hoh, I. Yusuff, Z. Zolkapli

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez Hernandez

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

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

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

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

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

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Gorski, M. Kazana, M. Szlepet, P. Zalewski

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

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

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Alvarez Fernandez, M. Barrio Luna,
Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colina,
B. De La Cruz, A. Delgado Peris, D. Fernandez Del Val, J.P. Fernandez Ramos,
J. Flix, M.C. Fouzi, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez,
M.I. Jos, J. Leon Hogado, D. Moran, C. Perez Dengra, A. Perez-Calero Yzquierdo,
J. Puerta Pelayo, I. Redonde, D.D. Redondo Ferrer, L. Romero, S. Sanchez Navas,
J. Sastre, L. Urda Gomez, J. Vazquez Escobar, C. Willmott

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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez,
Caballero, J.R. Gonzalez Fernandez, E. Palencia Cortezon, C. Ramon Alvarez,
V. Rodriguez Bouza, A. Soto Rodriguez, A. Trapote, C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez,
C. Fernandez Madrazo, A. Garcia Alonso, G. Gomez, C. Lasaoa Garcia,
C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas,
J. Piedra Gomez, C. Priels, A. Ruiz-Jimenez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy, D.U.J. Sonnadara, D.D.C. Wickramarathna

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, D. Barney, J. Bendavid, M. Bianci, B. Bilir, A. Bocci, E. Brondolin, C. Caillo, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d’Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Do¨nser, N. Dupont, A. Elliott-Peisert, F. Fallavollita, A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Lauria, P. Lecocq, E. Leutgeb, A. Lintulait, C. Lourenco, B. Maiert, L. Malgeri, M. Mannelli, A.C. Marin, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrussiani, A. Pfeiffer, M. Pierini, D. Pipano, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérez, M. Roveri, H. Sakulin, J. Salfeld-Nebgen, S. Scarff, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas, A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada, A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli, L. Noehte, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov, M. Backhaus, P. Berger, A. Calandrini, K. Datta, A. De Cost, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedda, F. Glessgen, T.A. Gómez Espinosa, M. Goria, D. Hits, D. Lustermann, M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani, M.T. Meinhard, F. Nussi-Tedaldi, J. Niedziela, F. Paus, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reidt-Spiess, B. Ristic, F. Rit, D. Ruini, D.A. Sanz Becerra, J. Steggemann, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler, P. Bärtschi, C. Botti, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Joffre-hei, B. Kilmistern, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff, C.M. Kuo, W. Lin, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Cead, Y. Chao, K.F. Chen, P.S. Chen, H. Cheng, W.-S. Hou, Yy. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.Y. Wu, E. Yazgan, Pr. Yu

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
C. Asawatangtrakuldee, N. Sriganobhas

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

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar, K. Ocalan, M. Yalvac

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, Ö. Özçelik, S. Tekten

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, Y. Komurcu, S. Sen

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci, B. Hacisahinoglu, I. Hos, B. Isildak, B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci

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

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

University of Bristol, Bristol, United Kingdom
D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou, K. Walkingshaw Pass, R. White

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

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal, D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negri, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash, M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shiptiysi, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee, M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

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

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittman, K. Hatakeyama, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson
Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio, C. West

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

Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubèz, D. Cutts, M. Hadley, U. Heintz, J.M. Hogan, T. Kwong, G. Landsberg, K.T. Lau, D. Li, J. Luci, M. Narain, N. Pervar, S. Sagir, F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
J. Bonilla, C. Brainerd, R. Breeder, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Hazi, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yad, F. Zhang

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

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

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

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

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

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

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, F. Marin, R. Patel, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper
Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Far, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou.

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, L.A.T. Bauer, D. Berry, J. Berryhill, P.C. Bhat, K. Burket, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrello, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Geese, L. Gray, D. Green, S. Grunendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahr, J. Ngadiubra, D. Noonar, V. Papadimitriou, N. Pastika, K. Pedrosa, C. Pena, F. Ravera, A. Reinsvold, L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soh, L. Spiegel, J. Straif, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, I. Zoi.

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

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Askel, R. Habibullah, V. Hagopian, R. Khurana, T. Kolberg, G. Martinez, H. Prospet, C. Schiber, O. Viazlo, R. Yohay, J. Zhang.

Florida Institute of Technology, Melbourne, Florida, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy, M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva.

University of Illinois at Chicago (UIC), Chicago, Illinois, USA
M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D.S. Lemos, A.H. Merriit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo.

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, K. Dilsiz, L. Emediato, R.P. Gandrajula, G. Karamar, O.K. Koseyan, J.-P. Merlo, A. Mestvirishvili, J. Nachtman, O. Neogi, H. Ogul, Y. Onei, A. Penzo, C. Snyder, E. Tiras.

Johns Hopkins University, Baltimore, Maryland, USA
O. Amram, B. Blumenfeld, L. Corcedilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, J. Roskes, S. Sekhar, M. Swartz, T.A. Vami.

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bear, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickef, C. Rogan, C. Royor, R. Salvatico, S. Sanders, E. Schmitz, C. Smith, Q. Wang, J. Williams, G. Wilson.

Kansas State University, Manhattan, Kansas, USA
B. Cardwell, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald

Wayne State University, Detroit, Michigan, USA

P.E. Karchin, N. Poudyal

University of Wisconsin - Madison, Madison, Wisconsin, USA

S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraki, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens

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

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov, E. Boos, V. Borshch, D. Budkouski, V. Bunichev, V. Chekhovsky, R. Chistov, M. Danilov, A. Demenev, T. Dimova, I. Dremin, M. Dubinin, L. Dudko, V. Epshteyn, A. Ershov, G. Gavrilov, V. Golovtcov, S. Golenkov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, V. Ivanenchenko, Y. Ivanov, V. Kachanov, L. Kardapoltsev, V. Karjavin, A. Karneyeu, V. Kim, M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova, D. Konstantinov, V. Korenkov, A. Kozyrev, N. Krasnikov, E. Kuznetsova, A. Lanev, P. Levchenko, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev, V. Murzin, A. Nikitenko, S. Obraztsov, V. Okhotnikov, A. Osokin, I. Ovtin, V. Palichik, P. Parygin, V. Perelygin, M.Perfilov, G. Pavlov, S. Polikarpov, V. Popov, O. Radchenko, M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen, S. Slabospitskii, V. Smirnov, D. Sosnov, A. Stepennov, V. Sulimov, E. Tchkhebukov, A. Terkulov, O. Teryaev, I. Tlisova, M. Toms, A. Toropin, L. Uvarov, A. Uzuniar, E. Vlasov, A. Vorobyev, N. Voytishin, B.S. Yuldashev, A. Zarubin, I. Zhizhin, A. Zhokin

†: Deceased

1Also at Yerevan State University, Yerevan, Armenia
2Also at TU Wien, Vienna, Austria
3Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
4Also at Université Libre de Bruxelles, Bruxelles, Belgium
5Also at Universidade Estadual de Campinas, Campinas, Brazil
6Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
7Also at UFMS, Nova Andradina, Brazil
8Also at The University of the State of Amazonas, Manaus, Brazil
9Also at University of Chinese Academy of Sciences, Beijing, China
10Also at Nanjing Normal University Department of Physics, Nanjing, China
11Now at The University of Iowa, Iowa City, Iowa, USA
12Also at University of Chinese Academy of Sciences, Beijing, China
13Also at an institute or an international laboratory covered by a cooperation agreement with CERN
14Also at Helwan University, Cairo, Egypt
15Now at Zewail City of Science and Technology, Zewail, Egypt
Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
Also at Konya Technical University, Konya, Turkey
Also at Izmir Bakircay University, Izmir, Turkey
Also at Adiyaman University, Adiyaman, Turkey
Also at Istanbul Gedik University, Istanbul, Turkey
Also at Necmettin Erbakan University, Konya, Turkey
Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
Also at Marmara University, Istanbul, Turkey
Also at Milli Savunma University, Istanbul, Turkey
Also at Kafkas University, Kars, Turkey
Also at Hacettepe University, Ankara, Turkey
Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
Also at Yıldız Technical University, Istanbul, Turkey
Also at Vrije Universiteit Brussel, Brussel, Belgium
Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
Also at University of Bristol, Bristol, United Kingdom
Also at IPPP Durham University, Durham, United Kingdom
Also at Monash University, Faculty of Science, Clayton, Australia
Also at Università di Torino, Torino, Italy
Also at Bethel University, St. Paul, Minnesota, USA
Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
Also at California Institute of Technology, Pasadena, California, USA
Also at United States Naval Academy, Annapolis, Maryland, USA
Also at Bingol University, Bingol, Turkey
Also at Georgian Technical University, Tbilisi, Georgia
Also at Sinop University, Sinop, Turkey
Also at Erciyes University, Kayseri, Turkey
Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
Also at Texas A&M University at Qatar, Doha, Qatar
Also at Kyungpook National University, Daegu, Korea
Also at another institute or international laboratory covered by a cooperation agreement with CERN
Also at Yerevan Physics Institute, Yerevan, Armenia
Now at University of Florida, Gainesville, Florida, USA
Also at Imperial College, London, United Kingdom
Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan