EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2025-190
2026/02/13

CMS-B2G-24-015

Search for resonances decaying to an anomalous jet and a Higgs boson in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

arXiv:2509.13635v2 [hep-ex] 11 Feb 2026

Abstract

This paper presents a search for new physics through the process where a massive particle, X, decays into a Higgs boson and a second particle, Y. The Higgs boson subsequently decays into a bottom quark-antiquark pair, which is reconstructed as a single large-radius jet. The decay products of Y are also assumed to produce a single large-radius jet. The identification of the Y particle is enhanced by computing the anomaly score of its candidate jet using an autoencoder, which measures deviations from typical quark- or gluon-induced jets. This allows a simultaneous search for multiple Y decay scenarios within a single analysis. In the main benchmark process, Y is a scalar particle that decays into a W boson pair. Two other scalar Y decay processes are also considered as benchmarks: decays to a light quark-antiquark pair, and decays to a top quark-antiquark pair. A fourth benchmark process considers Y as a hadronically decaying top quark, arising from the decay of a vector-like quark into a top quark and a Higgs boson. Data recorded by the CMS experiment at a center-of-mass energy of 13 TeV in 2016–2018, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$, are analyzed. The search covers X masses between 1.4 and 3.0 TeV and Y masses between 90 and 400 GeV, with all simulated signals produced in the narrow-width approximation. No significant excess above the standard model background expectation is observed. The most stringent upper limits to date are placed on benchmark signal cross sections for various masses of X and Y particles.

Published in the European Physical Journal C as doi:10.1140/epjc/s10052-025-15176-9.

© 2026 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license

*See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics [1–3] is an exceptionally successful theory, demonstrating remarkable agreement across the whole range of experimental observations. Despite its success, there are indications that point toward the existence of physics beyond the SM (BSM). These include, among others, the unknown nature of dark matter [4], and the insufficient violation of the combined charge conjugation and parity symmetry to explain the observed baryon asymmetry of the universe [5].

To address such questions, a multitude of BSM theoretical models, such as supersymmetry [6, 7], large or warped extra dimensions [8–10], and those incorporating additional scalar or gauge particles [11] have been proposed. A common feature of these theoretical models is the prediction of new particles. Therefore, one avenue of exploration for BSM physics involves resonance searches, which aim to reconstruct the four-momentum of a new particle by analyzing its decay products. Recent advancements in machine-learning techniques have further motivated the development of inclusive, model-independent searches capable of probing multiple decay scenarios without reliance on specific assumptions [12]. Signatures involving the Higgs boson are well motivated in BSM searches, as new particles may preferentially couple to it [13, 14].

We search for processes of the form $X \to HY$, where X is a heavy BSM resonance, H is the 125 GeV Higgs boson, and Y can be either an SM or a BSM particle. We focus on the case where H decays to a bottom quark-antiquark pair ($b\bar{b}$), its most probable decay mode, and Y gives rise to a hadronic jet. The analysis targets the regime where X is sufficiently massive that both H and Y are produced with large Lorentz boosts, causing their decay products to be collimated and reconstructed as large-radius jets clustered with a distance parameter of 0.8 [15, 16]. An illustration of the process of interest is shown in Fig. 1. The analysis uses proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment at the CERN LHC in 2016–2018, and corresponding to an integrated luminosity of 138 fb^{-1}.

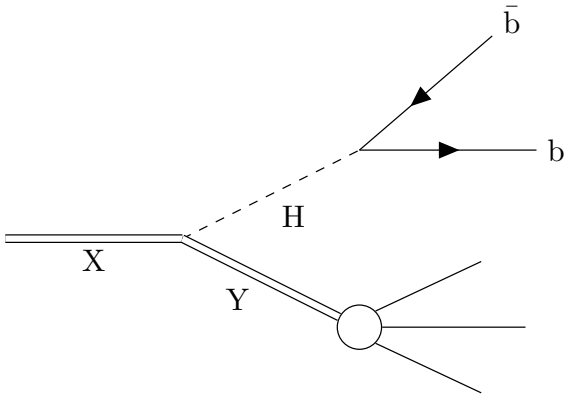

Figure 1: An illustration showing the signal targeted by this analysis. The final state consists of a large-radius jet originating from H decaying to $b\bar{b}$ and another large-radius jet originating from the decay of a second particle, Y.

We evaluate the results in four benchmark signal scenarios. In the main scenario, Y is a scalar particle decaying to a VV pair, where V (W or Z boson) decays hadronically. We choose the WW decay as the proxy for this process; however, similar sensitivity is expected also for the ZZ or WZ decays. The decay allows for one or both vector bosons to be off-shell. Two additional scalar particle decay modes are considered, with Y decaying either into a light-flavored quark-antiquark pair ($q\bar{q}$) or a top quark-antiquark pair ($t\bar{t}$), in which both top quarks decay fully

hadronically. In the fourth scenario, Y is a top quark decaying fully hadronically. These four scenarios span a range of jet substructures, enabling the evaluation of the analysis performance across diverse signal signatures. The first three benchmark scenarios are motivated by theoretical models, such as the next-to-minimal supersymmetric extension of the SM (NMSSM) [17], in which cascade decays involving more than one new particle become possible. Reference [13] provides an overview of CMS searches for the $pp \to S' \to H + S$ process, where S′ and S represent new scalar particles and S is assumed to decay to $b\bar{b}$. However, depending on the NMSSM parameters, other S decay modes may be favored, motivating searches targeting alternative S decays. The presented analysis thus complements Ref. [13] by exploring benchmark models with different S decay modes. The fourth signal scenario is motivated by models predicting the existence of vector-like quarks [18].

This work builds on a generic dijet anomaly search performed by the CMS Collaboration [19], but it specifies one particle and its decay mode ($H \to b\bar{b}$). This enables the application of more specific event selection criteria, enhancing the sensitivity of the analysis, while retaining a degree of generality in the characterization of the second particle.

The PARTICLENET [20] jet tagging algorithm, is applied to H candidate jets to assign scores indicating consistency with the decay of a massive resonance into $b\bar{b}$. The PARTICLENET score is used to define "Pass" and "Fail" analysis regions. An autoencoder (AE) [19] is applied to Y candidate jets to assign anomaly scores, with higher scores indicating deviation from jets typical of multijet production via quantum chromodynamics (QCD). This approach enables the identification of jets with unusual substructure, potentially arising from BSM decays, without relying on specific signal models. The anomaly score is used to define measurement (MR) and control (CR) analysis regions. Thus, the analysis uses four orthogonal regions, with the search performed in MR Pass. The specific selection criteria for these regions are defined in Section 4.

The search is carried out in a two-dimensional (2D) plane defined by the mass of the Y candidate jet, M_j^Y, and the dijet invariant mass of the Y and H candidate jets, M_{jj}. For a signal process, the two variables correspond to the masses of Y and X, denoted as M_Y and M_X, respectively. As a result, the analysis searches for a localized excess of events in the M_{jj}-M_j^Y plane.

The paper is organized as follows. After the description of the CMS detector and event reconstruction in Section 2, we describe signal and background processes in Section 3. The event selection is discussed in Section 4, followed by the description of the statistical model in Section 5 and systematic uncertainties in Section 6. The results are presented in Section 7, followed by a summary of the paper in Section 8.

2 The CMS detector and event reconstruction

The CMS apparatus [21] is a multipurpose, nearly hermetic detector, designed to trigger on [22–24] and identify electrons, muons, photons, and charged and neutral hadrons [25–27]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. 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. [21, 28].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [22]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to a few kHz before data storage [23, 24].

A particle-flow algorithm [29] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti-k_{T} algorithm [15, 16] with a radius parameter of either 0.4 (AK4 jets) or 0.8 (AK8 jets). Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole transverse momentum (p_{T}) spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions to the jet momentum. The pileup-per-particle identification algorithm [30, 31] is used to mitigate the effect of pileup at the reconstructed particle level, making use of local shape information, event pileup properties, and tracking information. A local shape variable is defined, which distinguishes between collinear and soft diffuse distributions of other particles surrounding the particle under consideration. The former is attributed to particles originating from the hard scatter and the latter to particles originating from pileup interactions. Charged particles identified to be originating from pileup vertices are discarded. For each neutral particle, this variable is computed using the surrounding charged particles compatible with the primary interaction vertex within the tracker acceptance ($|\eta| < 2.5$), and using both charged and neutral particles in the region outside of the tracker coverage. The momenta of the neutral particles are then rescaled according to their probability to originate from the primary interaction vertex deduced from the local shape variable, superseding the need for jet-based pileup corrections [30].

For AK8 jets, masses are computed after applying grooming [32] techniques, which remove soft, wide-angle and collinear radiation from the jets, in order to mitigate the effects of contamination from initial-state radiation, the underlying event, and multiple hadron scattering. The trimming algorithm [33] uses a subjet size parameter of 0.3 and a radiation fraction parameter $z = 0.1$, which determines the minimum p_{T} fraction that the reclustered jet constituents need to have in order not to be removed. The mass of the resultant jet is referred to as its "trimmed mass". The "soft-drop mass" of the jet is obtained as follows. The constituents of the AK8 jets are reclustered using the Cambridge–Aachen algorithm [34, 35]. Then, the "modified mass drop tagger" algorithm [36, 37], also known as the "soft drop" algorithm, is applied. The algorithm is applied with angular exponent $\beta = 0$, soft cutoff threshold $z_{\mathrm{cut}} < 0.1$, and characteristic radius $R_0 = 0.8$ [38], which corresponds to the AK8 jet clustering distance parameter.

3 Signal and background processes

The main benchmark decay mode in this paper is $X \to HY \to b\bar{b}W^+W^-$, where X and Y are scalar particles, and where both W bosons decay hadronically. It is simulated at leading order (LO) using the MADGRAPH5_aMC@NLO 2.6.5 [39] event generator and the NMSSM model [17, 40]. The samples are generated for 42 different combinations of M_X and M_Y values, with M_X ranging from 1400 to 3000 GeV, and M_Y ranging from 90 to 400 GeV. The range of M_X is chosen to ensure full trigger efficiency at low mass and sufficient background event yields for the background estimation procedure at high mass, while the M_Y values are selected to maintain validity of the Lorentz-boosted regime across the M_X spectrum. Two other scalar decay modes, $Y \to q\bar{q}$ (with $u\bar{u}$ used as a proxy) and $Y \to t\bar{t}$, are also simulated at LO with the NMSSM model using MADGRAPH5_aMC@NLO 2.6.5, each with a fixed M_Y (200 and 400GeV, respectively) and the same range of M_X values as the main benchmark. The above scalar benchmark processes are modeled assuming production via gluon-gluon fusion. The $Y \to bq\bar{q}'$ decay mode is also considered, motivated by models predicting vector-like quarks [18]. In this scenario, X is identified as a vector-like quark and Y as the top quark. Here, the anomalous jet originates from the fully hadronic decay of the top quark, providing an example that such jets do not necessarily have to come from a BSM particle. This scenario is simulated at LO for six different M_X values with M_Y set to the mass of the top quark. In the rest of the paper, we differentiate between the signal models by specifying the decay mode of Y. All generated signal samples assume the narrow-width approximation for X and Y.

The SM background consists of $t\bar{t}$ production, QCD multijet events, W+jets and Z+jets processes, and H production, with and without an associated vector boson.

The $t\bar{t}$ events in all-hadronic or lepton(s)+jets final states are modeled using POWHEG 2.0 [41–44], at next-to-LO (NLO). The simulated $t\bar{t}$ event yields are normalized using a cross section of 834 pb, calculated at next-to-NLO (NNLO) in QCD with soft gluon resummation at next-to-next-to-leading logarithmic precision [45]. The theoretical uncertainty on this cross section is approximately 5%, combining scale, parton distribution function (PDF), and top mass uncertainties in quadrature.

The QCD multijet, W+jets, and Z+jets event samples are simulated at LO using the MADGRAPH5_aMC@NLO event generator. These backgrounds have nonresonant distributions in the analysis observables and are thus jointly estimated using data from the sidebands. Their simulated samples are only used to develop the tools for the analysis. The gluon-gluon fusion H boson production process is simulated using the MINLO event generator [46]. The POWHEG generator [47, 48] is used to model H production via vector boson fusion and associated production with a W or Z boson at NLO accuracy.

All samples are generated using the NNPDF3.1 [49] NNLO PDFs from the LHAPDF6 PDF library [50]. The showering and hadronization of partons are simulated with PYTHIA 8.240 [51] and the CP5 underlying event tune [52].

All generated events are processed through a simulation of the CMS detector based on GEANT4 [53]. The effects of pileup are modeled assuming a total inelastic pp cross section of 69.2 mb [54] by overlapping simulated minimum bias events with the hard-scattering process. All simulated event samples are weighted to match the distribution of pileup vertices observed in the data.

4 Event selection

The online selection uses triggers based on significant jet activity. Different trigger thresholds were used in 2016 (2017 and 2018) as follows. One trigger criterion required a single AK8 jet with $p_T > 450$ (500) GeV. A second trigger required that H_T, the scalar sum of the p_T of all AK4 jets with $p_T > 30$ GeV and $|\eta| < 2.5$, must be greater than 900 (1050) GeV. Additionally, in 2017–2018, a third trigger algorithm required an AK8 jet with a trimmed mass > 30 GeV along with $p_T > 400$ GeV. The combined logical OR of all the triggers is used. The trigger selection is fully efficient with respect to the offline selection.

The offline selection requires the two leading (in p_T) AK8 jets to have $p_T > 300$ GeV and $|\eta| < 2.4$. A requirement is also placed on the invariant mass of the two jets, $M_{jj} > 1300$ GeV, where M_{jj} is computed from the jet four-vectors, including the jet mass. A selection is also placed on the difference in η between the jets, $|\Delta\eta_{jj}| < 1.3$, in order to further suppress the QCD multijet background, which is characterized by larger jet separation. Finally, the H candidate jet, defined below, is required to have its soft-drop mass in the 100–150 GeV range.

The ParticleNet algorithm [55] is used to discriminate AK8 jets consistent with the decay of a massive particle into $b\bar{b}$ against the background from jets originating from QCD multijet production. A mass-decorrelated version of ParticleNet [56] is used to ensure that background-enriched regions can be defined using jets with low ParticleNet scores while maintaining the same background mass distributions in the regions passing the ParticleNet selection. The jet with the higher ParticleNet score is considered to be the H candidate jet and the other to be the Y candidate jet. The soft-drop mass of the Y candidate jet (M_j^Y) is used as a second observable alongside M_{jj}.

An AE neural network [57] is used to quantify the anomaly score of the Y candidate jet. An AE consists of two parts. The first part, the "encoder", compresses an input into a latent representation of reduced dimensionality. The second part, the "decoder", reverses this process and attempts to reconstruct the original input from the reduced representation. We choose to represent jets as 32×32 pixel images [58], covering a region of η–ϕ space with width $\Delta\eta = \Delta\phi = 1.2$ centered on the jet axis, where ϕ is the azimuthal angle in radians. The intensity of each pixel is determined by the sum of energies from the constituent particles within the given η–ϕ region. We define the anomaly score as the mean squared difference between the pixel intensities of the input image and the reconstructed output. This AE architecture was previously used in Ref. [19] as part of the "Tag N' Train" method (as discussed in Appendix A.2 of Ref. [19]). The training is performed on simulated QCD jets, allowing the AE to compress these jets with minimal information loss. However, for non-QCD jets (from signal, $t\bar{t}$ production, etc.), which exhibit different substructure patterns, this procedure leads to poor compression and reconstruction of the original jet. This enables effective discrimination of non-QCD jets.

Each event is categorized into one of four groups based on the ParticleNet score of the H candidate jet (pass or fail) and the anomaly score of the Y candidate jet (control region or measurement region): CR Pass, CR Fail, MR Pass, and MR Fail. The CR is used to validate the background estimation method, described below, whereas the MR is used to extract the signal. The Fail regions are used to help estimate the shape of the QCD multijet background in their corresponding Pass regions.

A ParticleNet working point corresponding to a ≈60% signal efficiency (defined as the fraction of signal jets passing the selection), as measured on the main benchmark with $M_X = 2000$ GeV and $M_Y = 250$ GeV, and a ≈0.5% mistag rate (defined as the fraction of multijet background jets passing the selection) defines the boundary between the Pass and Fail tagging

categories.

An anomaly score working point with ≈85% signal efficiency and 30% mistag rate on the same benchmark defines the MR region. The CR consists of jets that fail the anomaly score MR working point. A lower bound on the anomaly score is applied so that the CR remains similar to the MR, which helps with the validation of the background estimation method. As a result, about 10% of signal and 30% of QCD jets are assigned to the CR.

The PARTICLENET efficiency for correctly identifying $H \to b\bar{b}$ jets is calibrated in observed data using a sample of jets originating from fragmentation of a gluon to $b\bar{b}$, which are similar to $H \to b\bar{b}$ jets. Such jets are selected from the observed data using a boosted decision tree classifier, such that their ensemble PARTICLENET score resembles that of $H \to b\bar{b}$ jets [59]. A systematic uncertainty is assigned to account for the sensitivity of the results to changes in the boosted decision tree requirement applied to the jets. The data-to-simulation correction factors for the PARTICLENET signal selection efficiency range from 0.93–1.05, with uncertainties up to 15%, depending on the jet p_T and data-taking period. The PARTICLENET efficiency for misidentifying jets from the $t\bar{t}$ background as $H \to b\bar{b}$ jets is constrained directly in the fit to data by allowing the yield in the Pass and Fail regions to vary while keeping the total yield constant.

The data-to-simulation scale factors for the efficiency of the anomaly score selection are calculated using the Lund plane reweighting method [60], separately for each signal process and for the $t\bar{t}$ background. The method involves applying per-jet event weights based on their distribution in the Lund plane, a 2D representation defined by the logarithms of splitting angle and p_T. These weights are used to adjust the simulated radiation pattern so that the density in the Lund plane matches that observed in the data. It was found that the shapes of the two observables, M_j^Y and M_{jj}, do not change significantly with the application of per-jet weights. This allows applying an overall correction to the anomaly tagging efficiency instead of per-jet event reweighting. The corrections are calculated as the ratio of the anomaly tagging efficiency before and after per-jet reweighting. They are found to be compatible with unity, with 10–20% uncertainty.

5 Statistical model

The analysis searches for a localized signal in the 2D M_{jj}-M_j^Y plane. The M_{jj} (M_j^Y) axis spans the 1300–3000 (40–500) GeV range. For higher masses, the bin widths are increased in order to ensure sufficient population of each bin. As a result, all the bins in the MR Fail have 8 or more observed events. This helps to reduce the per-bin statistical uncertainties in the QCD multijet background in the Pass region. The M_{jj}-M_j^Y distributions for the background and signal predictions are simultaneously fitted to data in either the MR Pass and MR Fail, or CR Pass and CR Fail. The contributions from different data-taking periods are added together in data and simulation to construct 2D histogram templates. The templates for the $t\bar{t}$ and H production background processes, and for the signal benchmarks, are obtained from simulation. A pass-to-fail ratio method, described in the following paragraphs, is used to model the nonresonant background.

The pass-to-fail ratio method is based on the ratio of M_{jj}-M_j^Y distributions between PARTICLENET Pass and Fail regions: $R_{P/F}(M_{jj}, M_j^Y)$. It is defined through the relation:

$$n_{P,nr}(i) = n_{F,nr}(i) R_{P/F}(M_{jj}, M_j^Y), \tag{1}$$

where $n_{\mathrm{F(P),nr}}(i)$ is the number of nonresonant events in bin i of the M_{jj}-$M_{\mathrm{j}}^{\mathrm{Y}}$ distribution in the Fail (Pass) region. Since the Fail region is dominated by nonresonant events, $n_{\mathrm{F,nr}}(i)$ can be directly estimated from data by subtracting the relatively small simulated yields of other processes. The $R_{\mathrm{P/F}}$ is a priori unknown and is determined during the fit of signal and background distributions to the data. It is modeled as a polynomial in M_{jj} and $M_{\mathrm{j}}^{\mathrm{Y}}$ of order n and is defined as a linear combination of $M_{\mathrm{jj}}^{a}\mathrm{M}_{\mathrm{jY}}^{b}$ terms where the exponents a and b satisfy $a + b \leq n$. Simulation shows no strong dependence of the PARTICLENET mistag rate in either of the two observables, whereas the mistag rate of anomaly tagging is observed to rise with jet mass in the simulation. This makes PARTICLENET tagging the preferred method for defining the Pass and Fail regions for background estimation, ensuring that polynomials with low n will be able to well describe $R_{\mathrm{P/F}}$. A Fisher's F-test [61] is used to determine the minimum polynomial order necessary and sufficient for the model. Starting from polynomials of order zero, the F-test is used to determine if the next higher order provides a significant improvement in the fit quality. The $R_{\mathrm{P/F}}$ polynomial orders in the CR and MR are discussed in Section 7.

Systematic uncertainties, described in Section 6, are included in the statistical model by generating template histograms representing one standard deviation variations from the nominal simulation. These variations correspond to individual sources of uncertainty. Each is assigned a nuisance parameter in the likelihood function used for statistical interpretation, using a unit Gaussian distribution for shape uncertainties, and a log-normal distribution for normalization uncertainties [62]. These distributions change the simulated template shape according to the corresponding template uncertainty histograms.

6 Systematic uncertainties

Several sources of systematic uncertainty are considered, affecting both the shapes and yields of the signal and background templates. Data-to-simulation scale factors for the PARTICLENET signal and H boson background efficiency are calculated with the method discussed in Section 4. They have approximately 10% uncertainty. For the $\mathrm{t\bar{t}}$ background, the mistag rate correction is directly determined during the fit using the Pass and Fail regions. The scale factors for signal and $\mathrm{t\bar{t}}$ anomaly tagging efficiency, also discussed in Section 4, have uncertainties of about 15–30%. For the H boson background, a 20% uncertainty is assigned to the anomaly tagging efficiency.

Initial- and final-state radiation uncertainties are evaluated separately by varying the renormalization scale used in the parton shower by factors of 0.5 and 2. Measured uncertainties on jet energy scale and resolution are propagated to the jets used in the analysis in order to evaluate their effects. Scale and resolution uncertainties are considered uncorrelated.

The PDF uncertainties are evaluated as the square root of differences of squared PDF Hessian eigenvector sets using NNPDF3.1 PDF sets. The uncertainties coming from the choice of renormalization and factorization scales are evaluated by separately varying each of the scales while keeping the other fixed to the nominal value, and also by scaling both by factors of 0.5 and 2.0. The effect of these variations is found to be negligible for signal acceptance and thus only the $\mathrm{t\bar{t}}$ and H boson backgrounds are affected.

A 1.6% uncertainty in the total integrated luminosity is applied [63–65]. During the 2016–2017 data taking, a gradual shift in the timing of the inputs of the ECAL hardware level trigger in the region of $|\eta| > 2$ caused a specific trigger inefficiency. Event-level weight corrections and their uncertainties are included in the simulation to account for this. A pileup correction is

applied to simulated events based on the true number of interactions in the event. The corresponding uncertainty is generated by varying the inelastic pp cross section at 13 TeV (69.2 mb) by 4.6% [54]. Finally, a 5% normalization uncertainty is applied to the $\mathrm{t\bar{t}}$ cross section.

The impact of each uncertainty source on the fitted signal strength parameter is estimated by varying the corresponding nuisance parameter within its postfit uncertainty and refitting the signal strength, using the $M_X = 2200\,\text{GeV}$ and $M_Y = 250\,\text{GeV}$ simulated signal sample as a representative test case. The uncertainties with the largest impacts, ranging from 5% to 8%, are associated with the efficiency of tagging anomalous jets, the efficiency of tagging $\mathrm{H} \to \mathrm{b\bar{b}}$ jets, parton showering, and the renormalization and factorization scales. Other uncertainties, such as those related to the jet energy scale and resolution, integrated luminosity, and pileup, have smaller effects, altering the signal strength by 3% or less.

Overall, the sensitivity of the analysis is statistically limited, due to the limited amount of the observed data.

7 Results

Maximum likelihood fits are performed with the CMS statistical analysis tool COMBINE [62] to estimate the background and extract the fitted signal. The fits are performed separately in the CR and MR. The F-test favors an $R_{P/F}$ polynomial order of $n = 0\,(2)$ in the CR (MR) fit. Both fits pass the goodness-of-fit test, performed using the saturated model [66]. The p-value [67], indicating the level of agreement with the background-only hypothesis and the observed data, is found to be 0.59 (0.26) in the CR (MR) fit. The postfit distributions from the CR and MR fits are shown in Figs. 2 and 3, respectively.

The joint likelihoods of the signal-plus-background M_{jj}-M_j^Y distributions in the MR Pass and Fail regions are constructed for different signal hypotheses. The maximum likelihood fits are used to extract the observed signal strengths. Out of the 42 $X \to H(b\bar{b})Y(WW)$ mass points considered, the $M_X = 1600\,\text{GeV}$ and $M_Y = 90\,\text{GeV}$ combination corresponds to the largest local significance of 2.1 standard deviations.

The same likelihoods are used to compute upper limits on the signal cross section with a modified frequentist approach, using the $\mathrm{CL_s}$ criterion [68, 69] with the profile likelihood ratio used as the test statistic, in an asymptotic approximation [70].

Figure 4 shows the expected and observed limits at 95% confidence level (CL), assuming the $Y \to W^+W^-$ decay to an all-hadronic final state. These limits range from 0.3–19.1 fb. In the upper left corner of the figures, where M_X is low and M_Y is high, we begin to exit the Lorentz-boosted regime. This results in the Y decay products being reconstructed as separate jets, reducing the efficiency of the offline selection and leading to higher upper limits.

Comparable searches have been performed by the ATLAS Collaboration using both unsupervised [71, 72] and weakly supervised [73] anomaly detection techniques in two-body and dijet final states. The search in Ref. [71] targets several two-body final states, while Ref. [72] specifically focuses on the $X \to H(b\bar{b})Y$ topology, where Y decays to a fully hadronic state, using anomalous-jet tagging. These unsupervised searches explore broader ranges of both M_X and M_Y than the analysis presented here, whereas the weakly supervised search [73] focuses on higher M_X regions. Finally, a targeted ATLAS search for $X \to HS$, with $H \to \gamma\gamma$ and $S \to b\bar{b}$ [74], explores complementary lower-mass regions with $M_X < 1\,\text{TeV}$. Overall, these analyses provide complementary sensitivity across different mass ranges and final-state topologies. The presented results can be compared to the CMS search for resonances decaying into two

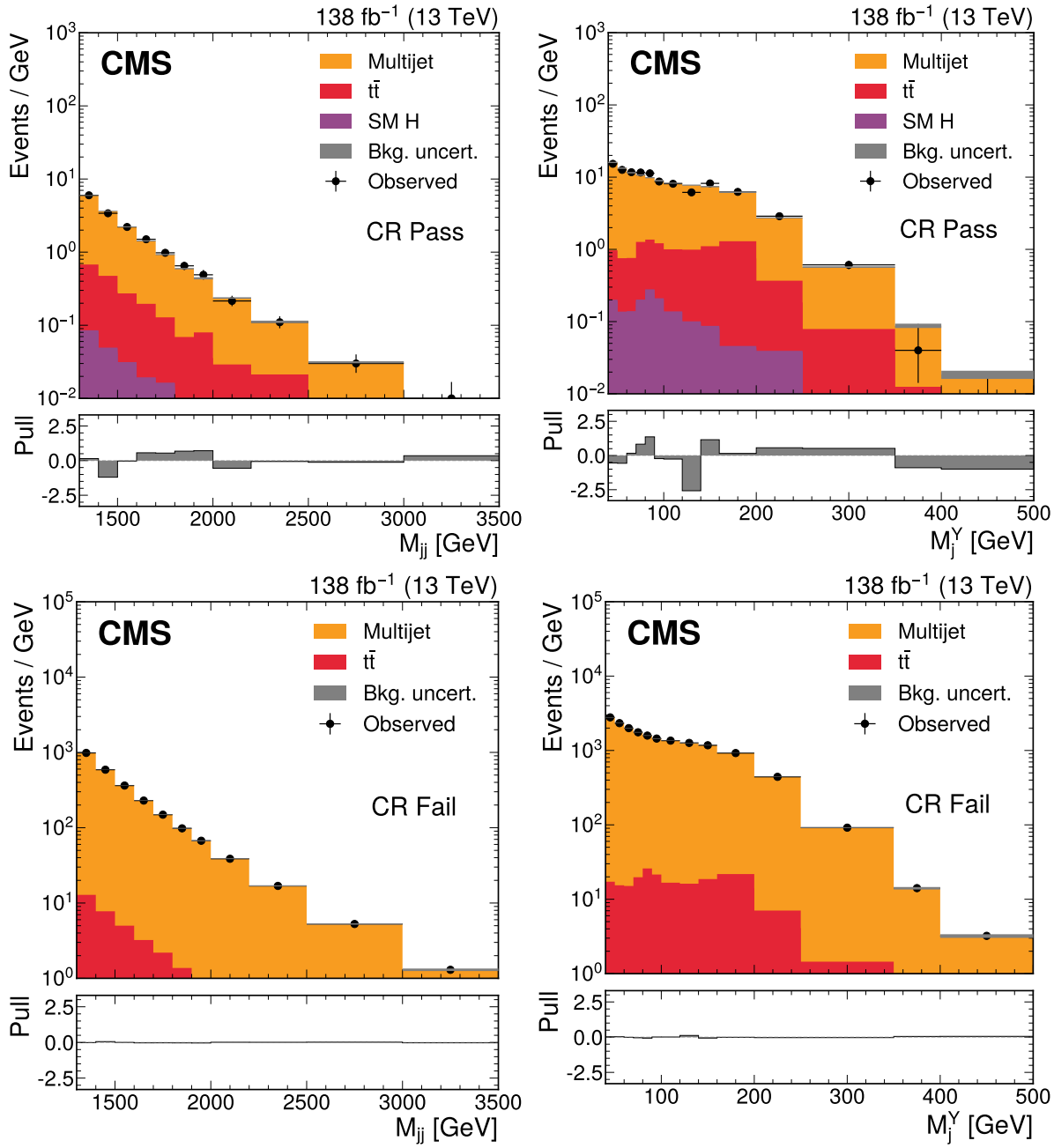

Figure 2: The M_{jj} (left) and M_j^Y (right) projections showing the number of observed events per GeV (black markers) compared with the backgrounds estimated in the fit to the data (filled histograms) in the CR. Pass (upper) and Fail (lower) categories are shown. The high level of agreement between the model and the data in the Fail region arises because this region is used to constrain the background estimate. The lower panels show the "Pull" defined as $(\text{observed events} - \text{expected events})/\sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{bkg}}^2}$, where σ_{obs} and σ_{bkg} are the total uncertainties in the observation and the background estimation, respectively.

jets [19], which reports expected model-independent limits on dijet resonances in the 50–600 fb range for M_X values between 1.8 and 3.0 TeV, depending on the method and M_X. The most sensitive method sets limits around 60 fb across this M_X range. Reference [19] also provides limits on a process that consists of a Kaluza–Klein excitation of a W boson (W_{KK}) decaying into

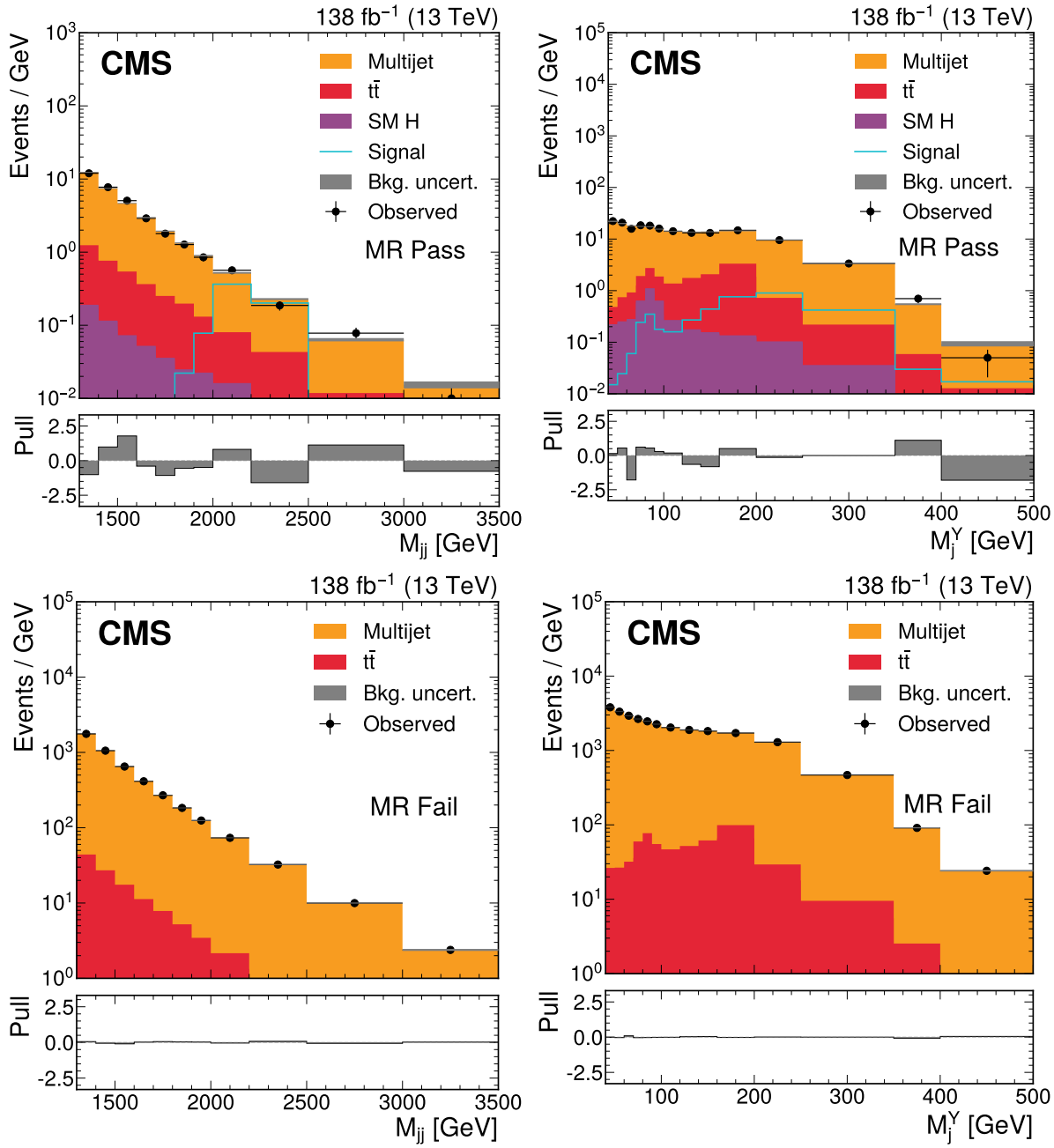

Figure 3: The M_{jj} (left) and M_j^Y (right) projections showing the number of observed events per GeV (black markers) compared with the backgrounds estimated in the fit to the data (filled histograms) in the MR. Pass (upper) and Fail (lower) categories are shown. The expected contribution from the signal benchmark with $M_X = 2200\,\text{GeV}$ and $M_Y = 250\,\text{GeV}$ is overlaid in the MR Pass, assuming a production cross section of 5 fb. The high level of agreement between the model and the data in the Fail region arises because this region is used to constrain the background estimate. The lower panels show the "Pull" defined as $(\text{observed events} - \text{expected events})/\sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{bkg}}^2}$, where σ_{obs} and σ_{bkg} are the total uncertainties in the observation and the background estimation, respectively.

a radion and a W boson [75, 76]. The radion then decays into two W bosons, and all three W bosons undergo hadronic decays. The comparison to our results is motivated by the similarity

in jet substructure: both analyses involve a four-prong jet from the $Y \to W^+W^-$ decay and a two-prong jet originating from either H or W boson decay, where "prong" refers to the number of hard subjets within a large-radius jet. Although there are no directly overlapping mass points, we can compare the expected limits for a W_{KK} boson mass of 3000 GeV and a radion mass of 170 GeV (22.1 fb) with our limits for $M_X = 3000$ GeV and $M_Y = 200$ GeV (0.4 fb). In all cases, our analysis sets more stringent limits, as expected, mostly because we require one of the jets to originate from $H \to b\bar{b}$. While this requirement makes the results less general, it enables the use of PARTICLENET tagging, which provides most of the sensitivity in the analysis, with the autoencoder giving a modest additional improvement. Figure 5 shows 95% CL upper limits on the cross section for the three additional signal scenarios considered. Notably, the $Y \to t\bar{t}$ scenario constitutes the first search performed in the Lorentz-boosted regime for this process. The differences in the limits among the scenarios arise mainly from their distinct kinematic properties and the varying background levels in the corresponding regions of phase space, both influenced by the different assumed Y masses.

Tabulated results of this analysis are available on HEPData [77]. The HepData entry also includes the trained AE weights used for the anomaly score evaluation.

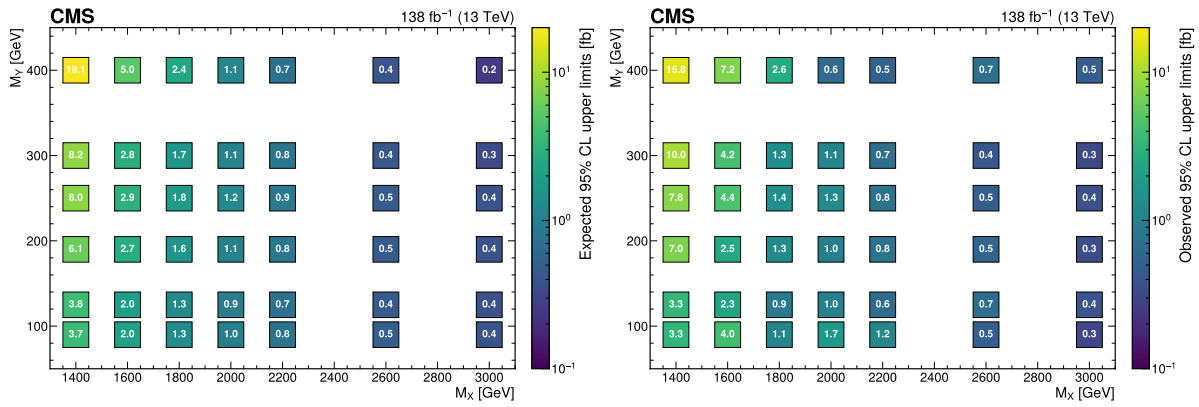

Figure 4: The expected (left) and observed (right) 95% confidence level upper limits on $\sigma(p \to X \to HY)\mathcal{B}(H \to b\bar{b})\mathcal{B}(Y \to WW \to 2q2\bar{q}')$ for different values of M_X and M_Y. The limits have been evaluated in discrete steps corresponding to the centers of the boxes. The numbers in the boxes are given in fb.

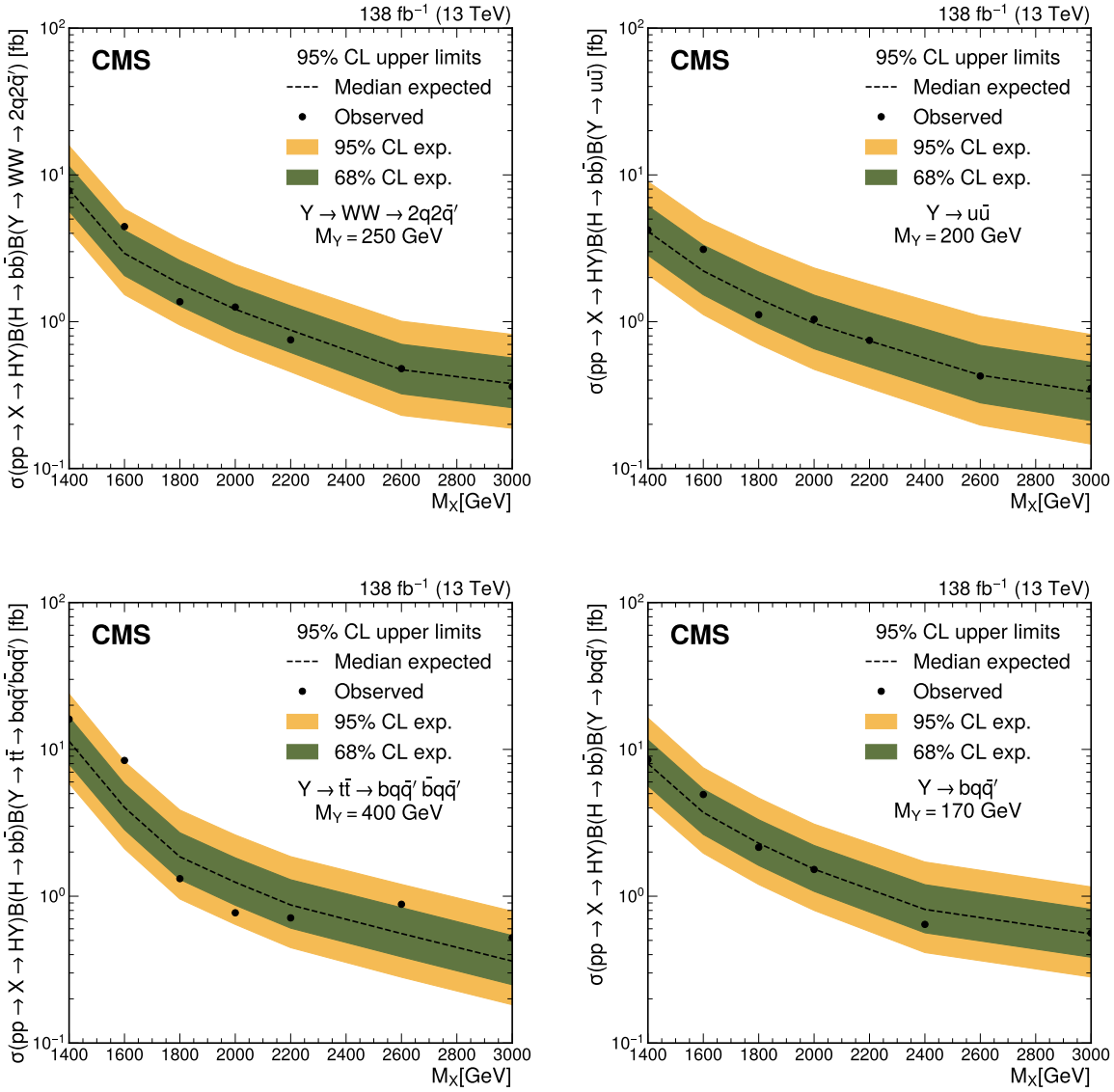

Figure 5: The median expected (dashed line) 95% confidence level upper limits on the main and three alternative signal scenarios as a function of M_X. The inner (green) and outer (yellow) bands represent the regions containing 68% and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The solid dots indicate the observed limits, which are only evaluated at the simulated mass points.

8 Summary

A search for beyond the standard model physics through the process where a resonant particle decays into a Higgs boson, H, and an additional particle Y has been presented. The H subsequently decays into a bottom quark-antiquark pair, $\mathrm{b\bar{b}}$, reconstructed as a large-radius jet in the Lorentz-boosted regime. The H candidate jets are tagged using the PARTICLENET algorithm that is designed to recognize jets originating from a decay of a massive particle into $\mathrm{b\bar{b}}$. The identification of the second particle, Y, is performed by computing the anomaly score of its candidate jet using an autoencoder, allowing the simultaneous search for multiple Y decay modes within a single analysis. This approach combines the targeted identification of H decays with model-independent anomaly detection technique, enabling a broad search for new physics. By combining the strong discrimination power of the H boson decay to $\mathrm{b\bar{b}}$ with a model-independent anomaly detection for the second particle, this analysis achieves enhanced sensitivity for scenarios involving a Higgs boson in the decay chain, while maintaining applicability across a range of such models.

The analysis considers four benchmark models. The main benchmark assumes $\mathrm{Y} \to \mathrm{W^+W^-}$, with further hadronic decays of the W bosons. It is simulated for M_X values within 1400–3000 GeV and M_Y values within 90–400 GeV, covering 42 signal hypotheses. No significant excess above the standard model background expectations is observed. Upper limits on benchmark signal cross sections at 95% confidence level are set on the main benchmark model in the 0.3–15.8 fb range. Additionally, exclusion limits are calculated for three alternative benchmark models, assuming $\mathrm{Y} \to \mathrm{u\bar{u}}$, $\mathrm{Y} \to \mathrm{t\bar{t}}$, or $\mathrm{Y} \to \mathrm{bq\bar{q}'}$ decay modes, for which the most stringent limits to date are achieved.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: 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, TARISTU24-TK10 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMFTR, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES, NSC, and NAWA (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Türkiye); 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, 101001205, 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 Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Beijing Municipal Science & Technology Commission, No. Z191100007219010, the Fundamental Research Funds for the Central Universities, the Ministry of Science and Technology of China under Grant No. 2023YFA1605804, and the Natural Science Foundation of China under Grant No. 12061141002 (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), among others, 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, TKP2021-NKTA-64, and 2021-4.1.2-NEMZ_KI-2024-00036 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing, FAIR – Future Artificial Intelligence Research, and CUP I53D23001070006 (Mission 4 Component 1), 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, 2021/43/B/ST2/01552, 2023/49/B/ST2/03273, and the NAWA contract BPN/PPO/2021/1/00011 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MICIU/AEI/10.13039/501100011033, ERDF/EU, "European Union NextGenerationEU/PRTR", 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 B39G680009 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

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

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

[3] A. Salam, "Weak and electromagnetic interactions", in *Elementary particle physics: relativistic groups and analyticity*, N. Svartholm, ed., p. 367. Almqvist & Wiksell, Stockholm, 1968.

[4] Planck Collaboration, "Planck 2018 results: I. Overview and the cosmological legacy of Planck", *Astron. Astrophys.* **641** (2020) A1, doi:10.1051/0004-6361/201833880, arXiv:1807.06205.

[5] J. de Vries, M. Postma, and J. van de Vis, "The role of leptons in electroweak baryogenesis", *JHEP* **04** (2019) 024, doi:10.1007/JHEP04(2019)024, arXiv:1811.11104.

[6] P. Fayet, "Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino", *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7.

[7] P. Fayet, "Spontaneously broken supersymmetric theories of weak, electromagnetic and strong interactions", *Phys. Lett. B* **69** (1977) 489, doi:10.1016/0370-2693(77)90852-8.

[8] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, "The hierarchy problem and new dimensions at a millimeter", *Phys. Lett. B* **429** (1998) 263, doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.

[9] L. Randall and R. Sundrum, "Large mass hierarchy from a small extra dimension", *Phys. Rev. Lett.* **83** (1999) 3370, doi:10.1103/PhysRevLett.83.3370, arXiv:hep-ph/9905221.

[10] L. Randall and R. Sundrum, "An alternative to compactification", *Phys. Rev. Lett.* **83** (1999) 4690, doi:10.1103/PhysRevLett.83.4690, arXiv:hep-th/9906064.

[11] T. Robens, T. Stefaniak, and J. Wittbrodt, "Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios", *Eur. Phys. J. C* **80** (2020) 151, doi:10.1140/epjc/s10052-020-7655-x, arXiv:1908.08554.

[12] G. Kasieczka et al., "The LHC Olympics: a community challenge for anomaly detection in high energy physics", *Rep. Prog. Phys.* **84** (2021) 124201, doi:10.1088/1361-6633/ac36b9, arXiv:2101.08320.

[13] CMS Collaboration, "Searches for Higgs boson production through decays of heavy resonances", *Phys. Rep.* **1115** (2025) 368, doi:10.1016/j.physrep.2024.09.004, arXiv:2403.16926.

[14] F. Domingo and S. Paßehr, "About the bosonic decays of heavy Higgs states in the (N)MSSM", *Eur. Phys. J. C* **82** (2022) 962, doi:10.1140/epjc/s10052-022-10919-4, arXiv:2207.05776.

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

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

[17] U. Ellwanger, C. Hugonie, and A. M. Teixeira, "The next-to-minimal supersymmetric standard model", *Phys. Rep.* **496** (2010) 1, doi:10.1016/j.physrep.2010.07.001, arXiv:0910.1785.

[18] A. Carvalho et al., "Single production of vectorlike quarks with large width at the Large Hadron Collider", *Phys. Rev. D* **98** (2018) 015029, doi:10.1103/physrevd.98.015029, arXiv:1805.06402.

[19] CMS Collaboration, "Model-agnostic search for dijet resonances with anomalous jet substructure in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Rep. Prog. Phys.* **88** (2025) 067802, doi:10.1088/1361-6633/add762, arXiv:2412.03747.

[20] H. Qu and L. Gouskos, "ParticleNet: Jet tagging via particle clouds", *Phys. Rev. D* **101** (2020) 056019, doi:10.1103/PhysRevD.101.056019, arXiv:1902.08570.

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

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

[23] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[24] CMS Collaboration, "Performance of the CMS high-level trigger during LHC Run 2", *JINST* **19** (2024) P11021, doi:10.1088/1748-0221/19/11/P11021, arXiv:2410.17038.

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

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

[27] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[28] CMS Collaboration, "Development of the CMS detector for the CERN LHC Run 3", *JINST* **19** (2024) P05064, doi:10.1088/1748-0221/19/05/P05064, arXiv:2309.05466.

[29] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[30] CMS Collaboration, "Pileup mitigation at CMS in 13 TeV data", *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/p09018, arXiv:2003.00503.

[31] D. Bertolini, P. Harris, M. Low, and N. Tran, "Pileup per particle identification", *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.

[32] G. P. Salam, "Towards jetography", *Eur. Phys. J. C* **67** (2010) 637, doi:10.1140/epjc/s10052-010-1314-6, arXiv:0906.1833.

[33] D. Krohn, J. Thaler, and L.-T. Wang, "Jet trimming", *JHEP* **02** (2010) 084, doi:10.1007/JHEP02(2010)084, arXiv:0912.1342.

[34] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, "Better jet clustering algorithms", *JHEP* **08** (1997) 001, doi:10.1088/1126-6708/1997/08/001, arXiv:hep-ph/9707323.

[35] M. Wobisch and T. Wengler, "Hadronization corrections to jet cross-sections in deep inelastic scattering", in *Proceedings of the Workshop on Monte Carlo Generators for HERA Physics*. DESY, Hamburg, 1998. arXiv:hep-ph/9907280.

[36] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, "Towards an understanding of jet substructure", *JHEP* **09** (2013) 029, doi:10.1007/JHEP09(2013)029, arXiv:1307.0007.

[37] J. M. Butterworth, A. R. Davison, M. Rubin, and G. P. Salam, "Jet substructure as a new Higgs search channel at the LHC", *Phys. Rev. Lett.* **100** (2008) 242001, doi:10.1103/PhysRevLett.100.242001, arXiv:0802.2470.

[38] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, "Soft drop", *JHEP* **05** (2014) 146, doi:10.1007/JHEP05(2014)146, arXiv:1402.2657.

[39] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[40] A. Djouadi et al., "Benchmark scenarios for the NMSSM", *JHEP* **07** (2008) 002, doi:10.1088/1126-6708/2008/07/002, arXiv:0801.4321.

[41] S. Frixione, G. Ridolfi, and P. Nason, "A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction", *JHEP* **09** (2007) 126, doi:10.1088/1126-6708/2007/09/126, arXiv:0707.3088.

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

[43] S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX", *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

[44] P. Nason, "A new method for combining NLO QCD with shower Monte Carlo algorithms", *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[45] M. Czakon and A. Mitov, "Top++: A program for the calculation of the top-pair cross-section at hadron colliders", *Comput. Phys. Commun.* **185** (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.

[46] K. Hamilton, P. Nason, E. Re, and G. Zanderighi, "NNLOPS simulation of Higgs boson production", *JHEP* **10** (2013) 222, doi:10.1007/jhep10(2013)222.

[47] P. Nason and C. Oleari, "NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG", *JHEP* **02** (2010) 037, doi:10.1007/JHEP02(2010)037, arXiv:0911.5299.

[48] G. Luisoni, P. Nason, C. Oleari, and F. Tramontano, "$HW^{\pm}$/HZ+0 and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO", *JHEP* **10** (2013) 083, doi:10.1007/JHEP10(2013)083, arXiv:1306.2542.

[49] NNPDF Collaboration, "Parton distributions from high-precision collider data", *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.

[50] A. Buckley et al., "LHAPDF6: parton density access in the LHC precision era", *Eur. Phys. J. C* **75** (2015) 132, doi:10.1140/epjc/s10052-015-3318-8, arXiv:1412.7420.

[51] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[52] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA 8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

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

[54] CMS Collaboration, "Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13\,\text{TeV}$", *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.

[55] CMS Collaboration, "Identification of highly Lorentz-boosted heavy particles using graph neural networks and new mass decorrelation techniques", CMS Detector Performance Summary CMS-DP-2020-002, 2020.

[56] CMS Collaboration, "Calibration of the mass-decorrelated ParticleNet tagger for boosted $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ jets using LHC Run 2 data", CMS Detector Performance Summary CMS-DP-2022-005, 2022.

[57] G. E. Hinton and R. R. Salakhutdinov, "Reducing the dimensionality of data with neural networks", *Science* **313** (2006) 504, doi:10.1126/science.1127647.

[58] S. Macaluso and D. Shih, "Pulling out all the tops with computer vision and deep learning", *JHEP* **10** (2018) 121, doi:10.1007/JHEP10(2018)121, arXiv:1803.00107.

[59] CMS Collaboration, "Performance of heavy-flavour jet identification in boosted topologies in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *JINST* **20** (2025) P11006, doi:10.1088/1748-0221/20/11/P11006, arXiv:2510.10228.

[60] CMS Collaboration, "A method for correcting the substructure of multiprong jets using the Lund jet plane", *JHEP* **11** (2025) 038, doi:10.1007/JHEP11(2025)038, arXiv:2507.07775.

[61] R. A. Fisher, "On the interpretation of χ^2 from contingency tables, and the calculation of P", *J. R. Stat. Soc.* **85** (1922) 87, doi:10.2307/2340521.

[62] CMS Collaboration, "The CMS statistical analysis and combination tool: COMBINE", *Comput. Softw. Big Sci.* **8** (2024) 19, doi:10.1007/s41781-024-00121-4, arXiv:2404.06614.

[63] CMS Collaboration, "Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ in 2015 and 2016 at CMS", *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[64] CMS Collaboration, "CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13\,\text{TeV}$", CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

[65] CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13\,\text{TeV}$", CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[66] R. D. Cousins, "Lectures on statistics in theory: Prelude to statistics in practice", 2018. arXiv:1807.05996.

[67] E. Gross and O. Vitells, "Trial factors for the look elsewhere effect in high energy physics", *Eur. Phys. J. C* **70** (2010) 525, doi:10.1140/epjc/s10052-010-1470-8, arXiv:1005.1891v3.

[68] T. Junk, "Confidence level computation for combining searches with small statistics", *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[69] A. L. Read, "Presentation of search results: the CL_s technique", *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.

[70] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[71] ATLAS Collaboration, "Search for new phenomena in two-body invariant mass distributions using unsupervised machine learning for anomaly detection at $\sqrt{s} = 13$ TeV with the ATLAS detector", *Phys. Rev. Lett.* **132** (2024) 081801, doi:10.1103/PhysRevLett.132.081801, arXiv:2307.01612.

[72] ATLAS Collaboration, "Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states using $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector", *Phys. Rev. D* **108** (2023) 052009, doi:10.1103/PhysRevD.108.052009, arXiv:2306.03637.

[73] ATLAS Collaboration, "Weakly supervised anomaly detection for resonant new physics in the dijet final state using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *Phys. Rev. D* **112** (2025) 072009, doi:10.1103/2yq5-vj59, arXiv:2502.09770.

[74] ATLAS Collaboration, "Search for a resonance decaying into a scalar particle and a Higgs boson in the final state with two bottom quarks and two photons in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *JHEP* **11** (2024) 047, doi:10.1007/jhep11(2024)047, arXiv:2404.12915.

[75] K. Agashe, P. Du, S. Hong, and R. Sundrum, "Flavor universal resonances and warped gravity", *JHEP* **01** (2017) 016, doi:10.1007/JHEP01(2017)016, arXiv:1608.00526.

[76] K. Agashe et al., "Dedicated strategies for triboson signals from cascade decays of vector resonances", *Phys. Rev. D* **99** (2019) 075016, doi:10.1103/PhysRevD.99.075016, arXiv:1711.09920.

[77] HEPData record for this analysis, 2025. doi:10.17182/hepdata.158363.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, V. Makarenko, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, L. Benato, T. Bergauer, M. Dragicevic, C. Giordano, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, M. Matthewman, I. Mikulec, J. Schieck[2], R. Schöfbeck[2], D. Schwarz, M. Shooshtari, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, D. Ocampo Henao, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
J. Bierkens, N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, Y. Hong, P. Kashko, S. Lowette, I. Makarenko, D. Müller, J. Song, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, A. Khalilzadeh, F.A. Khan, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, F. Zhang

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, J. Knolle, D. Marckx, K. Skovpen, N. Van Den Bossche, J. van der Linden, J. Vandenbroeck, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Bein, A. Benecke, A. Bethani, G. Bruno, A. Cappati, J. De Favereau De Jeneret, C. Delaere, A. Giammanco, A.O. Guzel, V. Lemaitre, J. Lidrych, P. Malek, P. Mastrapasqua, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Barroso Ferreira Filho, E. Coelho, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[5], A. Vilela Pereira[4]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], M. Costa Reis, E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, S. S. Jesus, T. Laux Kuhn[7], M. Macedo, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[8]

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], F. Damas, 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, V. Scheurer

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

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

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, D. Laroze, S. Thakur

Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
W. Brooks

Beihang University, Beijing, China
T. Cheng, T. Javaid, L. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu, X. Wang

Institute of High Energy Physics, Beijing, China
G.M. Chen[9], H.S. Chen[9], M. Chen[9], Y. Chen, Q. Hou, X. Hou, F. Iemmi, C.H. Jiang, A. Kapoor[10], H. Liao, G. Liu, Z.-A. Liu[11], J.N. Song[11], S. Song, J. Tao, C. Wang[9], J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, B. Guo, Q. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, J. Wang, H. Yang, M. Zhang, Y. Zhao, C. Zhou

State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
K. Jaffel, N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[12,13], B. Li[14], H. Wang, K. Yi[15], J. Zhang

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

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[16]

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

Universidad de Antioquia, Medellin, Colombia
C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[17,18], R. Aly[19,17]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M. Abdullah Al-Mashad, A. Hussein, H. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Ehataht, M. Kadastik, T. Lange, C. Nielsen, J. Pata, M. Raidal, N. Seeba, L. Tani

Department of Physics, University of Helsinki, Helsinki, Finland
A. Milieva, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, R. Kumar Verma, T. Lampén, K. Lassila-Perini, B. Lehtela, S. Lehti, T. Lindén, N.R. Mancilla Xinto, M. Myllymäki, M.m. Rantanen, S. Saariokari, N.T. Toikka, J. Tuominiemi

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, P. Devouge, J.L. Faure, F. Ferri, P. Gaigne, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, G. Boldrini, P. Busson, C. Charlot, M. Chiusi, T.D. Cuisset, O. Davignon, A. De Wit, T. Debnath, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, L. Kalipoliti, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, L. Urda Gómez, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard,

G. Coulon, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, P. Vaucelle

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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, B. Massoteau, L. Mirabito, A. Purohit, M. Vander Donckt, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia[22], I. Lomidze, Z. Tsamalaidze[23]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, P. Nattland, V. Oppenländer, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
C. Daumann, S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, N. Kumar, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, F. Nowotny, A. Pozdnyakov, W. Redjeb, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, V. Vaulin, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M.R. Beckers, C. Dziwok, G. Flügge, N. Hoeflich, T. Kress, A. Nowack, O. Pooth, A. Stahl, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, A. Abel, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, I. Andreev, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[24], K. Borras[25], A. Campbell, S. Chatterjee, L.X. Coll Saravia, G. Eckerlin, D. Eckstein, E. Gallo[24], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K.-Y. Lin, K. Lipka[26], W. Lohmann[27], J. Malvaso, 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, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham[28,25], S. Schnake[25], P. Schütze, C. Schwanenberger[24], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, M. Torkian, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[25], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A.R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, K. El Morabit, Y. Fischer, M. Frahm, E. Garutti, A. Grohsjean, A.A. Guvenli, J. Haller, D. Hundhausen, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, F. Labe, J. Lange, A. Lobanov, L. Moureaux, A. Nigamova, K. Nikolopoulos, A. Paasch, K.J. Pena Rodriguez, N. Prouvost, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt,

M. Sommerhalder, H. Stadie, G. Steinbrück, R. Ward, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, E. Butz, Y.M. Chen, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[29], R. Hofsaess, M. Horzela, F. Hummer, U. Husemann, J. Kieseler, M. Klute, R. Kunnilan Muhammed Rafeek, O. Lavoryk, J.M. Lawhorn, A. Lintuluoto, S. Maier, M. Mormile, Th. Müller, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, C. Verstege, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, M. Wassmer, R. Wolf, W.D. Zeuner, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, E. Tzovara, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
T. Chatzistavrou, G. Karapostoli, K. Kousouris, E. Siamarkou, G. Tsipolitis

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
D. Druzhkin, C. Hajdu, D. Horvath[30,31], K. Márton, A.J. Rádl[32], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[33], M.M.A. Gadallah[34], Á. Kadlecsik, M. León Coello, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[33], F. Nemes[33], T. Novak, I. Szanyi[35]

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, S. Phor, K. Ranjan, M.K. Saini

University of Hyderabad, Hyderabad, India

S. Acharya[37], B. Gomber[37], B. Sahu[37]

Indian Institute of Technology Kanpur, Kanpur, India
S. Mukherjee

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[38], T. Mishra, P.R. Pujahari, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

IISER Mohali, India, Mohali, India
B.K. Sirasva

Tata Institute of Fundamental Research-A, Mumbai, India
L. Bhatt, S. Dugad, G.B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Barman[39], R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, B.M. Joshi, S. Kumar, M. Maity[39], G. Majumder, K. Mazumdar, S. Parolia, R. Saxena, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[40], D. Maity[41], P. Mal, K. Naskar[41], A. Nayak[41], S. Nayak, K. Pal, R. Raturi, P. Sadangi, S.K. Swain, S. Varghese[41], D. Vats[41]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, P. Hazarika, B. Kansal, A. Laha, R. Sharma, S. Sharma, K.Y. Vaish

Indian Institute of Technology Hyderabad, Telangana, India
S. Ghosh

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[42], A. Jafari[43], V. Sedighzadeh Dalavi, M. Zeinali[44]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[46]

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

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], M. Barbieri[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,17], N. Ferrara[a,c], L. Fiore[a], 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], F. Nenna[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]

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

G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,47], 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]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,48], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,48]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
J. Altork[a,b], P. Assiouras[a], G. Barbagli[a], G. Bardelli[a], M. Bartolini[a,b], A. Calandri[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], L. Damenti[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]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[49], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Alves Gallo Pereira[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], F. Brivio[a], V. Camagni[a,b], 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.R. Kim[a], G. Lavizzari[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,29], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Universita degli Studi di Cagliari[c], Cagliari, Italy
P. Azzi[a], N. Bacchetta[a,51], D. Bisello[a,b], P. Bortignon[a,c], G. Bortolato[a,b], A.C.M. Bulla[a,c], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a,52], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], F. Montecassiano[a], 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]

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

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], C. Carrivale[a,b], D. Ciangottini[a,b], L. Della Penna[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,53], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

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

Università di Siena[d], Siena, Italy
C. Aimè[a,b], 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], L. Calligaris[a,b], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,d], M. Cipriani[a,b], R. Dell'Orso[a], S. Donato[a,b], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,54], T. Sarkar[a], A. Scribano[a], P. Solanki[a,b], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Akrap[a,b], C. Basile[a,b], S.C. Behera[a], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], G. Organtini[a,b], N. Palmeri[a,b], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], V. Vladimirov[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a,c], 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], L. Lanteri[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[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], E. Vlasov[a,b], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
J. Babbar[a,b], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b], R. Delli Gatti[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, J. Kim, T. Kim, D. Lee, H. Lee, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, D.H. Moon, J. Seo

Hanyang University, Seoul, Korea
E. Asilar, F. Carnevali, J. Choi[55], T.J. Kim, Y. Ryou

Korea University, Seoul, Korea
S. Ha, S. Han, B. Hong, J. Kim, K. Lee, K.S. Lee, S. Lee, J. Yoo

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

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

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, H. Kim, J. Kim, T. Kim, Y. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, J. Shin, U.K. Yang, I. Yoon

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

Yonsei University, Department of Physics, Seoul, Korea
G. Cho, K. Hwang, B. Kim, S. Kim, K. Lee, H.D. Yoo

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

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

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, O.M. Eberlins, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, R. Plese, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, S. Nargelas, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[56], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, A. Cota Rodriguez, L.E. Cuevas Picos, H.A. Encinas Acosta, L.G. Gallegos Maríñez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, W.A. Khan

AGH University of Krakow, Krakow, Poland
V. Avati, L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

National Centre for Nuclear Research, Swierk, Poland
M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

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

Warsaw University of Technology, Warsaw, Poland
P. Fokow, K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
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, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, L. Markovic, P. Milenovic, V. Milosevic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Alcalde Martinez, J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, J. Cuchillo Ortega, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, M. Gonzalez Hernandez, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, R. Paz Herrera, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, J. Vazquez Escobar

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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Ayllon Torresano, A. Cardini, J. Cuevas, J. Del Riego Badas, D. Estrada Acevedo, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, A. Soto Rodríguez, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Blanco Fernández, 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, C. Quintana San Emeterio, L. Scodellaro, I. Vila, R. Vilar Cortabitarte, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[57], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[58], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, R. Ardino, E. Auffray, J. Baechler, D. Barney, J. Bendavid, M. Bianco, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, C.E. Brown, C. Caillol, G. Cerminara, P. Connor, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, P.J. Fernández Manteca, W. Funk, A. Gaddi, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[27], G. Karathanasis, S. Laurila, P. Lecoq, C. Lourenço, A.-M. Lyon, M. Magherini, L. Malgeri, M. Mannelli, A. Mehta, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, M. Migliorini, F. Monti, F. Moortgat, M. Mulders, M. Musich, I. Neutelings, S. Orfanelli, F. Pantaleo, M. Pari, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, A. Reimers, B. Ribeiro Lopes, F. Riti, P. Rosado, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[59], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, E. Vernazza, J. Wanczyk[60], J. Wang, S. Wuchterl, M. Zarucki, P. Zehetner, P. Zejdl, G. Zevi Della Porta

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
T. Bevilacqua[61], L. Caminada[61], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, U. Langenegger, L. Noehte[61], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiacchiac[60], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, W. Lustermann, M. Malucchi, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[60], F. Nessi-Tedaldi, F. Pauss, V. Perovic, B. Ristic, R. Seidita, J. Steggemann[60], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[62], P. Bärtschi, F. Bilandzija, M.F. Canelli, G. Celotto, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, T.H. Kwok, S. Leontsinis, V. Lukashenko, A. Macchiolo, F. Meng, M. Missiroli, J. Motta, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano, P. Viscone

National Central University, Chung-Li, Taiwan
D. Bhowmik, C.M. Kuo, P.K. Rout, S. Taj, P.C. Tiwari[38]

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K.F. 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

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas

Tunis El Manar University, Tunis, Tunisia

Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Dolek, I. Dumanoglu[63], Y. Guler[64], E. Gurpinar Guler[64], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[65], B. Tali[66], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[67]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi[68], E. Gülmez, M. Kaya[69], O. Kaya[70], M.A. Sarkisla[71], S. Tekten[72]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[63,73], S. Sen[74]

Istanbul University, Istanbul, Turkey
O. Aydilek[75], B. Hacisahinoglu, I. Hos[76], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak[77], E. Simsek, D. Sunar Cerci, T. Yetkin[78]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, O. Dadazhanova, B. Grynyov

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

University of Bristol, Bristol, United Kingdom
J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, D. Dharmender, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, M.S. Sanjrani[42], J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[79], C. Brew, R.M. Brown, D.J.A. Cockerill, A. Elliot, K.V. Ellis, J. Gajownik, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, M. Moallemi, 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

Imperial College, London, United Kingdom
I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H.R. Hoorani, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, E. Leutgeb, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, L. Russell, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[29], M. Vojinovic, N. Wardle, D. Winterbottom

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

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish, J. Dittmann, K. Hatakeyama, V. Hegde, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Bethel University, St. Paul, Minnesota, USA
J.M. Hogan[81]

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, S. Raj, A.E. Simsek, S.S. Yu

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, S. Campbell, R. Chudasama, S.I. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, A. Khukhunaishvili, K. Matchev, E. Pearson, C.U. Perez, P. Rumerio[82], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
S. Cholak, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, J. Fulcher, F. Golf, S. Jeon, J. O'Cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, E. Wurtz, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, T. Kwon, L. Lambrecht, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, J. Roloff, T. Russell, S. Sagir[83], X. Shen, M. Stamenkovic, N. Venkatasubramanian

University of California, Davis, Davis, California, USA
S. Abbott, B. Barton, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, E. Cannaert, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, O. Kukral, G. Mocellin, S. Ostrom, I. Salazar Segovia, J.S. Tafoya Vargas, W. Wei, S. Yoo

University of California, Los Angeles, California, USA
K. Adamidis, M. Bachtis, D. Campos, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, Y.f. Lo, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, G. Hanson

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, B. D'Anzi, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, V. Krutelyov, R. Lee, J. Letts, H. Li, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, A. Yagil, Z. Zhao

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, S. Carron Montero[84], K. Downham, C. Grieco, M.M. Hussain, J. Incandela, M.W.K. Lai, A.J. Li, P. Masterson, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

California Institute of Technology, Pasadena, California, USA
A. Albert, S. Bhattacharya, A. Bornheim, O. Cerri, R. Kansal, J. Mao, H.B. New-

man, G. Reales Gutiérrez, T. Sievert, M. Spiropulu, J.R. Vlimant, R.A. Wynne, S. Xie

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M. Cremonesi, V. Dutta, E.Y. Ertorer, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, C. Liu, P. Meiring, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, S. Kwan, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, New York, USA
J. Alexander, X. Chen, J. Dickinson, A. Duquette, J. Fan, X. Fan, J. Grassi, S. Hogan, P. Kotamnives, J. Monroy, G. Niendorf, M. Oshiro, J.R. Patterson, A. Ryd, J. Thom, P. Wittich, R. Zou, L. Zygala

Fermi National Accelerator Laboratory, Batavia, Illinois, 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, C. Cosby, G. Cummings, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, C. Lee, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[85], C.E. Perez Lara, F. Ravera, A. Reinsvold Hall[86], 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, C. Wang, I. Zoi

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

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Goff, R. Hashmi, R.S. Kim, T. Kolberg, G. Martinez, M. Mazza, H. Prosper, P.R. Prova, R. Yohay

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Butalla, S. Das, M. Hohlmann, M. Lavinsky, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, N. Barnett, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, C. Mills, S. Nanda, G. Nigmatkulov, B. Ozek, T. Phan, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[87], O.K. Köseyan, A. Mestvirishvili[88], O. Neogi, H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, S. Sekhar, M.V. Srivastav, M. Swartz

The University of Kansas, Lawrence, Kansas, 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, S. Popescu[91], C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, N. Islam, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, G.G. Reddy, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, P. Major, A.C. Mignerey, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[92], A. Shevelev, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, H. Bossi, S. Bright-Thonney, I.A. Cali, Y.c. Chen, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, G.M. Innocenti, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, T.a. Sheng, G.S.F. Stephans, D. Walter, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, W.J. Jackson, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, R. Rusack, O. Sancar, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, A. Rohilla, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, A. Mandal, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young, D. Yu

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Bonilla, B. Bylsma, M. Campana, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, M. Lu, N. Manganelli, R. Mccarthy, D.M. Morse, T. Orimoto, A. Parker, L. Skinnari, C.S. Thoreson, E. Tsai, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Dittmer, K.A. Hahn, Y. Liu, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco, J. Wang

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, A. Ehnis, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, A. Karneyeu, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister,

T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[23], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey

The Ohio State University, Columbus, Ohio, USA
A. Basnet, M. Carrigan, R. De Los Santos, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, D.A. Wenzl, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, M. Galli, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, R. Sharma

Purdue University, West Lafayette, Indiana, USA
S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, N.R. Saha, J.F. Schulte, F. Wang, A. Wildridge, W. Xie, Y. Yao, Y. Zhong

Purdue University Northwest, Hammond, Indiana, USA
N. Parashar, A. Pathak, E. Shumka

Rice University, Houston, Texas, USA
D. Acosta, A. Agrawal, C. Arbour, T. Carnahan, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, T. Huang, I. Krommydas, N. Lewis, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, M. Wulansatiti, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
O. Bessidskaia Bylund, A. Bodek, P. de Barbaro[†], R. Demina, A. Garcia-Bellido, H.S. Hare, O. Hindrichs, N. Parmar, P. Parygin[92], H. Seo, R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, S. Donnelly, D. Gadkari, Y. Gershtein, E. Halkiadakis, C. Houghton, D. Jaroslawski, A. Kobert, S. Konstantinou, I. Laflotte, A. Lath, J. Martins, M. Perez Prada, B. Rand, J. Reichert, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

University of Tennessee, Knoxville, Tennessee, USA
D. Ally, A.G. Delannoy, S. Fiorendi, J. Harris, T. Holmes, A.R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, B. Skipworth, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Bolshov, O. Bouhali[93], A. Cagnotta, V. D'Amante, R. Eusebi, P. Flanagan, J. Gilmore, Y. Guo, T. Kamon, S. Luo, R. Mueller, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, Y. Feng, N. Gogate, Y. Kazhykarim, K. Lamichhane, S.W. Lee, C. Madrid, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen,

J. Zhang

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, G. Hamilton Ilha Machado, R. Hirosky, M. Jose, A. Ledovskoy, C. Mantilla, C. Neu, C. Ramón Álvarez

Wayne State University, Detroit, Michigan, USA
S. Bhattacharya, P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, S. Lomte, R. Loveless, A. Mallampalli, A. Mohammadi, S. Mondal, T. Nelson, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, Yu. Andreev, T. Aushev, D. Budkouski, R. Chistov[94], M. Danilov[94], T. Dimova[94], A. Ershov[94], S. Gninenko, I. Gorbunov, A. Gribushin[94], A. Kamenev, V. Karjavine, M. Kirsanov, V. Klyukhin[94], O. Kodolova[95], V. Korenkov, I. Korsakov, A. Kozyrev[94], N. Krasnikov, A. Lanev, A. Malakhov, V. Matveev[94], A. Nikitenko[96,95], V. Palichik, V. Perelygin, S. Petrushanko[94], S. Polikarpov[94], O. Radchenko[94], M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[94], K. Slizhevskiy, V. Smirnov, O. Teryaev, I. Tlisova[94], A. Toropin, N. Voytishin, B.S. Yuldashev[†97], A. Zarubin, I. Zhizhin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
E. Boos, V. Bunichev, M. Dubinin[85], V. Savrin, A. Snigirev, L. Dudko, K. Ivanov, V. Kim[23], V. Murzin, V. Oreshkin, D. Sosnov

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Ghent University, Ghent, Belgium
[4]Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[5]Also at FACAMP - Faculdades de Campinas, Sao Paulo, 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 The University of the State of Amazonas, Manaus, Brazil
[9]Also at University of Chinese Academy of Sciences, Beijing, China
[10]Also at China Center of Advanced Science and Technology, Beijing, China
[11]Also at University of Chinese Academy of Sciences, Beijing, China
[12]Also at School of Physics, Zhengzhou University, Zhengzhou, China
[13]Now at Henan Normal University, Xinxiang, China
[14]Also at University of Shanghai for Science and Technology, Shanghai, China
[15]Now at The University of Iowa, Iowa City, Iowa, USA
[16]Also at Center for High Energy Physics, Peking University, Beijing, China
[17]Also at Helwan University, Cairo, Egypt
[18]Now at Zewail City of Science and Technology, Zewail, Egypt
[19]Also 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 Ilia State University, Tbilisi, Georgia
[23]Also at an institute formerly covered by a cooperation agreement with CERN
[24]Also at University of Hamburg, Hamburg, Germany
[25]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[26]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[27]Also at Brandenburg University of Technology, Cottbus, Germany
[28]Also at Forschungszentrum Jülich, Juelich, Germany
[29]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[30]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[31]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[32]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[33]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[34]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[35]Also at The University of Kansas, Lawrence, Kansas, USA
[36]Also at Punjab Agricultural University, Ludhiana, India
[37]Also at University of Hyderabad, Hyderabad, India
[38]Also at Indian Institute of Science (IISc), Bangalore, India
[39]Also at University of Visva-Bharati, Santiniketan, India
[40]Also at IIT Bhubaneswar, Bhubaneswar, India
[41]Also at Institute of Physics, Bhubaneswar, 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, Faculty of Science, Arak University, ARAK, Iran
[47]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[48]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[49]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[50]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[51]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[52]Also at Lulea University of Technology, Lulea, Sweden
[53]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[54]Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
[55]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[56]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[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 Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[64]Also at Konya Technical University, Konya, Turkey

[65]Also at Izmir Bakircay University, Izmir, Turkey
[66]Also at Adiyaman University, Adiyaman, Turkey
[67]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[68]Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
[69]Also at Marmara University, Istanbul, Turkey
[70]Also at Milli Savunma University, Istanbul, Turkey
[71]Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
[72]Also at Kafkas University, Kars, Turkey
[73]Now at Istanbul Okan University, Istanbul, Turkey
[74]Also at Hacettepe University, Ankara, Turkey
[75]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[76]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[77]Also at Yildiz Technical University, Istanbul, Turkey
[78]Also at Istinye University, Istanbul, Turkey
[79]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[80]Also at Monash University, Faculty of Science, Clayton, Australia
[81]Also at Bethel University, St. Paul, Minnesota, USA
[82]Also at Università di Torino, Torino, Italy
[83]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[84]Also at California Lutheran University;, Thousand Oaks, California, USA
[85]Also at California Institute of Technology, Pasadena, California, USA
[86]Also at United States Naval Academy, Annapolis, Maryland, USA
[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 another institute formerly covered by a cooperation agreement with CERN
[93]Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
[94]Also at another institute formerly covered by a cooperation agreement with CERN
[95]Also at Yerevan Physics Institute, Yerevan, Armenia
[96]Also at Imperial College, London, United Kingdom
[97]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan