Phys. Lett. B 860 (2025) 139202

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Study of WH production through vector boson scattering and extraction of the relative sign of the W and Z couplings to the Higgs boson in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration *

CERN, Geneva, Switzerland

ARTICLE INFO

Editor: M. Doser

Keywords:
CMS
Higgs
Vector boson scattering

ABSTRACT

A search for the production of a W boson and a Higgs boson through vector boson scattering (VBS) is presented, using CMS data from proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ collected from 2016 to 2018. The integrated luminosity of the data sample is $138\,\text{fb}^{-1}$. Selected events must be consistent with the presence of two jets originating from VBS, the leptonic decay of the W boson to an electron or muon, possibly also through an intermediate τ lepton, and a Higgs boson decaying into a pair of b quarks, reconstructed as either a single merged jet or two resolved jets. A measurement of the process as predicted by the standard model (SM) is performed alongside a study of beyond-the-SM (BSM) scenarios. The SM analysis sets an observed (expected) 95% confidence level upper limit of 14.3 (9.9) on the ratio of the measured VBS WH cross section to that expected by the SM. The BSM analysis, conducted within the so-called κ framework, excludes all scenarios with $\lambda_{WZ} < 0$ that are consistent with current measurements, where $\lambda_{WZ} = \kappa_W/\kappa_Z$ and κ_W and κ_Z are the HWW and HZZ coupling modifiers, respectively. The significance of the exclusion is beyond 5 standard deviations, and it is consistent with the SM expectation of $\lambda_{WZ} = 1$.

1. Introduction

Precise measurements of the Higgs boson couplings to the W and Z bosons serve as critical tests of electroweak symmetry breaking in the standard model (SM) [1–6]. Within the κ framework [7], where the HWW and HZZ coupling modifiers are denoted as κ_W and κ_Z, respectively, direct measurements of Higgs boson production and decay have tightly constrained the absolute values of κ_W and κ_Z [8,9]. However, the sign of $\lambda_{WZ} = \kappa_W/\kappa_Z$ has not been probed directly.

A process sensitive to the interference between the HWW and HZZ vertices is needed to extract the sign of λ_{WZ}. A natural choice is the production of a W boson and a Higgs boson (WH) via vector boson scattering (VBS) [10], which proceeds primarily through the leading-order (LO) Feynman diagrams shown in Fig. 1. This is a rare SM process, but the cross section grows quadratically with κ_W or κ_Z and the kinematic distributions are different for the SM ($\lambda_{WZ} = 1$), and $\lambda_{WZ} < 0$, where the W and Higgs bosons both receive a significant Lorentz boost. This is shown in Fig. 2, where the scalar sum of the transverse momentum (p_T) of the Higgs and W bosons is displayed for $\kappa_Z = 1$ and various values of κ_W.

In this Letter, we present a study of the production of WH through VBS using the leptonic decay of the W boson to an electron or a muon, possibly also through an intermediate τ lepton, and the decay of the Higgs boson to $b\bar{b}$. The study focuses both on the SM scenario, where $\kappa_W = \kappa_Z = 1$, and on beyond-the-SM (BSM) scenarios, where $\lambda_{WZ} < 0$. The BSM analysis targets events where the Higgs boson decay to b quarks is reconstructed as a single merged jet because of the Lorentz boost it receives, whereas the SM analysis targets events where the b quarks from the Higgs boson are reconstructed as two resolved jets. The two scenarios are analyzed separately and use different methods. The study is based on data from proton-proton collisions at a center-of-mass energy of 13 TeV. The data were collected with the CMS detector [11] at the CERN LHC from 2016 to 2018, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$. Tabulated results are provided in the HEPData record for this work [12].

2. The CMS detector and object reconstruction

The CMS apparatus [11,13] is a multipurpose, nearly hermetic detector, designed to trigger on [14,15] and identify electrons, muons,

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

https://doi.org/10.1016/j.physletb.2024.139202
Received 26 May 2024; Received in revised form 9 November 2024; Accepted 13 December 2024

Available online 18 December 2024

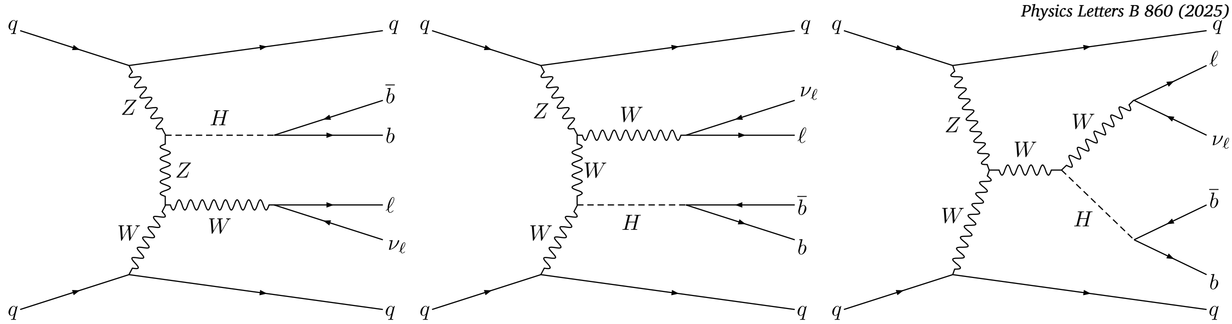

Fig. 1. Tree-level Feynman diagrams for the production of $\mathrm{WH} \to \ell\nu\mathrm{b\bar{b}}$ via VBS, where ℓ is an electron or muon.

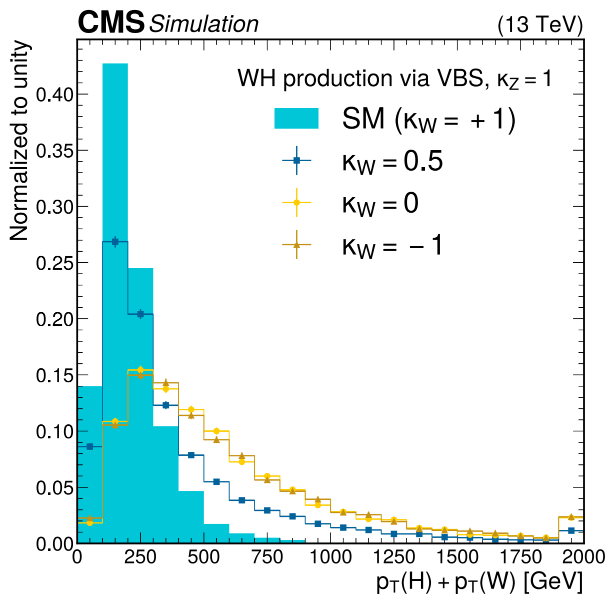

Fig. 2. Distributions of the scalar sum of the Higgs boson and W boson p_{T}, as generated by MadGraph, for simulated signal events with $\kappa_{\mathrm{Z}} = 1$ and the following κ_{W} values: $\kappa_{\mathrm{W}} = 1$ (SM) in light blue (filled), $\kappa_{\mathrm{W}} = 0.5$ in dark blue, $\kappa_{\mathrm{W}} = 0$ in yellow, and $\kappa_{\mathrm{W}} = -1$ in gold. The highest bin also contains the overflows.

photons, and (charged and neutral) hadrons [16–18]. A global "particle-flow" (PF) algorithm [19] aims to reconstruct all individual particles in an event (PF candidates), combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters (ECAL and HCAL, respectively), operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The PF candidates are used to build τ leptons, jets, and missing transverse momentum [20–22]. Forward calorimeters, made of steel and quartz-fibers, extend the pseudorapidity coverage provided by the barrel and endcap detectors. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [11,13].

Events of interest are collected using single-lepton triggers, where the charged lepton is required to be isolated from other significant detector activity and have p_{T} exceeding a threshold that depends on the data-taking period (year). The single-muon trigger requires $p_{\mathrm{T}} > 24\,(27)$ GeV in 2016 and 2018 (2017), whereas the single-electron trigger requires $p_{\mathrm{T}} > 27\,(32)$ GeV in 2016 (2017–18).

Muon candidates are reconstructed within the pseudorapidity range $|\eta| < 2.4$ by combining the information from the silicon tracker and the muon chambers [17]. The muon candidates are also required to satisfy a set of quality criteria based on the number of hits measured in the silicon tracker and the muon system, the properties of the muon track, and the impact parameters of the track with respect to the primary vertex (PV) of the event, which 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. [23].

Electron candidates within $|\eta| < 2.5$ are reconstructed by associating fitted tracks in the silicon tracker with electromagnetic energy clusters in the ECAL [24]. Electron candidates are required to satisfy identification criteria based on the shower shape of the energy deposit, the matching of the electron track to the ECAL energy cluster, the relative amount of energy deposited in the HCAL detector, and the consistency of the electron track with the PV. Electron candidates in the transition region between the ECAL barrel and endcaps, $1.44 < |\eta| < 1.57$, are discarded because of suboptimal detector performance. Electron candidates identified as originating from photon conversions in the detector are also rejected.

Muons and electrons are required to be isolated from hadronic activity in the event. The isolation value is defined by summing the p_{T} of all PF candidates originating from the PV in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4\,(0.3)$ around the muon (electron) track, where ϕ is the azimuthal angle in radians. The sum is corrected for the contribution of neutral particles from additional interactions in the same or nearby bunch crossings (pileup) [17,24]. The relative isolation, defined as the isolation sum divided by the p_{T} of the lepton, is used in selecting well-isolated electrons and muons.

Both the SM and BSM analyses use the "tight" identification criteria described in Refs. [16,17] to further identify electrons and muons, respectively. The electron identification criteria use a boosted decision tree (BDT) trained to identify electrons based on their kinematic values and isolation, whereas muons are required to pass a set of selections, including the requirement that their relative isolation be less than 0.15. In addition, a less stringent set of identification and isolation criteria, referred to as the "veto" criteria, are used to identify and reject additional leptons.

Jets are clustered using the anti-k_{T} algorithm [25,26] taking as input the PF candidates. The clustering algorithm is used with distance parameters of 0.4 and 0.8 to reconstruct so-called AK4 and AK8 jets, respectively. The momenta of jets are corrected to mitigate the contributions of pileup particles, by discarding particles identified originating from pileup vertices and applying an offset correction to subtract the contributions from neutral particles. Further corrections are derived from simulation and by performing in situ measurements of the momentum balance in data. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [21]. Additional selection criteria are applied to each jet to remove those potentially dominated by anomalous contributions from various subdetector components or reconstruction failures, while jets originating from pileup collisions are rejected via a multivariate discriminator [27]. The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is computed as the negative vector $\vec{p}_{\mathrm{T}}$ sum of all PF candidates reconstructed in the event. Its magnitude is denoted as $p_{\mathrm{T}}^{\mathrm{miss}}$ [22]. The $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event. The corrections are propagated via the AK4 jet collection.

The AK4 jets originating from b quark hadronization and decay (b jets) are identified using DeepJet [28–30], a deep neural network whose inputs are the kinematic values of the jets and their constituents, including secondary vertices associated with the jets. A requirement is placed on the output of DeepJet in order to classify jets as "b-tagged." For the chosen working point, the efficiency to select b jets ranges from 71 to 81%, depending on the p_{T} and η of the jet, and the rate for incorrectly tagging jets originating from the hadronization of gluons or light quarks is approximately 1%. Pairs of b-tagged AK4 jets are used to identify Higgs boson candidates in the SM analysis.

The AK8 jets are used to reconstruct the Higgs boson candidates in the BSM analysis. The mass-decorrelated $X \to \mathrm{b\bar{b}}$ ParticleNet tagger [31], a graph neural network that uses the constituents of an AK8 jet to identify its source, is used to identify $\mathrm{H} \to \mathrm{b\bar{b}}$ candidates. The soft-drop grooming algorithm [32] with angular exponent $\beta = 0$ and soft radiation fraction $z = 0.1$, also known as the modified mass-drop algorithm [33], is applied to the AK8 jets to remove soft and wide-angle radiation when estimating the Higgs boson candidate mass. This estimate of the mass is referred to as the soft-drop mass, or m_{SD}, whereas the ungroomed jet mass is denoted as m.

3. Simulated event samples

We model VBS WH events at LO using the MadGraph5_aMC@NLO (v2.6.5) [34] Monte Carlo (MC) event generator, interfaced with the pythia (v8.240) [35] program, which is responsible for the modeling of the boson decays. The SM cross section of the generated events is 13 ± 1 fb after the W boson decays leptonically and the Higgs boson decays to $\mathrm{b\bar{b}}$. W decays that produce a muon or electron through an intermediate τ lepton are included in this sample and considered part of the signal. In order to study different λ_{WZ} scenarios, in addition to the SM value of $\kappa_{\mathrm{W}} = \kappa_{\mathrm{Z}} = 1$, we also generate events with $\kappa_{\mathrm{W}} = -1$ and $\kappa_{\mathrm{Z}} = +1$ to test the hypothesis $\lambda_{\mathrm{WZ}} = -1$, by manually modifying the κ_{W} coupling. These BSM events are generated using a different version (v2.6.1) of MadGraph5_aMC@NLO. With these same settings, a third VBS WH sample is generated using the MadGraph event-by-event reweighting implementation, with a reweighting scheme for 625 different values of κ_{W} and κ_{Z} in the range $[-2, 2]$, allowing for a two-dimensional scan of the parameter space.

The main sources of background for both the SM and BSM analyses are $\mathrm{t\bar{t}}$ and W + jets production, because of the presence of at least one W boson and a high jet multiplicity. The $\mathrm{t\bar{t}}$ background [36] is generated at next-to-leading-order (NLO) accuracy in perturbative quantum chromodynamics (QCD) with the powheg (v2.0) program [37–39]. The W + jets background is generated with MadGraph5_aMC@NLO (v2.6.5) at LO accuracy for up to 4 additional partons merged using the MLM matching scheme [40].

The largest subleading backgrounds for both the SM and BSM analyses are diboson and single top quark production. Diboson events are generated with MadGraph5_aMC@NLO at NLO with up to one additional parton, using the FxFx merging scheme [41], or with powheg at NLO accuracy. The tW and t-channel single top quark processes are generated to NLO accuracy with powheg, whereas s-channel single top quark production is modeled with MadGraph5_aMC@NLO (v2.6.5) at NLO accuracy [42–44].

We also consider backgrounds from VBS production of a W boson, quark-initiated WH, and Z + jets production. The Z + jets events are generated with the same settings used to generate W + jets events. The VBS W background events are also generated with these settings, without any additional jets. Finally, quark-initiated WH production is generated at NLO QCD accuracy using the powheg event generator extended with the MiNLO procedure [45].

The generated matrix-element-level background events are interfaced with pythia v8.240 or later versions to model parton showers and hadronization, as well as the underlying event. In the case of VBS WH production, we also use pythia, but with a dipole recoil scheme chosen to correctly emulate the color structure [46]. The generation of all samples is based on the CP5 tune [47] for pythia and the NNPDF v3.1 next-to-next-to-leading-order (NNLO) parton distribution functions (PDFs) [48,49]. Simulated pileup interactions are added to the hard-scattering process, with a multiplicity matched to the pileup profiles of the data. Finally, the response of the CMS detector is modeled with Geant4 [50].

4. Event selection and background estimation

The selection criteria that target the leptonic W boson decay, a single electron or muon plus $p_{\mathrm{T}}^{\mathrm{miss}}$ from a neutrino, are common for the SM and BSM analyses. Events are required to contain a tight muon with $p_{\mathrm{T}} > 26\,(30)$ GeV in 2016 and 2018 (2017) data, or a tight electron with $p_{\mathrm{T}} > 30\,(35)$ GeV in 2016 (2017–18) data. Events are rejected if they contain an additional electron or muon with $p_{\mathrm{T}} > 10$ GeV that satisfies the veto criteria. Events are also required to have $p_{\mathrm{T}}^{\mathrm{miss}}$ larger than 30 GeV. In addition, in both the SM and BSM analyses, events must contain at least two AK4 jets (the VBS signature jets) that are not b-tagged, do not overlap with the Higgs boson decay products, and satisfy $p_{\mathrm{T}} > 30$ GeV, $|\eta| < 4.7$, $m_{\mathrm{jj}} > 500$ GeV, and $|\Delta\eta_{\mathrm{jj}}| > 2.5$, where m_{jj} is the invariant mass of the dijet system and $\Delta\eta_{\mathrm{jj}}$ is the difference in pseudorapidity between the jets.

The SM analysis is based on selecting two AK4 jets instead of a single AK8 jet to construct the Higgs boson candidate. Specifically, events are required to have two b-tagged AK4 jets with $p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.5$, and a dijet invariant mass (m_{bb}) in the range $50 < m_{\mathrm{bb}} < 150$ GeV.

A BDT, referred to as the signal BDT, is employed to discriminate between the SM signal and the sum of all backgrounds. The signal events are assigned a target output of 1 and the background events are assigned a target output of 0. The BDT is trained using simulated events to regress the target output with the mean squared error loss function. The training and inference are performed with the XGBoost Python package [51]. The variables that are input to the signal BDT include the p_{T}, η, and ϕ of the selected lepton and four jets; the p_{T} and ϕ of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$; the b jet discriminator value of the four selected jets; and m_{jj}, $\Delta\eta_{\mathrm{jj}}$, and m_{bb}. Finally, the SM signal region is defined by requiring the signal BDT output to be larger than 0.5, in addition to the m_{bb}, m_{jj}, and $\Delta\eta_{\mathrm{jj}}$ selections already applied.

The background in the SM BDT output signal region is estimated from two control regions used to determine the overall rate of the W + jets and $\mathrm{t\bar{t}}$ processes. The distributions of these backgrounds, along with both the distributions and overall rates of other smaller backgrounds, are taken from simulation. The control region used to constrain the W + jets process is defined by inverting the BDT output requirement for the signal region. In this control region, a second BDT, referred to as the W + jets BDT, is trained to discriminate between W + jets and all other processes using the same set of input variables as the signal BDT. Then, the W + jets BDT distribution is used to extract the overall rate of W + jets production. The control region used to constrain the $\mathrm{t\bar{t}}$ process has the signal BDT output requirement removed and the signal region m_{jj} requirement modified to $100 < m_{\mathrm{jj}} < 500$ GeV. In this control region, the m_{jj} distribution is fit to extract the overall $\mathrm{t\bar{t}}$ production rate.

The signal region for the BSM analysis requires events to have one AK8 jet with $p_{\mathrm{T}} > 300$ GeV, $|\eta| < 2.5$, an $X \to \mathrm{b\bar{b}}$ ParticleNet score greater than 0.9, $m > 50$ GeV, and $40 < m_{\mathrm{SD}} < 150$ GeV. Events are also required to have no b-tagged AK4 jets. Finally, each event must satisfy $p_{\mathrm{T}}(\ell) + p_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T}}(\mathrm{H} \to \mathrm{b\bar{b}}\ \text{jet}) > 900$ GeV, and the requirements on the VBS jets are increased to $m_{\mathrm{jj}} > 600$ GeV and $|\Delta\eta_{\mathrm{jj}}| > 4$.

The background in the BSM signal region is estimated using a modification of the "ABCD" method (e.g. [52,53]), where two approximately independent variables are used to define four orthogonal regions: region A, the signal region, and regions B, C, and D, which are dominated by background events. In this work, $\Delta\eta_{\mathrm{jj}}$ and m_{SD} are used, such that inverting one or both selections on each variable gives the background-dominated regions: $|\Delta\eta_{\mathrm{jj}}| \leq 4$ and $m_{\mathrm{SD}} < 150$ GeV for region B, $|\Delta\eta_{\mathrm{jj}}| > 4$

Table 1
The background yield estimated from data and the signal yield predicted by MC simulation for the $\kappa_W = -1$, $\kappa_Z = 1$ scenario, and for another example scenario ($\kappa_W = 0$, $\kappa_Z = 1$) in the BSM signal region are shown with their associated statistical and systematic uncertainties. The systematic uncertainty in the signal yield quoted here is the sum in quadrature of the independent relative systematic uncertainties. The observed data yield is also tabulated.

Type	Yield	Uncertainty	
		Stat.	Syst.
VBS WH ($\kappa_W = -1$, $\kappa_Z = 1$)	366	3	68
VBS WH ($\kappa_W = 0$, $\kappa_Z = 1$)	89	2	17
Background	108	14	14
Observed data	130		

and $m_{SD} \geq 150\,\text{GeV}$ for region C, and $|\Delta\eta_{jj}| \leq 4$ and $m_{SD} \geq 150\,\text{GeV}$ for region D. The predicted background yield in the signal region $A^{\text{pred}}_{\text{data}}$ is then obtained by the following relation:

$$A^{\text{pred}}_{\text{data}} = \left(B_{\text{data}} \frac{C_{\text{data}}}{D_{\text{data}}} \right) \left(\frac{A_{\text{MC}}/B_{\text{MC}}}{C_{\text{MC}}/D_{\text{MC}}} \right),$$

where B_{data}, C_{data}, and D_{data} are the yields of the three regions in data, and the simulated background yields A_{MC}, B_{MC}, C_{MC}, and D_{MC} are used as a correction (right term) to the standard method (left term). This correction accounts for a small correlation between $\Delta\eta_{jj}$ and m_{SD} for background events that causes an 11% discrepancy between the ABCD prediction in simulation and A_{MC}. This discrepancy is taken as a baseline for the systematic uncertainty in the prediction. However, the background composition varies across regions A, B, C, and D, and it is not known to high precision. As a result, the baseline systematic uncertainty is extended by varying the subleading backgrounds within their respective uncertainties, representing scenarios in which the contributions from each background are larger or smaller, and recalculating the discrepancy of the method.

Based on studies of the discrepancy in the various scenarios, we assign a systematic uncertainty of 13% in the background prediction. The yields in the BSM signal region, with $\kappa_W = -1$, $\kappa_Z = 1$, are tabulated in Table 1 and the yields in regions A, B, C, and D are shown in Fig. 3. Another example scenario ($\kappa_W = 0$, $\kappa_Z = 1$), where the signal sample is generated using the MadGraph event-by-event reweighting, is reported.

5. Systematic uncertainties

Results are obtained from binned maximum likelihood fits of the signal and predicted background expectations to the data yields [54]. Three distributions—m_{jj} in the $\text{t}\bar{\text{t}}$ control region, the W + jets BDT in the W + jets control region, and the signal BDT in the signal region—are fit simultaneously in the SM analysis, whereas a single-bin counting experiment is performed for the BSM analysis. Several sources of systematic uncertainties are estimated for these measurements. Systematic uncertainties are treated as nuisance parameters with either Gaussian function priors (shape uncertainties) for the SM analysis, or log-normal function priors (normalization uncertainties) for the BSM analysis, and are included in the likelihood function. Theoretical sources of uncertainty include the renormalization and factorization scales (μ_R and μ_F, respectively), the PDFs, and the modeling of initial- and final-state radiation. Experimental sources of uncertainty include the single-lepton trigger efficiency, lepton identification efficiency, jet energy scale and resolution [21], DeepJet b-tagging efficiency, ParticleNet $X \to \text{b}\bar{\text{b}}$ tagger efficiency, and integrated luminosity measurement [55–57]. In the SM analysis, the finite statistical power of the simulated samples is considered as a source of uncertainty using the Barlow-Beeston method [58]. In the BSM analysis, the statistical uncertainties in the background estimation method and the signal simulation are considered as two additional log-normal constraints. The leading systematic uncertainty in the SM signal yield comes from the uncertainty in the b jet tagging efficiency due to the purity of the b jet enriched region where the efficiency is measured in data. The rate of non-b jets in this region is subtracted based on simulation, so the uncertainty is determined by varying the size of the subtraction up and down by 20% [28]. The leading systematic uncertainty in the BSM signal yield comes from the variation of μ_F. In particular, μ_F is varied up and down by a factor of 2, and the largest difference in the signal yield is taken as the systematic uncertainty.

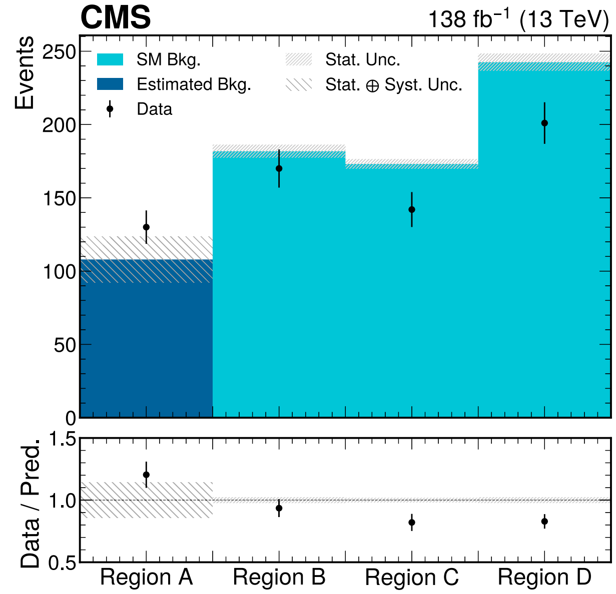

Fig. 3. Event yields observed in the data (black points) for regions A, B, C, and D of the BSM analysis, where region A is the signal region. The simulated SM background event yields in the control regions B, C, and D are shown in light blue. The background in the signal region estimated from data in regions B, C, and D is plotted in dark blue. The lower panel shows the ratio of the data to the estimated background yields. The vertical bars on the points give the statistical uncertainty in the data, while the gray and hatched areas represent the statistical and total uncertainties in the estimated backgrounds, respectively.

6. Results

The BDT distribution in the signal region for the SM analysis is shown in Fig. 4. The observed (expected) signal strength, the rate of the VBS WH signal relative to the SM, is $2.2^{+6.1}_{-5.8}$ ($1.0^{+4.8}_{-4.1}$). The observed (expected) signal significance is $0.34\,\sigma$ ($0.22\,\sigma$), where σ is a standard deviation. Finally, the observed (expected) 95% confidence level CLs [59,60] upper limit is 14.3 (9.9) times the SM prediction.

The limits in the BSM analysis are set following the procedure described in Section 3.2 of Ref. [61]. We find that the scenario where $\lambda_{WZ} = \kappa_W/\kappa_Z = -1$, with $|\kappa_W| = 1$ and $|\kappa_Z| = 1$, is excluded at a confidence level (CL) higher than 99.99%, with an expected and observed significance beyond $5\,\sigma$. This procedure is repeated for 625 different values of κ_W and κ_Z. The exclusion significance regions in the two-dimensional κ_W-κ_Z plane are shown in Fig. 5. The observed 95% CL ($2\,\sigma$) and 99.99% ($5\,\sigma$) contours are given by the dark and light blue colors, respectively, while the expected contours are given by the labeled yellow lines. The contours correspond to the conditions $-2\Delta\log L < 6.18$ and <28.7, respectively, where L is the value of the likelihood function. We find that all of the opposite sign scenarios with κ_W and κ_Z values compatible with the current measurements, $|\kappa_W| = 1.02 \pm 0.08$ and $|\kappa_Z| = 1.04 \pm 0.07$ [8], are excluded at a CL higher than 99.99%.

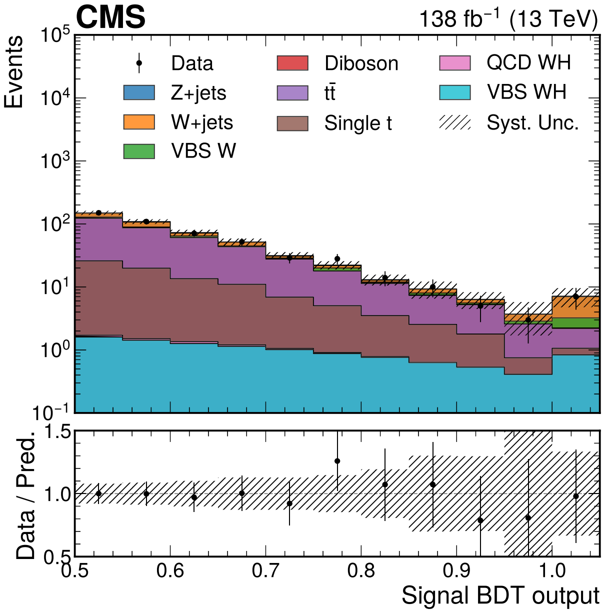

Fig. 4. Observed and expected distributions of the BDT output in the signal region of the SM analysis. The data are shown by the points and the expected contributions from the various sources after the fit to the data by the colored histograms. The lower plot displays the ratio of the data to the sum of the predicted distributions. The vertical bars on the points indicate the statistical uncertainty in the data, and the hatched regions show the systematic uncertainty in the sum of the predicted yields. The rightmost bin includes overflow.

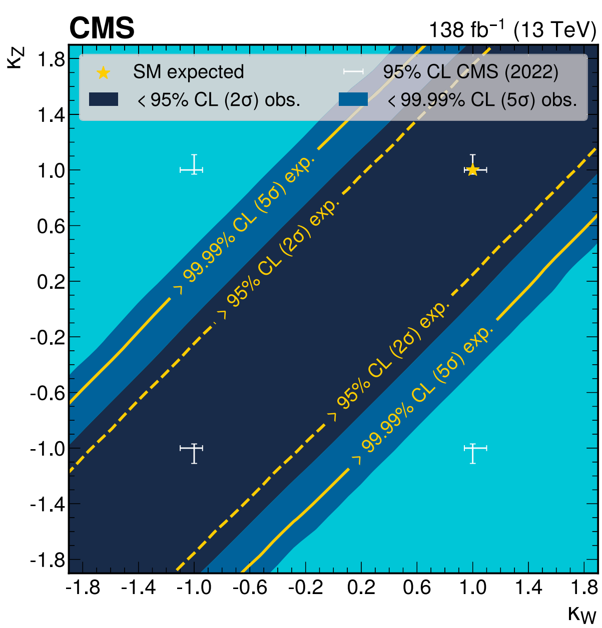

Fig. 5. The >95% (2σ) and >99.99% (5σ) exclusion regions in the two-dimensional κ_W-κ_Z plane are shown by the dark and light blue colors, respectively. Previous CMS measurements of the magnitude of κ_W and κ_Z at the 95% CL [8] are represented by the horizontal and vertical bars, and the SM expectation is given by the gold star.

7. Summary

In this Letter, we have reported the first study of WH production through vector boson scattering (VBS) using 138 fb^{-1} of data recorded with the CMS detector at the LHC between 2016 and 2018 at a center-of-mass energy of 13 TeV. We focused on both the standard model (SM) scenario and scenarios where $\lambda_{WZ} = \kappa_W/\kappa_Z$, with κ_W and κ_Z being the HWW and HZZ coupling modifiers, respectively, is modified from the SM value of 1. Events were selected by requiring exactly one isolated charged lepton (electron or muon) and the magnitude of the missing transverse momentum p_T^{miss} being consistent with the W boson leptonic decay, two jets consistent with a VBS interaction, and one or two additional jets consistent with the Higgs boson decay to $b\bar{b}$. Assuming a signal with SM features, the observed (expected) ratio between the measured rate of VBS WH and the expectation from the SM is $2.2^{+6.1}_{-5.8}$ $(1.0^{+4.8}_{-4.1})$, corresponding to an observed (expected) 95% confidence level upper limit of 14.3 (9.9) times the SM prediction. The BSM scenario where $\lambda_{WZ} = -1$, with $|\kappa_W| = |\kappa_Z| = 1$, and all the opposite-sign scenarios with κ_W and κ_Z values compatible with the current measurements are excluded with a significance greater than 5 standard deviations, corresponding to a confidence level higher than 99.99%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid 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: SC (Armenia), 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); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, Conahcyt, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; The Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); 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) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe"

– 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); 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 Fundação 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 B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

References

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

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

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

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

[5] P.W. Higgs, Spontaneous symmetry breakdown without massless bosons, Phys. Rev. 145 (1966) 1156, https://doi.org/10.1103/PhysRev.145.1156.

[6] T.W.B. Kibble, Symmetry breaking in non-Abelian gauge theories, Phys. Rev. 155 (1967) 1554, https://doi.org/10.1103/PhysRev.155.1554.

[7] LHC Higgs Cross Section Working Group, Higgs properties: report of the LHC Higgs cross section working group, in: Handbook of LHC Higgs Cross Sections, CERN Yellow Reports: Monographs, 2013, arXiv:1307.1347.

[8] CMS Collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery, Nature 607 (2022) 60, https://doi.org/10.1038/s41586-022-04892-x, arXiv:2207.00043.

[9] ATLAS Collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, Nature 607 (2022) 52, https://doi.org/10.1038/s41586-022-04893-w, arXiv:2207.00092; Erratum: https://doi.org/10.1038/s41586-022-05581-5.

[10] D. Stolarski, Y. Wu, Tree-level interference in vector boson fusion production of Vh, Phys. Rev. D 102 (2020) 033006, https://doi.org/10.1103/PhysRevD.102.033006, arXiv:2006.09374.

[11] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[12] HEPData record for this analysis, https://doi.org/10.17182/hepdata.151278, 2024.

[13] CMS Collaboration, Development of the CMS detector for the CERN LHC Run 3, J. Instrum. 19 (2024) P05064, https://doi.org/10.1088/1748-0221/19/05/P05064, arXiv:2309.05466.

[14] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P10017, https://doi.org/10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[15] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[16] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. 16 (2021) P05014, https://doi.org/10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.

[17] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P06015, https://doi.org/10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[18] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, https://doi.org/10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[19] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[20] CMS Collaboration, Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P10005, https://doi.org/10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.

[21] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[22] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, J. Instrum. 14 (2019) P07004, https://doi.org/10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.

[23] CMS Collaboration, Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, http://cds.cern.ch/record/2020886, 2015.

[24] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P06005, https://doi.org/10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[25] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, https://doi.org/10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[26] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_T jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, https://doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[27] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, J. Instrum. 15 (2020) P09018, https://doi.org/10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.

[28] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, J. Instrum. 13 (2018) P05011, https://doi.org/10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

[29] E. Bols, J. Kieseler, M. Verzetti, M. Stoye, A. Stakia, Jet flavour classification using DeepJet, J. Instrum. 15 (2020) P12012, https://doi.org/10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.

[30] CMS Collaboration, Performance of the DeepJet b tagging algorithm using 41.9/fb of data from proton-proton collisions at 13 TeV with Phase 1 CMS detector, CMS Detector Performance Summary CMS-DP-2018-058, http://cds.cern.ch/record/2646773, 2018.

[31] H. Qu, L. Gouskos, ParticleNet: jet tagging via particle clouds, Phys. Rev. D 101 (2020) 056019, https://doi.org/10.1103/PhysRevD.101.056019, arXiv:1902.08570.

[32] A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop, J. High Energy Phys. 05 (2014) 146, https://doi.org/10.1007/JHEP05(2014)146, arXiv:1402.2657.

[33] M. Dasgupta, A. Fregoso, S. Marzani, G.P. Salam, Towards an understanding of jet substructure, J. High Energy Phys. 09 (2013) 029, https://doi.org/10.1007/JHEP09(2013)029, arXiv:1307.0007.

[34] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.

[35] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[36] S. Frixione, P. Nason, G. Ridolfi, A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction, J. High Energy Phys. 09 (2007) 126, https://doi.org/10.1088/1126-6708/2007/09/126, arXiv:0707.3088.

[37] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, https://doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[38] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, https://doi.org/10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[39] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, https://doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.

[40] J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M.L. Mangano, M. Moretti, C.G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, M. Worek, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, Eur. Phys. J. C 53 (2008) 473, https://doi.org/10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.

[41] R. Frederix, S. Frixione, Merging meets matching in MC@NLO, J. High Energy Phys. 12 (2012) 061, https://doi.org/10.1007/JHEP12(2012)061, arXiv:1209.6215.

[42] E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method, Eur. Phys. J. C 71 (2011) 1547, https://doi.org/10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
[43] R. Frederix, E. Re, P. Torrielli, Single-top t-channel hadroproduction in the four-flavour scheme with POWHEG and aMC@NLO, J. High Energy Phys. 09 (2012) 130, https://doi.org/10.1007/JHEP09(2012)130, arXiv:1207.5391.
[44] S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s- and t-channel contributions, J. High Energy Phys. 09 (2009) 111, https://doi.org/10.1088/1126-6708/2009/09/111, arXiv:0907.4076; Erratum: https://doi.org/10.1007/JHEP02(2010)011.
[45] G. Luisoni, P. Nason, C. Oleari, F. Tramontano, HW$^{\pm}$/HZ + 0 and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO, J. High Energy Phys. 10 (2013) 083, https://doi.org/10.1007/JHEP10(2013)083, arXiv:1306.2542.
[46] B. Cabouat, T. Sjöstrand, Some dipole shower studies, Eur. Phys. J. C 78 (2018) 226, https://doi.org/10.1140/epjc/s10052-018-5645-z, arXiv:1710.00391.
[47] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, Eur. Phys. J. C 80 (2020) 4, https://doi.org/10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
[48] R.D. Ball, et al., NNPDF, Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040, https://doi.org/10.1007/JHEP04(2015)040, arXiv:1410.8849.
[49] R.D. Ball, et al., NNPDF, Parton distributions from high-precision collider data, Eur. Phys. J. C 77 (2017) 663, https://doi.org/10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
[50] S. Agostinelli, et al., (GEANT4), GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.
[51] T. Chen, C. Guestrin, XGBoost: a scalable tree boosting system, in: Proc. 22nd ACM SIGKDD Int. Conf. on Knowledge Discovery and Data Mining, KDD '16, Association for Computing Machinery, New York, NY, USA, 2016, p. 785.
[52] CMS Collaboration, Search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV with 137 fb^{-1} in final states with a single lepton using the sum of masses of large-radius jets, Phys. Rev. D 101 (2020) 052010, https://doi.org/10.1103/PhysRevD.101.052010, arXiv:1911.07558.
[53] F. Abe, et al., CDF, A measurement of $\sigma B(W \to e\nu)$ and $\sigma B(Z^0 \to e^+e-)$ in $\bar{p}p$ collisions at $\sqrt{s} = 1800$ GeV, Phys. Rev. D 44 (1991) 29, https://doi.org/10.1103/PhysRevD.44.29.
[54] Particle Data Group, R.L. Workman, et al., Review of particle physics, Prog. Theor. Exp. Phys. 2022 (2022) 083C01, https://doi.org/10.1093/ptep/ptac097.
[55] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, Eur. Phys. J. C 81 (2021) 800, https://doi.org/10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
[56] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, https://cds.cern.ch/record/2621960/, 2018.
[57] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, https://cds.cern.ch/record/2676164/, 2019.
[58] R.J. Barlow, C. Beeston, Fitting using finite Monte Carlo samples, Comput. Phys. Commun. 77 (1993) 219, https://doi.org/10.1016/0010-4655(93)90005-W.
[59] A.L. Read, Presentation of search results: the CL$_s$ technique, J. Phys. G 28 (2002) 2693, https://doi.org/10.1088/0954-3899/28/10/313.
[60] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods A 434 (1999) 435, https://doi.org/10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
[61] ATLAS CMS Collaborations, Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 08 (2016) 045, https://doi.org/10.1007/JHEP08(2016)045, arXiv:1606.02266.

The CMS Collaboration

A. Hayrapetyan, A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler [2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck [2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz [2]

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish [3], T. Janssen, T. Van Laer, P. Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat [4], G.P. Van Onsem, S. Van Putte, D. Vannerom

Vrije Universiteit Brussel, Brussel, Belgium

B. Bilin, B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Université Libre de Bruxelles, Bruxelles, Belgium

M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, K. Mota Amarilo, A. Samalan, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

Ghent University, Ghent, Belgium

A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

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

G.A. Alves, M. Alves Gallo Pereira, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[5], A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira[5]

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[8], L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

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

C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, B. Lopes Da Costa, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

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

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

S. Keshri, S. Thakur

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

T. Cheng, T. Javaid, L. Yuan

Beihang University, Beijing, China

Z. Hu, Z. Liang, J. Liu, K. Yi[9,10]

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen[11], H.S. Chen[11], M. Chen[11], F. Iemmi, C.H. Jiang, A. Kapoor[12], H. Liao, Z.-A. Liu[13], R. Sharma[14], J.N. Song[13], J. Tao, C. Wang[11], J. Wang, Z. Wang[11], H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, L. Zhang, Y. Zhao, C. Zhou

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

S. Yang

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China

Z. You

Sun Yat-Sen University, Guangzhou, China

K. Jaffel, N. Lu

University of Science and Technology of China, Hefei, China

G. Bauer[15], B. Li, J. Zhang

Nanjing Normal University, Nanjing, China

X. Gao[16]

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

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Los Andes, Bogota, Colombia

F. Ramirez, C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

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

M. Kovac, A. Petkovic, T. Sculac

University of Split, Faculty of Science, Split, Croatia

P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, S. Mishra, A. Starodumov [17], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr., A. Kveton

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran [18,19], B. El-mahdy, S. Elgammal [19]

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

M.A. Mahmoud, Y. Mohammed

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

S. Bharthuar, N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [20], P. Simkina, M. Titov, M. Tornago

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

F. Beaudette, G. Boldrini, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

J.-L. Agram[21], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

A. Di Florio

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

D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

I. Lomidze, T. Toriashvili[23], Z. Tsamalaidze[17]

Georgian Technical University, Tbilisi, Georgia

V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

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

S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[24], S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

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

H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[25], K. Borras[26], A. Campbell, A. Cardini, C. Cheng, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[25], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[27], W. Lohmann[28], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, Y. Otarid, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, A. Saggio, M. Scham[29,26], S. Schnake[26], P. Schütze, C. Schwanenberger[25], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso,

R. Walsh, D. Wang, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[26], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

University of Hamburg, Hamburg, Germany

S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[30], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, B. Maier, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[30], A. Stakia

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

P. Kontaxakis, G. Melachroinos, Z. Painesis, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

C. Hajdu, D. Horvath[31,32], K. Márton, A.J. Rádl[33], F. Sikler, V. Veszpremi

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

M. Csanád, K. Farkas, A. Fehérkuti[34], M.M.A. Gadallah[35], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

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

B. Ujvari, G. Zilizi

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

F. Nemes[34], T. Novak

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, M.K. Saini, S. Saumya

University of Delhi, Delhi, India

S. Baradia, S. Barman[37], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], D. Kumar[38], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Indian Institute of Technology Madras, Madras, India

S. Dugad, G.B. Mohanty, B. Parida, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-A, Mumbai, India

A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati[39], C. Kar, D. Maity[40], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[40], K. Naskar[40], A. Nayak[40], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[40], D. Vats[40]

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Acharya[41], A. Alpana, S. Dube, B. Gomber[41], P. Hazarika, B. Kansal, A. Laha, B. Sahu[41], S. Sharma, K.Y. Vaish

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

H. Bakhshiansohi[42], A. Jafari[43], M. Zeinali[44]

Isfahan University of Technology, Isfahan, Iran

S. Bashiri, S. Chenarani[45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie[46], M. Mohammadi Najafabadi, S. Tizchang[47]

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia[a,b], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,48], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

[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], P. Capiluppi[a,b], A. Castro[a,b,†], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,49], M. Lorusso[a,b],

L. Lunerti [a], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], G. Paggi [a,b], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], S. Rossi Tisbeni [a,b], T. Rovelli [a,b], G.P. Siroli [a,b]

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

S. Costa [a,b,50], A. Di Mattia [a], A. Lapertosa [a], R. Potenza [a,b], A. Tricomi [a,b,50], C. Tuve [a,b]

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

P. Assiouras [a], G. Barbagli [a], G. Bardelli [a,b], B. Camaiani [a,b], A. Cassese [a], R. Ceccarelli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], T. Kello [a], G. Latino [a,b], P. Lenzi [a,b], M. Lizzo [a], M. Meschini [a], S. Paoletti [a], A. Papanastassiou [a,b], G. Sguazzoni [a], L. Viliani [a]

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

L. Benussi, S. Bianco, S. Meola [51], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Chatagnon [a], 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], F. Brivio [a], F. Cetorelli [a,b], F. De Guio [a,b], M.E. Dinardo [a,b], P. Dini [a], S. Gennai [a], R. Gerosa [a,b], A. Ghezzi [a,b], P. Govoni [a,b], L. Guzzi [a], M.T. Lucchini [a,b], M. Malberti [a], S. Malvezzi [a], A. Massironi [a], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], S. Palluotto [a,b], D. Pedrini [a], A. Perego [a,b], B.S. Pinolini [a], G. Pizzati [a,b], 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], A. Cagnotta [a,b], F. Carnevali [a,b], N. Cavallo [a,c], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b,52], P. Paolucci [a,30]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli 'Federico II', Napoli, Italy
[c] Università della Basilicata, Potenza, Italy
[d] Scuola Superiore Meridionale (SSM), Napoli, Italy

R. Ardino [a], P. Azzi [a], N. Bacchetta [a,53], M. Benettoni [a], A. Bergnoli [a], D. Bisello [a,b], P. Bortignon [a], G. Bortolato [a,b], A. Bragagnolo [a,b], A.C.M. Bulla [a], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], F. Gasparini [a,b], U. Gasparini [a,b], E. Lusiani [a], M. Margoni [a,b], M. Migliorini [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], M. Tosi [a,b], A. Triossi [a,b], S. Ventura [a], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

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

C. Aimè [a], A. Braghieri [a], S. Calzaferri [a], D. Fiorina [a], P. Montagna [a,b], V. Re [a], 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

S. Ajmal [a,b], M.E. Ascioti [a,b], G.M. Bilei [a], C. Carrivale [a,b], D. Ciangottini [a,b], L. Fanò [a,b], M. Magherini [a,b], V. Mariani [a,b], M. Menichelli [a], F. Moscatelli [a,54], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a], T. Tedeschi [a,b]

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

C.A. Alexe [a,c], P. Asenov [a,b], P. Azzurri [a], G. Bagliesi [a], R. Bhattacharya [a], L. Bianchini [a,b], T. Boccali [a], E. Bossini [a], D. Bruschini [a,c], R. Castaldi [a], M.A. Ciocci [a,b], M. Cipriani [a,b], V. D'Amante [a,d], R. Dell'Orso [a], S. Donato [a], A. Giassi [a], F. Ligabue [a,c], A.C. Marini [a], D. Matos Figueiredo [a], A. Messineo [a,b], M. Musich [a,b], F. Palla [a], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a], T. Sarkar [a], A. Scribano [a], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], F. Vaselli [a,c], 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
[d] Università di Siena, Siena, Italy

C. Baldenegro Barrera [a,b], P. Barria [a], C. Basile [a,b], M. Campana [a,b], F. Cavallari [a], L. Cunqueiro Mendez [a,b], D. Del Re [a,b], E. Di Marco [a,b], M. Diemoz [a], F. Errico [a,b], E. Longo [a,b], J. Mijuskovic [a,b], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], A. Bellora [a,b], C. Biino [a], C. Borca [a,b], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], L. Finco [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], F. Luongo [a,b], C. Mariotti [a], L. Markovic [a,b], S. Maselli [a], A. Mecca [a,b], L. Menzio [a,b], P. Meridiani [a], E. Migliore [a,b], M. Monteno [a], R. Mulargia [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c], F. Siviero [a,b], V. Sola [a,b], A. Solano [a,b], A. Staiano [a], C. Tarricone [a,b], D. Trocino [a], G. Umoret [a,b], R. White [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], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], K. De Leo [a], G. Della Ricca [a,b]

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

S. Dogra, J. Hong, C. Huh, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Kyungpook National University, Daegu, Korea

M.S. Kim

Department of Mathematics and Physics – GWNU, Gangneung, Korea

G. Bak, P. Gwak, H. Kim, D.H. Moon

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

E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

J. Goh, S. Yang

Kyung Hee University, Department of Physics, Seoul, Korea

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

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

University of Seoul, Seoul, Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Gharbia

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

K. Dreimanis, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

Riga Technical University, Riga, Latvia

N.R. Strautnieks

University of Latvia (LU), Riga, Latvia

M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

I. Yusuff[55], Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[56], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

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

C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, N. Raicevic

University of Montenegro, Podgorica, Montenegro

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

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

V. Avati, L. Grzanka, M. Malawski

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

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

K. Pozniak, W. Zabolotny

Warsaw University of Technology, Warsaw, Poland

M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

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

P. Adzic, P. Milenovic

Faculty of Physics, University of Belgrade, Belgrade, Serbia

M. Dordevic, J. Milosevic, V. Rekovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

J. Alcaraz Maestre, Cristina F. Bedoya, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Martin Viscasillas, D. Moran, C.M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, P. Leguina, E. Palencia Cortezon, J. Prado Pico, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

B. Kailasapathy[57], D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna[58], K. Liyanage, N. Perera

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

D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani,

D. Gigi, K. Gill, F. Glege, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[28], S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, M. Rovere, H. Sakulin, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[59], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[60], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. Bevilacqua[61], L. Caminada[61], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[61], L. Noehte[61], T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

T.K. Aarrestad, K. Androsov[60], M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[60], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[60], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, C. Reissel, B. Ristic, F. Riti, R. Seidita, J. Steggemann[60], A. Tarabini, D. Valsecchi, R. Wallny

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

C. Amsler[62], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, U. Molinatti, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

Universität Zürich, Zurich, Switzerland

C. Adloff[63], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[38], S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, K.F. Chen, P.s. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[64], E. Eskut, Y. Guler[65], E. Gurpinar Guler[65], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[66], A. Polatoz, B. Tali[67], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

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

G. Sokmen, M. Yalvac[68]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[69], O. Kaya[70], S. Tekten[71]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak[64,72], G.G. Dincer[64], Y. Komurcu, S. Sen[73]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek [74], B. Hacisahinoglu, I. Hos [75], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Istanbul University, Istanbul, Turkey

S. Cerci [67], B. Isildak [76], D. Sunar Cerci, T. Yetkin

Yildiz Technical University, Istanbul, Turkey

A. Boyaryntsev, B. Grynyov

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

L. Levchuk

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

D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou [77], K. Walkingshaw Pass

University of Bristol, Bristol, United Kingdom

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

Rutherford Appleton Laboratory, Didcot, United Kingdom

I. Andreou, R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal [79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, C.R. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, S. Mallios, M. Mieskolainen, J. Nash [80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee [30], M. Vojinovic, N. Wardle, D. Winterbottom

Imperial College, London, United Kingdom

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, E. Collins, J. Dittmann, K. Hatakeyama, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio [81], E. Usai, R. Yi

The University of Alabama, Tuscaloosa, AL, USA

A. Akpinar, C. Cosby, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Boston University, Boston, MA, USA

G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, N. Pervan, T. Russell, S. Sagir[83], F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan

Brown University, Providence, RI, USA

S. Abbott, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, Y. Yao, S. Yoo, F. Zhang

University of California, Davis, Davis, CA, USA

M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Los Angeles, CA, USA

R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si

University of California, Riverside, Riverside, CA, USA

A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, M. Quinnan, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

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

A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, S. Wang, D. Zhang

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

S. Bhattacharya, A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, CA, USA

J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, G. Karathanasis, N. Manganelli, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

University of Colorado Boulder, Boulder, CO, USA

J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, M. Oshiro, J.R. Patterson, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero,

O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera, A. Reinsvold Hall[85], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

University of Florida, Gainesville, FL, USA

T. Adams, A. Al Kadhim, A. Askew, S. Bower, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida State University, Tallahassee, FL, USA

B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[86], M. Hohlmann, E. Yanes

Florida Institute of Technology, Melbourne, FL, USA

M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D.S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

University of Illinois Chicago, Chicago, USA

M. Alhusseini, D. Blend, K. Dilsiz[87], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[88], O. Neogi, H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

The University of Iowa, Iowa City, IA, USA

B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

Johns Hopkins University, Baltimore, MD, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, M. Pitt, S. Popescu[91], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, G. Wilson

The University of Kansas, Lawrence, KS, USA

B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

Kansas State University, Manhattan, KS, USA

A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[92], A. Shevelev, L. Wang

University of Maryland, College Park, MD, USA

J. Bendavid, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, C. Paus, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T.J. Yang

Massachusetts Institute of Technology, Cambridge, MA, USA

B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, R. Rusack, R. Saradhy, N. Strobbe

University of Minnesota, Minneapolis, MN, USA

K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

University of Nebraska-Lincoln, Lincoln, NE, USA

H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

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

G. Alverson, E. Barberis, J. Bonilla, J. Dervan, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, D. Wood

Northeastern University, Boston, MA, USA

J. Bueghly, S. Dittmer, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

Northwestern University, Evanston, IL, USA

G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[17], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, OH, USA

H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

Princeton University, Princeton, NJ, USA

S. Malik

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A.K. Virdi, F. Wang, A. Wildridge, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar, A. Pathak

Purdue University Northwest, Hammond, IN, USA

D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, I. Krommydas, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

Rice University, Houston, TX, USA

A. Bodek, P. de Barbaro, R. Demina, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[92], R. Taus

University of Rochester, Rochester, NY, USA

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

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

D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

University of Tennessee, Knoxville, TN, USA

D. Aebi, M. Ahmad, T. Akhter, O. Bouhali[93], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

N. Akchurin, J. Damgov, N. Gogate, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev

Texas Tech University, Lubbock, TX, USA

E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

Vanderbilt University, Nashville, TN, USA

B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

University of Virginia, Charlottesville, VA, USA

S. Bhattacharya, P.E. Karchin

Wayne State University, Detroit, MI, USA

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

University of Wisconsin – Madison, Madison, WI, USA

S. Afanasiev, V. Alexakhin, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, V. Blinov[95], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, V. Chekhovsky, R. Chistov[95], M. Danilov[95], A. Dermenev, T. Dimova[95], D. Druzhkin[96], M. Dubinin[84], L. Dudko, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin[†], I. Gorbunov, Y. Ivanov, V. Kachanov, V. Karjavine, A. Karneyeu, V. Kim[95], M. Kirakosyan, D. Kirpichnikov,

M. Kirsanov, V. Klyukhin, O. Kodolova[97], D. Konstantinov, V. Korenkov, A. Kozyrev[95], N. Krasnikov, A. Lanev, P. Levchenko[98], N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[95], V. Murzin, A. Nikitenko[99,97], S. Obraztsov, V. Oreshkin, V. Palichik, V. Perelygin, M. Perfilov, S. Polikarpov[95], V. Popov, O. Radchenko[95], M. Savina, V. Savrin, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], S. Slabospitskii, V. Smirnov, D. Sosnov, V. Sulimov, A. Terkulov, O. Teryaev, I. Tlisova, A. Toropin, L. Uvarov, A. Uzunian, P. Volkov, A. Vorobyev[†], G. Vorotnikov, N. Voytishin, B.S. Yuldashev[100], A. Zarubin, I. Zhizhin, A. Zhokin

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

[†] Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[4] Also at Ghent University, Ghent, Belgium.
[5] Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.
[6] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[7] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[8] Also at UFMS, Nova Andradina, Brazil.
[9] Also at Nanjing Normal University, Nanjing, China.
[10] Now at The University of Iowa, Iowa City, Iowa, USA.
[11] Also at University of Chinese Academy of Sciences, Beijing, China.
[12] Also at China Center of Advanced Science and Technology, Beijing, China.
[13] Also at University of Chinese Academy of Sciences, Beijing, China.
[14] Also at China Spallation Neutron Source, Guangdong, China.
[15] Now at Henan Normal University, Xinxiang, China.
[16] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[17] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[18] Also at Suez University, Suez, Egypt.
[19] Now at British University in Egypt, Cairo, Egypt.
[20] Also at Purdue University, West Lafayette, Indiana, USA.
[21] Also at Université de Haute Alsace, Mulhouse, France.
[22] Also at Istinye University, Istanbul, Turkey.
[23] Also at Tbilisi State University, Tbilisi, Georgia.
[24] Also at The University of the State of Amazonas, Manaus, Brazil.
[25] Also at University of Hamburg, Hamburg, Germany.
[26] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[27] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[28] Also at Brandenburg University of Technology, Cottbus, Germany.
[29] Also at Forschungszentrum Jülich, Juelich, Germany.
[30] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[31] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[32] Now at Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania.
[33] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[34] Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[35] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[36] Also at Punjab Agricultural University, Ludhiana, India.
[37] Also at University of Visva-Bharati, Santiniketan, India.
[38] Also at Indian Institute of Science (IISc), Bangalore, India.
[39] Also at IIT Bhubaneswar, Bhubaneswar, India.
[40] Also at Institute of Physics, Bhubaneswar, India.
[41] Also at University of Hyderabad, Hyderabad, India.
[42] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[43] Also at Isfahan University of Technology, Isfahan, Iran.
[44] Also at Sharif University of Technology, Tehran, Iran.
[45] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[46] Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
[47] Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
[48] Also at Helwan University, Cairo, Egypt.
[49] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[50] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[51] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[52] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[53] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[54] Also at Consiglio Nazionale delle Ricerche – Istituto Officina dei Materiali, Perugia, Italy.
[55] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[56] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[57] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[58] Also at Saegis Campus, Nugegoda, Sri Lanka.
[59] Also at National and Kapodistrian University of Athens, Athens, Greece.
[60] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[61] Also at Universität Zürich, Zurich, Switzerland.

[62] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[63] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[64] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[65] Also at Konya Technical University, Konya, Turkey.
[66] Also at Izmir Bakircay University, Izmir, Turkey.
[67] Also at Adiyaman University, Adiyaman, Turkey.
[68] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[69] Also at Marmara University, Istanbul, Turkey.
[70] Also at Milli Savunma University, Istanbul, Turkey.
[71] Also at Kafkas University, Kars, Turkey.
[72] Now at Istanbul Okan University, Istanbul, Turkey.
[73] Also at Hacettepe University, Ankara, Turkey.
[74] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[75] Also at Istanbul University – Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[76] Also at Yildiz Technical University, Istanbul, Turkey.
[77] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[78] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[79] Also at IPPP Durham University, Durham, United Kingdom.
[80] Also at Monash University, Faculty of Science, Clayton, Australia.
[81] Also at Università di Torino, Torino, Italy.
[82] Also at Bethel University, St. Paul, Minnesota, USA.
[83] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[84] Also at California Institute of Technology, Pasadena, California, USA.
[85] Also at United States Naval Academy, Annapolis, Maryland, USA.
[86] Also at Ain Shams University, Cairo, Egypt.
[87] Also at Bingol University, Bingol, Turkey.
[88] Also at Georgian Technical University, Tbilisi, Georgia.
[89] Also at Sinop University, Sinop, Turkey.
[90] Also at Erciyes University, Kayseri, Turkey.
[91] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[92] Now at an institute or an international laboratory covered by a cooperation agreement with CERN.
[93] Also at Texas A&M University at Qatar, Doha, Qatar.
[94] Also at Kyungpook National University, Daegu, Korea.
[95] Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[96] Also at Universiteit Antwerpen, Antwerpen, Belgium.
[97] Also at Yerevan Physics Institute, Yerevan, Armenia.
[98] Also at Northeastern University, Boston, Massachusetts, USA.
[99] Also at Imperial College, London, United Kingdom.
[100] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.